



**AMPACITY OF HIGH VOLTAGE CABLES AND ANALYSIS OF SELECTION
OF OPTIMAL SHEATH BONDING ARRANGEMENT**

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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Ampacity of High Voltage Cables and Analysis of Selection of Optimal Sheath Bonding Arrangement

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High voltage power cable usage has been common practise in transmission and distribution networks for several decades, but its significance has been emphasized in recent years due to the increase in load levels, especially in densely populated areas such as cities, where there is limited space for large overhead lines and visual obstructions need to be minimized.

The thesis delved into the continuous load capacity of high-voltage cables, based on the IEC 60287 series of standards. In addition, the thesis presented special metallic sheath bonding systems and their impact on the load capacity of high voltage power cables and modeled the ampacity rating calculation according to IEC 60287 in Microsoft Excel software.

The manufacturing technology of high voltage power cables has advanced to a point where it is difficult to further increase the ampacity rating with cable structure. Therefore, special attention should be paid to the backfilling materials of cable trenches in order to maintain the soil thermal resistance as low as possible. The use of special filling materials, such as Weak Mix, is recommended in situations where the inherent thermal resistance of the soil is high, or where there are external heat sources near the cable connection that reduce the cable's load capacity.

The thesis questions the current dimensioning calculation methods for high voltage power cables, which are based on 100 % steady-state ampacity rating. The cost-effectiveness of cable connections could potentially be improved by transitioning to dynamic sizing calculations based on the emergency and cyclic ampacity ratings of the high voltage power cable.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT

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Sähkötekniikka

Markus Kohtamäki

Suurjännitekaapelin kuormitettavuus ja analyysi optimaalisesta kosketussuojan maadoitustavan valinnasta

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Suurjännitekaapeleiden käyttö on ollut arkipäivää jo useampien vuosikymmenien ajan siirto- ja jakeluverkoissa, mutta sen merkitys korostuu nykyvuosina kuormitustason nousun takia erityisesti tiheästi asutuilla alueilla, kuten kaupungeissa, koska suurille avojohdoille ei ole tilaa ja mahdolliset visuaaliset haitat halutaan pitää poissa kaupunkiympäristöistä.

Opinnäytetyössä perehdyttiin suurjännitekaapeleiden jatkuvaan kuormitettavuuteen, joka perustuu IEC 60287 standardisarjaan. Tämän lisäksi työssä esitetään kosketussuojan spesiaaleja maadoitusjärjestelmiä ja niiden vaikutusta suurjännitekaapelien kuormitettavuuteen ja mallinnettiin IEC 60287:n mukaisesti kuormitettavuuden laskenta Microsoft Excel ohjelmistoon.

Suurjännitekaapeleiden valmisteknologia on jo kehitetty niin pitkälle, että sillä ei juuri voida enää kasvattaa kaapeleiden kuormitettavuutta. Tästä syystä huomiota tulee erityisestä kiinnittää kaapelioiden täyttömateriaaleihin, jotta maaperän lämpöresistanssi saadaan pidettyä mahdollisimman alhaisena. Spesiaalien täyttömateriaalien, kuten Weak Mixin, käyttö suositellaan tilanteissa, joissa maaperän ominainen lämpöresistanssi on korkea, tai kaapeliyhteyden lähellä on ulkoisia lämmönlähteitä, jotka heikentävät kaapelin kuormitettavuutta.

Diplomityössä kyseenalaistetaan nykyistä suurjännitekaapeleiden mitoituslaskentaa, joka perustuu jatkuvaan kuormitettavuuteen. Kaapeliyhteyksien investointitehokkuutta voitaisiin mahdollisesti parantaa siirtymällä dynaamiseen mitoituslaskentaan, joka perustuu kaapelin sykliseen kuormitukseen.

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SYMBOLS AND ABBREVIATIONS

Roman characters

C	capacitance of the high voltage cable	[F/m]
d	geometric mean sheath diameter	[mm]
d_c	diameter of the conductor	[mm]
D'_a	external diameter of armour	[mm]
D_d	inside diameter of duct	[mm]
D_e	external diameter of cable	[mm]
DF	derating factor of power cable	[-]
D_o	outside diameter of duct	[mm]
D_s	external diameter of metallic sheath	[mm]
D_{it}	diameter of imaginary cylinder	[mm]
D_{oc}	diameter of the imaginary coaxial cylinder [[mm]
E_a	induced sheath voltage gradient in phase A	[V/m]
E_b	induced sheath voltage gradient in phase B	[V/m]
E_c	induced sheath voltage gradient in phase C	[V/m]
E_p	induced sheath voltage gradient for parallel conductor	[V/m]
f	nominal supply frequency of the system	[Hz]
I_a	rms current of phase A	[A]
I_b	rms current of phase B	[A]
I_c	rms current of phase C	[A]
j	complex number definition	-
L	distance from surface of the ground to cable axis	[mm]

n	number of conductors in a cable	-
U_0	rated phase-to-earth voltage of the high voltage cable	[kV]
U_{ab}	induced sheath voltage between phases A and B	[kV]
U_{bc}	induced sheath voltage between phases B and C	[kV]
U_{ac}	induced sheath voltage between phases A and C	[kV]
U_c	maximum continuous operating voltage	[kV]
U_n	rated voltage of the high voltage cable	[kV]
U_m	maximum operating voltage of the high voltage cable	[kV]
U_r	rated voltage of the sheath voltage limiter	[kV]
U_{res}	residual voltage of the sheath voltage limiter	[kV]
R'	dc resistance at max operating temperature of the conductor	[Ω/m]
R_0	dc resistance at 20 °C temperature of the conductor	[Ω/m]
R_c	ac resistance at max operating temperature of the conductor	[Ω/m]
R_s	sheath resistance at maximum operating temperature	[Ω/m]
R_{s0}	resistance of the cable sheath or screen at 20 °C	[Ω/m]
S	axial distance between phase conductors	[mm]
S_{ap}	axial distance between parallel and phase conductor A	[mm]
S_{ab}	axial distance between parallel and phase conductor B	[mm]
S_{ac}	axial distance between parallel and phase conductor C	[mm]
T	equivalent thermal resistance of cable per conductor	[Km/W]
t_1	thickness of insulation between the conductor and sheath	[mm]
t_2	thickness of bedding	[mm]
t_3	thickness of serving	[mm]
T_1	thermal resistance between conductor and sheath	[Km/W]

T_2	thermal resistance of the armouring	[Km/W]
T_3	thermal resistance of the outer covering	[Km/W]
T_4	external thermal resistance	[Km/W]
T_4'	thermal resistance between cable and duct	[Km/W]
T_4''	thermal resistance of duct or pipe	[Km/W]
T_4'''	external thermal resistance of duct	[Km/W]
W_a	losses the armouring	[W/m]
W_c	losses of the conductor	[W/m]
W_d	dielectric losses of the insulation	[W/m]
W_s	losses of the metallic sheath	[W/m]
X	reactance of the sheath in trefoil formation	[Ω /m]
X_1	reactance of the sheath in flat formation	[Ω /m]
X_m	mutual reactance between outer cable's sheet and other two cables	[Ω /m]

Greek characters

α_{20}	constant mass temperature coefficient at 20 °C per kelvin	-
ε	relative permittivity of insulation	[F/m]
ε_0	permittivity of vacuum	[F/m]
θ	temperature of the sheath above ambient temperature	[°C]
θ_{sc}	sheath temperature at maximum operating temperature	[°C]
$\Delta\theta$	permissible temperature rise of conductor	[°C]
λ_1	total sheath loss factor	-
λ_1'	circulating current loss factor of sheath	-
λ_1''	eddy current loss factor	-

λ'_{11}	sheath loss factor for an outer cable of group	-
λ'_{12}	sheath loss factor for other outer cable of group	-
λ'_{1m}	sheath loss factor for middle cable of group	-
ρ	thermal resistivity of soil	[Km/W]
ρ_1	thermal resistivity of insulation	[Km/W]
ρ_T	thermal resistivity of material	[Km/W]
ω	angular frequency of the supply system	[rad/s]

Constants

μ_0	Magnetic permeability of free space	-
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Abbreviations

AC	Alternating Current
DC	Direct Current
EMF	Electromotive Force
EHV	Extra High Voltage
EPR	Ethylene Propylene Rubber
FEM	Finite Element Method
GCC	Ground Continuity Conductor
GIS	Gas Insulated Switchgear
HDD	Horizontal Directional Drilling
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
MOV	Metal Oxide Varistor
PVC	Polyvinyl Chloride
PE	Polyethylene
pu	Per Unit
RFQ	Request for Proposal
SVL	Sheath Voltage Limiter
XLPE	Cross-linked Polyethylene

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1 Introduction

The replacement of old overhead lines with cables is a popular option, especially in urban areas, because high voltage power cables take up considerably less space, cause minimal visual disturbance, are protected from changing weather conditions, and, for example, the magnetic field generated by the cables is not as strong as with overhead lines. However, high voltage power cables are significantly more expensive in terms of investment compared to overhead lines and technically more complex implementation.

1.1 Scope

The objective of this thesis is to develop a computational basis for determining the ampacity of high voltage power cables, conforming to the standards outlined in the (IEC 60287, 2023), with potential for commercial application for $U_n = 5 - 400$ kV power cables. This computational foundation aims to address the calculation of ampacity in diverse installation conditions, encompassing variations in the surrounding medium, proximity to other power cable interfaces, the use of plastic or non-ferromagnetic protective tubing, and the influence of adjacent heat sources, each of which can derate the power cable ampacity.

The determination of ampacity ratings for high voltage power cables poses significant technical challenges, necessitating a comprehensive understanding of power cable technology and accessories, thermodynamics, material properties, high-voltage engineering, and personal safety considerations in the presence of hazard voltages. However, this thesis will not delve deeply into hazard voltage studies, considering them as a distinct area of inquiry, and will primarily focus on the elements in relation to ampacity calculation.

Given the direct correlation between the metallic sheath bonding arrangement of a power cable interface and the cable's ampacity rating, this thesis will provide a comprehensive overview of sheath bonding arrangements. Prevalent arrangements for power cables are single-point bonding and cross-bonding. Consequently, this work will aim to conduct an optimization analysis for choosing the correct sheath bonding arrangement for a given power cable route.

1.2 Limitations

High voltage cabling is complex area in the field of transmission lines, and it can be divided into multiple subsections. For the sake of this thesis, only the essential parts of high voltage cabling for the client are included in this thesis, which are single core onshore cables. Offshore (submarine) cables are not included in the thesis, as they are not in the scope of the client and require expensive machinery and expertise for the laying of the cables. In addition, high voltage cables are divided into high voltage alternating current (HVAC) cables and high voltage direct current (HVDC) cables. HVDC cables are excluded due to rarity of such cable interfaces and complexity of laying procedure and accessory installations.

1.3 Presentation of the Client

Client of the thesis is Destia Oy's department of substations. Destia is the largest infrastructure builders in Finland and is part of the global Colas group. Destia provides services in following fields: Urban construction, energy infrastructure, design services, smart transportation solutions, road services, railway services, maintenance, earth and rock services, and aggregates and circular economy. Destia has headcount of approximately 1600, and the turnover of 2022 was approximately 600 M€. (Destia Ltd, 2023)

The thesis was issued to provide new business opportunities for Destia's energy infrastructure business unit in the field of medium and high voltage cabling, and especially in 110 kV cabling. Optimization of sheath bonding arrangement is key design point in selection of correct high voltage cable type and cross-section of the core conductor. By choosing the correct sheath bonding arrangement provides possible savings for the end-clients as the cross-section of the cable can be optimized. In addition, optimal sheath bonding method is an essential part of the tendering process of high voltage cabling RFQ's. Therefore, the thesis scope includes an analysis of selection of optimal sheath bonding arrangement in addition with the calculation of permissible steady state ampacity of high voltage cables.

2 High Voltage Cables

High voltage power cable is a transmission line, which has one, or more insulated conductors inside an industrially manufactured cable covering, which is resistive for moisture and corrosion. High voltage power cables are constructed from layers (Elovaara & Haarla, 2011). Typical construction of a high voltage (HV) or extra high voltage (EHV) power cable with copper wire and tape sheath is introduced in Figure 2.1.

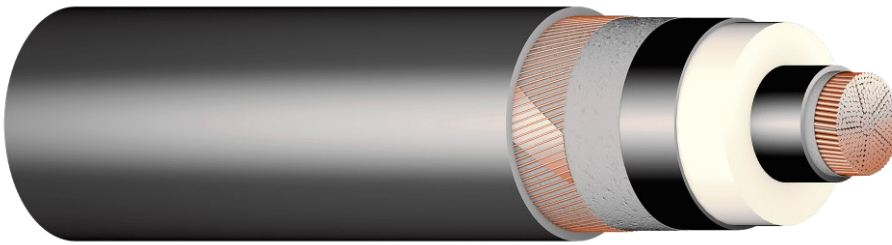


Figure 2.1. Construction of a high voltage power cable (Riyadh Cables Group, 2023).

Cable construction is as follows from the innermost to outermost layer. Core conductor (Solid, Stranded, or Milliken), conductor shield, insulation, insulation shield, swelling tape (optional), copper screen/metallic sheath, outer covering. Construction could also include longitudinally welded aluminium sheath to provide moisture barrier, and additional outer armouring depending on the application of the power cable. Armouring is mostly used in offshore and industrial facility applications.

Voltage ratings of a high voltage power cable are given in form of rated phase-to-ground voltage (U_0), rated voltage (U_n), and rated maximum operating voltage (U_m). In case of a 110 kV power cable, voltage notation would be 64/110 (123) kV. Table 2.1. Provides the similar voltage notations for all voltage levels from $U_n = 10$ kV to $U_n = 400$ kV found in a Finnish transmission and distribution system.

Table 2.1. Voltage levels in a Finnish transmission and distribution systems.

U_0 [kV]	U_n [kV]	(U_m) [kV]
5,8	10	(12)
11,6	20	(24)
18	30	(36)
26	45	(52)
64	110	(123)
127	220	(245)
231	400	(420)

When power system is operating in normal operating conditions, the power cable system is under the influence of similar voltages as the rated phase-to-ground voltage. However, the cable system must be able to withstand phase overvoltages close to, or higher than the rated voltage of the cable. Typically, such overvoltage conditions are met during an asymmetrical fault within the power system. The asymmetrical fault could be e.g., phase-to-ground fault, i.e., earth fault. In a three-phase system, during an earth fault, voltage of the faulty phase is nearly zero. However, for the other two healthy phases, the phase voltage tends to rise over the rated phase-to-ground voltage. The amplitude of the overvoltage found in healthy phases is dependent on the earth fault factor. Earth fault factor is entirely dependent on the grounding method of the neutral, and if the earth fault is subjected to any fault resistance. (Elovaara & Haarla, 2011)

Typically, in Finland medium voltage networks neutral of the system is either isolated from the ground, or resonant earthed, which utilizes an arc-suppression coil. For isolated networks, the earth fault factor is approximately 1.8. Neutral of the 110 kV networks is partly effectively earthed or resonant earthed. For such networks earth fault factor is 1.7. Finally, for 220 and 400 kV networks the neutral is fully effectively earthed, and the earth fault factor is 1.4. Overvoltage found in the healthy phases during earth fault is calculated by multiplying the phase-to-ground voltage with the earth fault factor (Elovaara & Haarla, 2011). However, it is good to note, that the value received is approximation. For more detailed results, symmetrical components or specialised power system study tool should be utilized.

3 Construct of High Voltage Cables

High voltage power cables are manufactured in many different countries around the world, and each country where high-voltage power cables are used also has its own standardised cable type and structure. This section briefly presents the various cable structures and the implementation methods utilized in Finland.

3.1 Core Conductors

Core conductor material is chosen based on its electrical conductivity, expansion coefficient, workability, breaking strength, heat resistance, and cost. Most common core conductor materials are either copper or aluminium. Generally copper conductors have higher transmission capacity than an aluminium conductor with similar cross-section. This is due to the lower electrical resistivity of copper conductors. Typically, use of aluminium conductors is preferred since the cost of aluminium power cables is drastically lower than copper power cables (Bartnikas & Srivastava, 2003). Round stranded or round Milliken conductors are used due to skin effect of alternating current. Construction of round stranded, and Milliken conductors are given in the Figure 3.1.



Figure 3.1. Round stranded conductor on the left, and Milliken conductor on the right.

Standard manufacturing ranges for power cables range between 25 mm² and 2500 mm². Ranges between 25 mm² and 300 mm² are typically for medium voltage applications. However, in a wind farm's medium voltage cable system, cross-section up to 1000 mm² can be found due to relatively high power levels within the collector system. In high voltage applications standardized cross-sections are 300, 500, 800, 1200, 1600, 2000 and 2500 mm².

3.1.1 Electrical Resistance

Direct current (DC) resistance at temperature of 20 °C is generally included in the datasheet of the power cable. However, to compute ampacity calculations, the DC resistance alone is not sufficient. First, the DC resistance must be converted to DC resistance at maximum operating temperature. After the DC resistance at maximum operating temperature must be converted into alternating current (AC) resistance. Calculation of direct current resistance at maximum operating temperature is given by Equation 3.1. (IEC 60287-1-1, 2023)

$$R' = R_0[1 + \alpha_{20}(\theta - 20 \text{ K})] \quad (3.1)$$

where R_0 is the direct current resistance at temperature of 20 °C [Ω/m], α_{20} is the constant mass temperature coefficient at 20 °C per kelvin, and θ is the maximum operating temperature of the conductor [°C].

Alternating current typically tends flow along the outer edge of the conductor. Such phenomena is known as skin effect. In addition, proximity of adjacent conductors has their own effect, which is known as proximity effect. DC resistance at maximum operating temperature therefore must be adjusted to skin and proximity effect. Calculation of skin and proximity effects are based on argument of Bessel function. (IEC 60287-1-1, 2023)

Argument of Bessel function for skin effect is given by Equation 3.2.

$$x_s^2 = \frac{8\pi f}{R'} \cdot 10^{-7} k_s \quad (3.2)$$

where f is the supply frequency of power system [Hz], R' is direct current resistance at maximum temperature of the conductor [Ω/m], k_s is given in Table 3.1.

Skin effect factor y_s is then derived from x_s . Factor for skin effect is given by Equations 3.3, 3.4, and 3.5.

For $0 < x_s \leq 2,8$

$$y_s = \frac{x_s^4}{192 + 0,8x_s^4} \quad (3.3)$$

For $2,8 < x_s \leq 3,8$

$$y_s = -0,136 - 0,0177x_s + 0,0563x_s^2 \quad (3.4)$$

For $x_s > 3,8$

$$y_s = 0,354x_s - 0,733 \quad (3.5)$$

Equation for proximity effect argument of Bessel function is given by Equation 3.6.

$$x_p^2 = \frac{8\pi f}{R'} \cdot 10^{-7} k_p \quad (3.6)$$

where k_p is given by Appendix 3.

Equation for calculation of proximity effect y_p for three-core cables and for three single-core cables is given by Equation 3.7.

$$y_p = \frac{x_p^4}{192 + 0,8x_p^4} \left(\frac{d_c}{s} \right)^2 \left[0,312 \left(\frac{d_c}{s} \right)^2 + \frac{1,18}{\frac{x_p^4}{192 + 0,8x_p^4} + 0,27} \right] \quad (3.7)$$

where d_c is the diameter of the conductor [mm], and s is the spacing between conductor axes [mm].

Finally, the AC resistance at maximum operating temperature of the conductor is calculated from Equation 3.8.

$$R_c = R' (1 + y_s + y_p) \quad (3.8)$$

Skin and proximity factors are dependent on the used conductor type, cable construction, its insulation system and cable system formation. Appendix 3. Provides correction factors for skin and proximity effect factors based on the utilized type of conductor and conductor insulation system. (IEC 60287-1-1, 2023)

Typically, the most common type of cable is a single-core round stranded and round Milliken conductors. Both copper, and aluminium are used in modern high voltage power cable interfaces.

3.1.2 Short Circuit Rating

High voltage power cables must be able to withstand passing short circuit currents similarly as any other current carrying component within the power system infrastructure. Typically, the maximum temperature of the insulation or cable jacket is the governing factor for the permissible short circuit current of the cable. The temperature of the core conductor or metallic sheath may not exceed the maximum temperature of the insulation or cable jacket. In addition, all the accessories related to the power cable should have at least similar short circuit ratings as the power cable itself. (Bartnikas & Srivastava, 2003)

Method utilized to calculate the permissible short circuit current of the power cable is known as the Adiabatic method. For this method, it is assumed that, for short duration short circuits, the heat developed by the fault is completely produced by the core conductor of the power cable (Bartnikas & Srivastava, 2003). The simplified equation from IEC standard for the adiabatic method is given by Equation 3.9.

$$I_{AD}^2 t = K^2 A^2 \ln \left(\frac{\theta_f + \beta}{\theta_i + \beta} \right) \quad (3.9)$$

where I_{AD} is the short circuit current [A], t is the duration of the short circuit [s], A is the cross-sectional area of the core conductor [mm²], θ_f is the final temperature of the core conductor after the short circuit [°C], θ_i is the initial temperature of the core conductor before the short circuit [°C], β is the temperature coefficient of resistance of the core conductor at temperature of 0 °C, and K is a constant, which depends on the material of the core conductor and calculation of it is given by Equation 3.10.

$$K = \left(\frac{\sigma_c (\beta + 20) \cdot 10^{-12}}{\rho_{20}} \right)^{0,5} \quad (3.10)$$

where σ_c is the volumetric specific heat of the core conductor [J/m³K], and ρ_{20} is the electrical resistivity of the current carrying component at 20 °C [Ω /m].

Naturally, the higher the cross-sectional area of the core conductor, the higher the withstanding ability of the short circuit currents. Therefore, larger high voltage power cables with cross-sectional area $\geq 400 \text{ mm}^2$, the short circuit withstanding ability is not the governing factor. However, it is good to note that larger high voltage power cables have longer cooling time constant.

3.2 Insulation

Purpose of power cable insulation is to isolate the energized power cable core from the surrounding medium. The most utilized insulation materials in extruded power cables nowadays are thermoplastic polyethylene. Formerly, low- and high-density polyethylene had been used. However, crosslinked polyethylene (XLPE) has become the dominant insulating material for medium and high voltage power cables. Crosslinked polyethylene has superior performance related advantages, which are: Higher steady state operating temperature, higher short-term thermal overloading capability, and higher short-circuit withstanding ability in terms of the maximum conductor temperature. In addition, XLPE has high dielectric breakdown strength and volume resistivity, and low dielectric constant and dissipation factor. (Bartnikas & Srivastava, 2003)

3.3 Dielectric Losses

Solid dielectric materials, such as thermoplastic polyethylene, act as a large capacitor when subjected to alternating voltage. Alternating voltage causes flow of charging currents, which derates the power cable's ampacity. Almost exceptionally, perfect insulating material does not exist nor free of dielectric losses. Every insulating material is prone to have leakage

current and dielectric losses. Only un-ionized gas can be considered as loss free insulating material. Dielectric losses are caused by movement of electrons and ions, interfacial polarization, and orientation of dipoles. The electrical characteristics that determine the properties of an insulating material are electrical conductivity and real permittivity/dielectric constant (Bartnikas & Srivastava, 2003). However, typically the required values for calculation of the phase capacitance of the power cable are given in the datasheet of the cable and therefore the simplified equation for capacitance can be used and it is given by Equation 3.11.

$$C = \frac{2\pi\epsilon_0\epsilon}{\ln\left(\frac{D_i}{d_c}\right)} \quad (3.11)$$

where ϵ_0 is the permittivity of the vacuum [F/m], ϵ is the relative permittivity of the insulation, D_i is the external diameter of the insulation, excluding screen [mm], and d_c is the diameter of the conductor [mm], including screen, if any.

Once the capacitance of the power cable has been calculated, the actual dielectric losses can be derived from the Equation 3.12. Value for the loss factor of the insulation at power frequency and operating temperature is given in Appendix 2.

$$W_d = \omega C U_0^2 \tan(\delta) \quad (3.12)$$

where ω is the nominal frequency of supply [rad/s], C is the capacitance per unit length of a cable [F/m], U_0 is the phase-to-ground voltage [V], and $\tan(\delta)$ is the loss factor of the insulation at power frequency and operating temperature (dissipation factor).

Dielectric losses can be neglected for medium voltage cables, however, for high voltage applications, dielectric losses must be considered as the dielectric losses tend to rise as a square of the phase-to-ground voltage of the power cable (IEC 60287-1-1, 2023).

3.4 Semiconducting Layers

High voltage power cables typically have two semiconducting layers within the cable construction. Semiconducting shields are typically made of polyethylene (PE). The semiconducting layers are called conductor shielding and insulation shielding. The purpose of conductor shield is to provide a uniform voltage stress over the rough stranded conductor surface. The conductor shield fills any possible voids between the conductor and the insulation inner surface. If such voids are left inside the cable, a source for harmful partial discharge is provided, which drastically shortens the life cycle of the power cable and makes it vulnerable to internal faults. (Bartnikas & Srivastava, 2003)

Similarly, the insulation shielding has purpose of eliminating any possible gaps or voids between the metallic sheath and insulation to minimize the possibility of partial discharges within the cable construction. The outer shielding over the insulation is grounded to provide radial symmetry for the electrical field. In addition, the insulation shielding protects the power cable from any potentials that could be induced extraneously. (Bartnikas & Srivastava, 2003)

3.5 Metallic Sheath

As explained previously, the insulation shielding must be grounded to provide radial symmetry for the electrical field. The most practical way to implement this is by adding metallic sheath to the cable construction. Most commonly, helically laid copper wires and tapes are used for such purpose. Such cable construction is given by Figure 3.1. In simplicity, the metallic sheath provides shielding effect for the insulation. In addition, the metallic sheath provides return path for fault currents. The metallic sheath must be able to withstand earth fault currents of the system without damaging the high voltage cable. (Bartnikas & Srivastava, 2003)

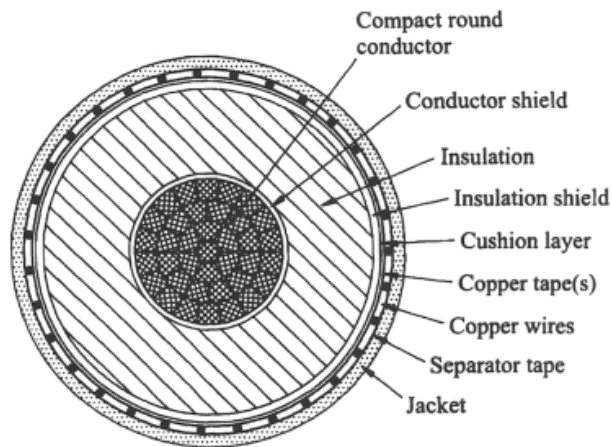


Figure 3.1. Simple high voltage cable cross-section with solid dielectric insulation and helically laid copper wires and tapes as the metallic sheath (Bartnikas & Srivastava, 2003).

High voltage cable with metallic sheath constructed from copper wires and tapes should only be utilized in either indoor installations or guaranteed dry conditions since copper wires and tapes do not provide radial water barrier. If conditions in the environment of high voltage cables are prone to have moisture or water, a laminated metallic sheath should be introduced to provide radial water barrier. Typical solutions for laminated sheaths are either longitudinally welded aluminium sheath or extruded lead sheath. Lead sheaths are the oldest solution in terms of metallic sheaths in the high voltage cable industry. Lead sheaths provide impervious water barrier for the cable. (Bartnikas & Srivastava, 2003) However, modern society tends to avoid lead sheaths as lead is considered as hazardous material for environment. Therefore, laminated aluminium shield is the preferred option if radial water barrier is required.

3.6 Protective Coverings

The metallic sheaths of high-voltage power cables are safeguarded by an extruded layer of polyethylene (PE) or polyvinyl chloride (PVC). Protective coverings are required for a multitude of reasons. (Bartnikas & Srivastava, 2003)

The protective covering serves to provide mechanical protection for the metallic sheath underneath. The jacket must withstand deformation before and after the installation process. Typically, these coverings are black to ensure good resistance to sunlight. Given that protective coverings are often exposed to corrosion, they must possess corrosion resistance. This attribute becomes especially crucial when the metallic sheath is made of aluminium, which is highly susceptible to corrosion. It is recommended that protective coverings include a flooding component beneath the jacket to provide a secondary protection mechanism against corrosion in the event of damage to the primary covering. The flooding compound prevents moisture from traveling longitudinally down the power cable. The integrity of the protective covering should be tested at appropriate intervals using an insulation resistance tester. (Bartnikas & Srivastava, 2003)

Protective coverings are also exposed to induced potentials, such as induced sheath voltage gradient during steady-state operation or transient phenomena. Induced sheath voltages are prevalent in cable systems that employ specific sheath bonding methods like single-point bonding, middle-point bonding, and cross-bonding. Since the metallic sheath must be insulated due to the presence of live potentials, the protective covering must exhibit adequate dielectric properties against induced sheath voltages and transients. (Bartnikas & Srivastava, 2003)

3.7 Cable Accessories

The accessories for the main circuit of the power cables can be used to either terminate or extend the cable connection. Failure of cable accessories during operation is generally the root cause for the unwanted interruption of the cable transmission line. For this reason, the manufacturing and installation of cable accessories require particularly precise experience and work.

3.7.1 Cable Terminations

Cable terminations are used to terminate the high voltage power cables and connect them to either overhead lines, air-insulated busbars, gas-insulated switchgear, or other electrical

equipment within the power system. Installation requires high precision since an installation error could cause failure of the insulation due to impurities within the surface of semiconducting layers or insulation. Figure 3.2 illustrates high voltage power cable terminations, which could be found from a modern power system infrastructure.

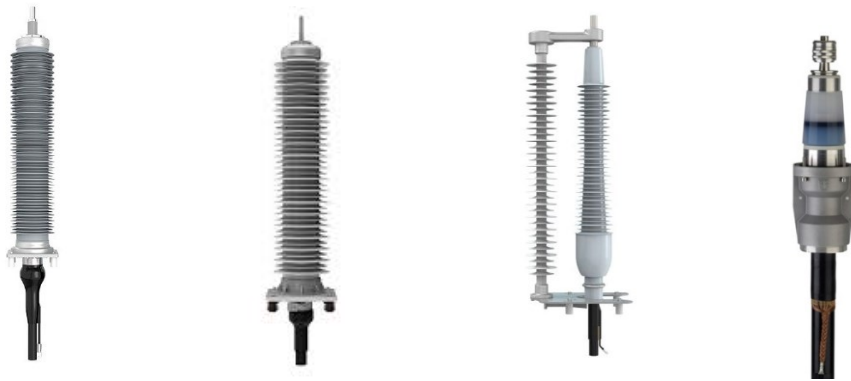


Figure 3.2. Different types of $U_n = 110$ kV power cable terminations. From the left: 1. Dry type termination, self-supporting, 2. Oil filled termination, self-supporting, 3. Dry type termination, flexible with support insulator, 4. Plug-in dry type GIS termination. (Pfisterer, 2023)

Typically, dry type terminations without oil or SF₆-gas are preferred, as they do not cause environmental hazard in case of a termination failure during operation, nor risk for leakage of insulating material is not present.

3.7.2 Cable Joints

Cable joints are utilized to extend the length of a power cable interface. Two types of cable joints are utilized within the industry. First one is a “straight joint”, which connects to cables and their metallic sheath together. Second one is a “sheath interruption joint”, which connects the core conductors together, but isolates their metallic sheaths from each other. Isolating joints are required to build a cross-bonded or middle-point bonded cable system. Interruption of the metallic sheaths is provided by an insulating cone, which interrupts the sheath continuity within the joint construction.

4 Bonding of Metallic Sheaths

Load current flowing in a single-core power cable's core conductor induces electromotive force (EMF) to the sheath. This induced sheath EMF causes current to flow in the metallic sheath if a closed circuit is formed. In power cable applications, closed circuit is typically formed, if both ends of the metallic sheaths are connected to the earth. This situation is achieved, for example, in a cable connection between substations, if the metallic sheath is connected to the earthing mesh at both ends of the cable interface. In such situation, circulating currents form in the metallic sheaths and cause additional losses, also known as circulating currents, which derate the power cable's ampacity rating. To eliminate longitudinal sheath currents, special sheath bonding methods has been developed. Most common special sheath bonding arrangements are single-point bonding, cross-bonding, and in some cases, impedance bonding. (Argaut & Pierre, 2023)

4.1 Solid Bonding

Solid bonding refers to a cable system where the metallic sheaths are directly earthed at both ends of the cable interface. In addition, intermediate earthing points are located along the cable route. Intermediate points are considered as precautions. Potential of the metallic sheath is at earth level, i.e., zero. (Argaut & Pierre, 2023)

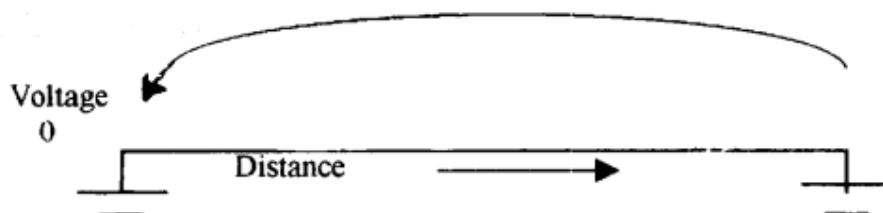


Figure 4.1. Induced sheath voltage of a solidly bonded cable interface (Thue, 2003).

If one end of the metallic sheath is disconnected from the earth, a relatively high standing sheath voltage will occur at the open circuit terminal of the metallic sheath, potentially causing damage to the cable jacket. To mitigate this risk, intermediate earthing points are strategically implemented to jointing locations to reduce induced sheath voltage under such circumstances. Opting for a solid bonding arrangement of metallic sheaths proves to be cost-effective, as it eliminates the need for sheath interruption joints and sheath voltage limiters. During fault scenarios, solid bonding provides a path for zero-sequence current by the metallic sheaths itself, and no ground continuity conductor is needed. However, it is essential to acknowledge that solidly bonded metallic sheaths introduce a path for induced circulating currents, leading to Joule losses in the cable system. These losses can be significant, reaching up to 80% of the phase current in the core conductor. Consequently, Joule losses play a critical role in derating the ampacity rating of the cable system. In summary, the decision between solid bonding and alternative arrangements necessitates careful consideration of the specific requirements and constraints within the power transmission and distribution systems. (Argaut & Pierre, 2023)

4.2 Single-point Bonding

Single-point bonding is typically regarded as the most simplistic form of special sheath bonding methods. Utilizing this method implies that only the other end of the metallic sheath is connected to a common earth potential and other end is connected to common earth potential through a sheath voltage limiter as shown in Figure 4.2.

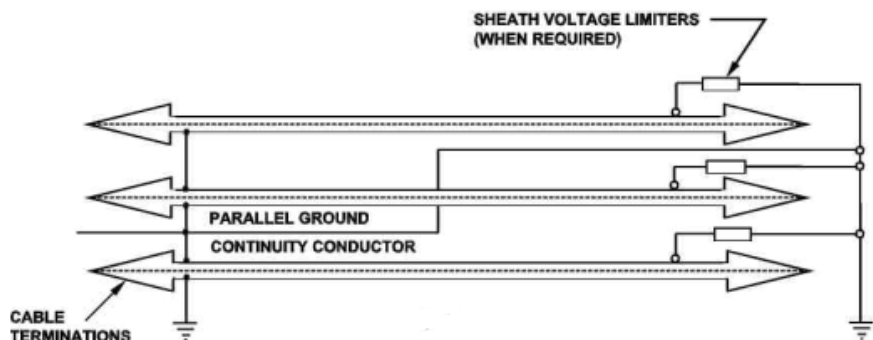


Figure 4.2. Single-point bonding configuration (IEEE Std. 575, 2014).

Single-point bonding is a cost-effective method, as it allows the use of smaller cable cross-sections. However, rms load current of the load does induce a voltage to the metallic sheath, increasing as a function of the cable length. In simpler terms, the longer the cable, the higher the amplitude of the induced standing sheath voltage. Figure 4.3. Illustrates the relationship between cable length and induced sheath voltage. (IEEE Std 575, 2014)

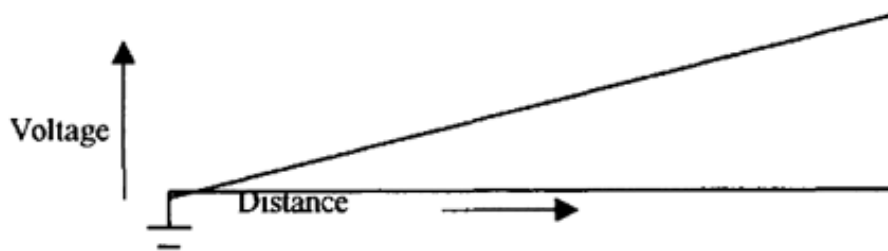


Figure 4.3. Induced sheath voltage of single-point bonded cable interface (Thue, 2003).

A significant limitation of a single-point bonded power cable interface is the length of the system, as the sheath voltage increases as a function of the cable system's length. The induced sheath voltage must be calculated to prove that the insulation of the sheath is adequate, especially given the absence of a continuous electrically closed loop. The single-point bonding method thereby eliminates circulating sheath currents, as no path for the circulating sheath currents is provided. This reduction in currents reduces the total thermal losses of the cable interface if compared to solid bonding method and enabling the utilization of smaller cable cross-sections. (IEEE Std. 575, 2014)

Other variation of single-point bonding is middle-point bonding, where the cable sheaths are connected to common earth potential at the middle of the cable interface. Such bonding configuration requires a sheath interruption splice and sheath voltage limiters at both ends of the cable interface. Figure 4.4. Illustrates middle-point bonding.

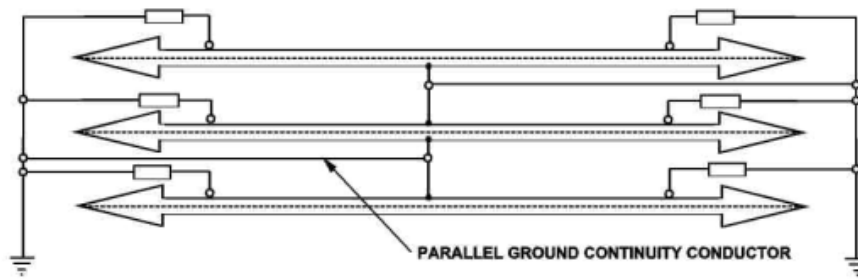


Figure 4.4. Middle-point bonding configuration (IEEE Std. 575, 2014)

Similarly, the sheath voltage increases as a function of the length of the cable interface. However, the maximum standing sheath voltage can be found from both ends of the cable interface. Figure 4.5. Visualizes the standing sheath voltage of middle-point bonded cable interface.

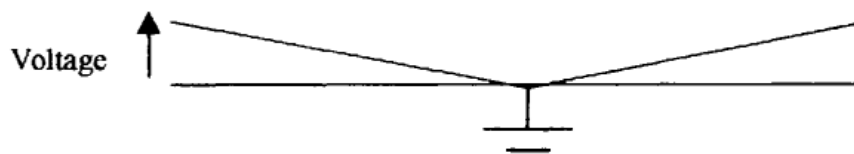


Figure 4.5. Standing sheath voltage of middle-point bonded cable interface (Thue, 2003).

If single-point bonding or middle-point methods are not sufficient, cable interface can be split into sections with sheath interruption joints so that the standing sheath voltage is within the regulatory limits for each minor section. Figure 4.6. Illustrates the sectionalized configuration where the cable interface is split into three sections, and each section utilizes single-point bonding.

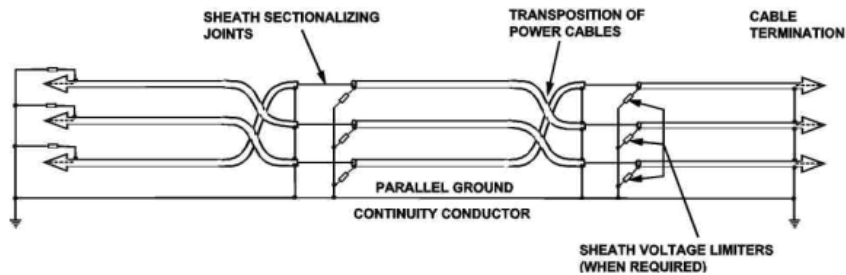


Figure 4.6. Single-point bonding method, where the cable interface is split into three sections (IEEE Std. 575, 2014).

Mitigating asymmetrical fault currents using single- or mid-point bonding presents challenges, primarily because only one end of the metallic sheath is earthed. This configuration means the metallic sheath cannot carry the zero-sequence current. Consequently, the earth serves as the return path for this current. In countries like Finland, where earth resistivity is notably high, this can lead to elevated earth potential and touch voltages. Therefore, a ground continuity conductor(s) (GCC) is laid in parallel with the high voltage cable itself, to provide a return path for the zero-sequence current. It is necessary to consider, that the GCC is subjected to induced voltage, as any other parallel conductor. To reduce the induced voltage, the GCC should be transposed at the midpoint of the high voltage cable transmission line to eliminate the induced voltage of the GCC. (IEEE Std. 575, 2014).

4.3 Cross-Bonding

Cross-bonding is a sheath bonding arrangement where the metallic sheaths of the cable circuit are divided into sections and transposing the metallic sheaths to neutralize the circulating sheath losses. In most cases the cable circuit is divided into three sections, or into number of sections which is dividable by three. Each point interval where the metallic sheath is transposed is called a minor section. If the metallic sheath is earthed at both ends of the cable interface, and the metallic sheath is transposed three times, a major section is formed. Figure 4.7. Visualizes a cross-bonded cable interface of one major section. (IEEE Std. 575, 2014)

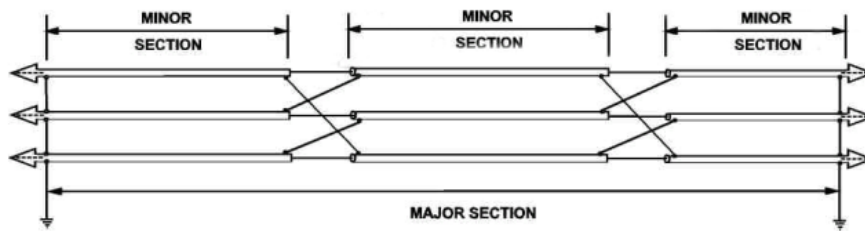


Figure 4.7. Cross-bonded cable interface with three minor sections and one major section (IEEE Std. 575, 2014).

Transposition of the cables is preferred to balance the induced sheath voltage for flat formation. However, in terms of practicality, heavy and rigid high voltage cables prevent the possibility of transposition of the cables. In cross-bonded trefoil formation, the standing sheath voltage is not present as the magnetic coupling for all three phases is identical. Cross-bonded and transposed cable interface is given by Figure 4.8. (IEEE Std. 575, 2014)

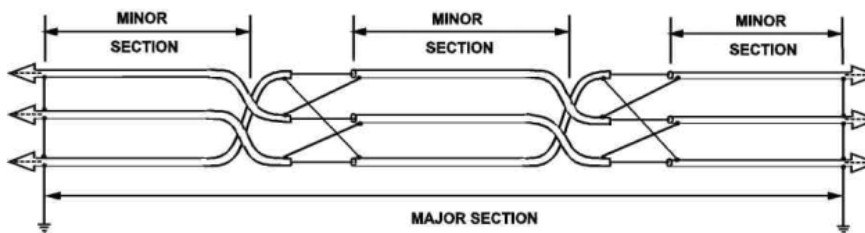


Figure 4.8. Cross-bonded and transposed cable interface (IEEE Std. 575, 2014).

Cross-bonding can also consist of several major sections connected in series. Such cross-bonding method is originally known as Kirke-Searing bonding, or more commonly as sectionalized cross-bonding. As stated before, sectionalized cross bonding must have at least three major sections, or number of major sections which are dividable by three. Metallic sheath of the cable is connected and earthed at each junction of major sections, and at both ends of the cable interface. Earthing of the junction of major sections should be connected

to GCC if one is provided, or to a local grounding rod. Sectionalized cross-bonded cable interface with multiple major sections is given by Figure 4.9. (IEEE Std. 575, 2014)

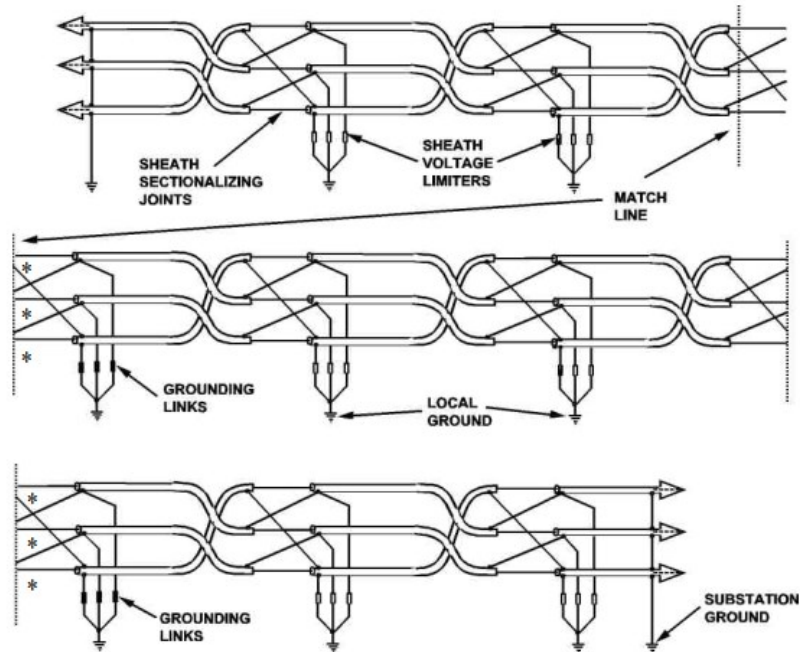


Figure 4.9. Sectionalized cross-bonded cable interface (IEEE Std. 575, 2014).

One of the other variables of cross-bonded cable interface is continuous cross-bonding. In continuous cross-bonding, the metallic sheaths of the cable are earthed only at the ends of the cable transmission line. Metallic sheaths are transposed at every sheath isolation joint and earthed through a sheath voltage limiter. Again, the amount of matched minor sections should be exactly divisible by three. However, it becomes less important when the number of minor sections increases. Continuous cross bonding is given by Figure 4.10. (IEEE Std. 575, 2014)

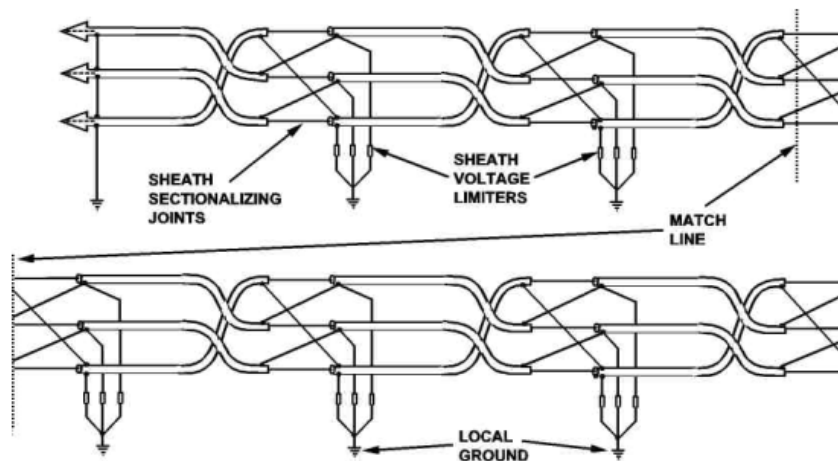


Figure 4.10. Continuously cross-bonded cable interface (IEEE Std. 575, 2014).

By utilizing cross-bonding, a ground continuity conductor is no more needed as both ends of the metallic sheaths are grounded and therefore a path for earth fault currents is provided by the metallic sheaths themselves. Naturally, as the need for ground continuity conductor is no longer present, also the costs of building the cable interface are reduced slightly. The absence of ground continuity conductor also improves the screening properties of the metallic sheaths.

4.4 Impedance Bonding

In case of impedance bonding, the metallic sheaths of the power cable are bonded at both ends of the cable interface through an impedance device. Some sheath current is allowed to reduce sheath losses and the induced sheath voltage gradient. Impedance bonding is efficient bonding arrangement in terms of minimizing sheath losses and suppressing sheath voltages. However, impedance bonding involves disadvantages, which limit the application of impedance bonding method (IEEE Std. 575, 2014). Disadvantages for impedance bonding are as follows:

- Power cable vaults require additional space for the impedance devices.
- The cost of the impedance devices is significant since they must be designed so that they can withstand the fault currents.

- During steady state operation, sheath bonding impedance devices can introduce 3rd harmonics into the metallic sheaths and interfere with nearby telecommunication lines.
- Stray direct currents can enter the system and cause saturation of the iron cores of the impedance devices.

One method of impedance bonding is known as transformer sheath bonding. For single-core cables, which are the focus of this thesis, the metallic sheaths of the cables, both ends of the metallic sheaths are electrically connected to a three-phase sheath bonding transformer (IEEE Std. 575, 2014). Such bonding method is shown in Figure 4.11.

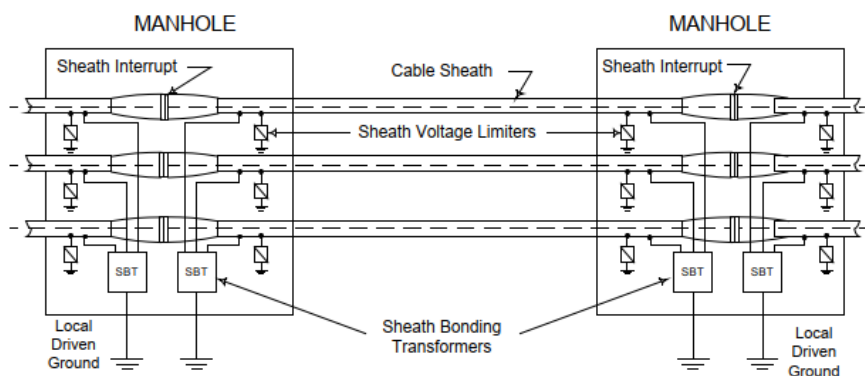


Figure 4.11. Impedance bonding using bonding transformers (IEEE Std. 575, 2014).

The winding configuration of the sheath bonding transformer is similar as a zigzag grounding transformer. By the design of the bonding transformer, impedance between the three phases and ground is relatively high when the voltages applied by phases L1, L2 and L3 are balanced three-phase voltages. If a single phase or zero sequence voltage is applied between any phases and ground of the sheath bonding transformer, the impedance between phases L1, L2 and L3 is low (IEEE Std. 575, 2014).

Under steady state operation, the induced sheath voltage gradients on the metallic sheaths of the cable are approximately equal, and 120 degrees out of phase. As a result, only very little sheath current flows to the ground through the sheath bonding transformers. Earth faults

produce zero sequence voltage, which appears across the bonding transformer windings and the fault current flows through the low impedance as explained before. Key factor for sheath bonding transformer design is to avoid saturation because of induced sheath voltage gradients produced by steady state operation and emergency operating conditions. Impedance bonding arrangement also requires sheath voltage limiters similarly as any other special sheath bonding method. (IEEE Std. 575, 2014)

Key advantages for impedance bonding method are as follows: Impedance bonding is very effective in limiting sheath losses, which does not require equal distances between cable vaults. As stated before, impedance bonding requires additional space for the impedance devices, and therefore, the cost of impedance bonding is relatively high, if compared to more traditional sheath bonding methods as single-point bonding or cross-bonding. (IEEE Std. 575, 2014)

5 Protection of Metallic Sheaths

Integrity of the high voltage power cable's structure is essential part of the operation reliability of a power cable transmission line. Therefore, special protection methods of the metallic sheaths has been developed and the most commonly utilized methods will be introduced within this Chapter.

5.1 Sheath Voltage Limiters

Standard surge arresters at nominal power system voltages are located at cable terminations and their fundamental task is to protect the primary insulation of the cable system. Sheath voltage limiter (SVL) is also essentially a surge arrester. Modern sheath voltage limiters are manufactured either from nonlinear metal oxide varistors (MOV), nonlinear silicon carbide (SiC), or a spark gap similarly with ordinary surge arresters. The purpose of SVL is to protect the sheath, sheath sectionalizing insulators and cable jackets from flashovers or punctures caused by transients within the power system by providing a safe path for the sheath overvoltage through the surge arrester to the ground. Typical transient overvoltages associated with power cables are lightning and switching surges, and faults. By utilizing SVL's, failures of sheaths, sheath insulators and cable jackets has reduced drastically since the early special sheath bonding arrangements. (IEEE Std. 575, 2014)

SVLs are installed to cable systems, where a special sheath bonding arrangement has been implemented to eliminate or reduce circulating sheath currents. For example, in a single-point bonding arrangement, SVLs are installed to the open end of the metallic sheath, as it is subjected overvoltages during transient state of the power system. In selection of SVL, a transient voltage analysis should be performed. Typically, a transient voltage analysis includes lightning surges entering the underground cable system from overhead lines, different fault conditions, which are typically asymmetrical faults, and switching surges, such as no-load transmission line energization. (IEEE Std. 575, 2014)

5.2 Induced Sheath Voltage

Typically, induced sheath voltage or induced voltage to parallel conductors is calculated during steady state operation and transient conditions of the power system. Following equations introduce the calculation of the maximum induced sheath voltage gradients. However, if wanted results are within a time domain, more advanced calculation methods should be utilized.

The general case for induced voltage gradient in any parallel conductor is given by Equation 5.1 (IEEE Std. 575, 2014).

$$E_p = j\omega I_b (2 \cdot 10^{-7}) \left[\frac{1}{2} \log_e \left(\frac{S_{ap} \cdot S_{cp}}{S_{bp}^2} \right) + j \frac{\sqrt{3}}{2} \log_e \left(\frac{S_{cp}}{S_{ap}} \right) \right] \quad (5.1)$$

where I_b is the rms current in conductor b [A], ω is the angular frequency of the system [rad/s], S_{ap} is the axial spacing of the parallel conductor and phase a conductor [mm], S_{bp} is the axial spacing of the parallel conductor and phase b conductor [mm], and S_{cp} is the axial spacing of the parallel conductor and phase c conductor [mm].

From the Equation 5.1. as the spacing between parallel conductors and the groups of cables increases, the induced voltage tends to approach zero. If the groups of cables are transposed regularly, the induced voltage in the parallel conductors sums to zero over the full cycle of the transposition. (IEEE Std. 575, 2014)

Induced sheath voltage in trefoil formation for phases A, B, and C of single circuit cable interface is given by Equation 5.2, 5.3, and 5.4. (IEEE Std. 575, 2014)

Induced sheath voltage gradient in phase A in V/m.

$$E_a = j\omega I_a (2 \cdot 10^{-7}) \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2} \right) \log_e \left(\frac{2S}{d} \right) \quad (5.2)$$

Induced sheath voltage gradient in phase B in V/m.

$$E_b = j\omega I_b (2 \cdot 10^{-7}) \log_e \left(\frac{2S}{d} \right) \quad (5.3)$$

Induced sheath voltage gradient in phase C in V/m.

$$E_c = j\omega I_c (2 \cdot 10^{-7}) \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2} \right) \log_e \left(\frac{2S}{d} \right) \quad (5.4)$$

where I_a , I_b , and I_c are the rms currents in conductor A, B, and C [A], d is the geometric mean sheath diameter [mm], and S is the axial spacing of phases [mm].

Induced sheath voltage in flat formation for phases A, B, and C of single circuit cable interface is given by Equation 5.5, 5.6, and 5.7.

Induced sheath voltage gradient in phase A in V/m.

$$E_a = j\omega I_a (2 \cdot 10^{-7}) \left(-\frac{1}{2} \log_e \frac{S}{d} + j\frac{\sqrt{3}}{2} \log_e \frac{4S}{d} \right) \quad (5.5)$$

Induced sheath voltage gradient in phase B in V/m.

$$E_b = j\omega I_b (2 \cdot 10^{-7}) \log_e \frac{2S}{d} \quad (5.6)$$

Induced sheath voltage gradient in phase C in V/m.

$$E_c = j\omega I_c (2 \cdot 10^{-7}) \left(-\frac{1}{2} \log_e \frac{S}{d} - j \frac{\sqrt{3}}{2} \log_e \frac{4S}{d} \right) \quad (5.7)$$

Gradient of voltages calculated from previous inducing voltage equations are a product of magnetic field caused by three phase currents. If any other current carrying conductor is adjacent, the voltage gradient will be modified. Specifically, if a ground continuity conductor is present to carry the induced current, then the voltage gradient in any parallel conductor will be reduced. (IEEE Std. 575, 2014)

It is desirable to place communication cables and ground continuity conductors in the same cable trench with the power cables itself. Therefore, it is essential to minimize the induced voltage gradient to such parallel conductors. If the metallic sheaths of the power cables are continuous throughout the cable route, and earthed at both ends of the cable interface, they act as screening conductors and therefore reduce the induced voltage gradient in parallel conductors. In case of specially bonded systems, e.g., single-point bonding or cross bonding, the sheaths do not carry currents, and therefore the screening effect is absent for balanced loads. If power cable system is feeding an unbalanced load, or during asymmetrical faults, and the metallic sheaths are cross bonded, the sheath currents will flow and therefore the important screening effect is present. (IEEE Std. 575, 2014)

As stated before, the induced voltage gradients in parallel conductors can be reduced or even eliminated by utilizing transposition of the power cables, which is especially desirable for specially bonded cable interfaces. In addition to reduced induced voltage gradients, also overall impedance of the power cable is balanced when transposition is utilized. However, transposition of heavy and robust high voltage power cables is not very applicable, expect

at joint positions. If the cable route consists of two or less lengths, it is not usual to transpose the cables. However, parallel conductors, e.g., communication cables and ground continuity conductors should be transposed to reduce the induced voltage gradient of parallel conductors. (IEEE Std. 575, 2014)

Previous equations described the calculation of voltage gradients induced to metallic sheaths and parallel conductors during steady state operation. In addition to steady state operation, also transient state induced voltage gradients must be calculated properly.

During a transient of power system, caused by a fault, the initial transient overvoltage is followed by power frequency overvoltage in the metallic sheath, which is caused by the fault current flowing in the core conductor of the power cable. In terms of insulation design, the power frequency overvoltage is not important. However, the duration of the fault is important factor in relation with the withstanding requirements of the sheath voltage limiters. The cable interface, including the chosen bonding arrangement and protection, must be able to safely withstand the effects of any external fault to the cable interface. Inducing sheath voltage gradient caused by external grid fault can be divided into three types, which are - three-phase symmetrical fault, phase-to-phase fault, and phase-to-ground fault. Equations given for induced sheath voltage gradients are derived based on simplifying assumptions. (IEEE Std. 575, 2014)

- Fault current is known and is not affected by the characteristics of the cable interface.
- For asymmetrical faults, the current flowing in the healthy phase(s) is negligible in relation to the fault current, unless the neutral of the system is grounded through an impedance.
- Other screening conductors are not present, unless the metallic sheaths of the system are single point bonded and a ground continuity conductor is running in parallel with the power cables.
- The cable interface is consisting of balanced major and minor sections if sectionalized cross bonding is utilized, and in case of continuous cross-bonding, the cable interface consists of uniform minor sections divisible exactly by three.

Phase-to-ground faults may be neglected in the calculations, if the neutral of the system is either impedance or resonant grounded since the fault currents tend to remain much lower amplitude than compared to three-phase or phase-to-phase faults. However, if the neutral is solidly grounded, it cannot be neglected anymore. Such calculations are not introduced as solid neutral grounding is not applicable in Finnish transmission and distribution systems. (IEEE Std. 575, 2014)

Inducing sheath voltage gradients for single-point bonded systems can be calculated from following equations. Three-phase faults are considered to represent balanced system, and therefore the equations used for steady state voltage gradients can be utilized by using the appropriate value of the rms current flowing in the core conductor. However, for phase-to-phase faults, individual equations must be used. General case of any cable formation is given by following equations for phase-to-phase fault. (IEEE Std. 575, 2014)

Induced sheath voltage gradient for phase A during a phase-to-phase fault in V/m.

$$E_a = j\omega I_{ab}(2 \cdot 10^{-7}) \log_e \left(\frac{2S_{ab}}{d} \right) \quad (5.8)$$

Induced sheath voltage gradient for phase B during a phase-to-phase fault in V/m.

$$E_b = -j\omega I_{ab}(2 \cdot 10^{-7}) \log_e \left(\frac{2S_{ab}}{d} \right) \quad (5.9)$$

Induced sheath voltage gradient for phase C during a phase-to-phase fault in V/m.

$$E_c = -j\omega I_{ab}(2 \cdot 10^{-7}) \log_e \left(\frac{S_{bc}}{S_{ac}} \right) \quad (5.10)$$

In case of a flat installation formation, the maximum induced sheath voltage gradient for outer cables is given by Equation 5.11.

$$E_a = -E_b = j\omega I_{ab}(2 \cdot 10^{-7}) \log_e \left(\frac{4S}{d} \right) \quad (5.11)$$

Calculation of induced sheath voltage gradients for cross-bonded systems becomes more complex when compared to single-point bonded systems. Therefore, calculation methods for cross-bonded systems will be introduced shortly within this thesis, since more complex computational methods would be needed to arrive at the exact correct result. However, it can be mentioned that equations utilized for symmetrical cases can be utilized for three-phase faults in a cross-bonded system, and for two-phase faults, the induced voltage gradient tends to be lower than for the three-phase case.

Earth faults within a cross-bonded system requires formulation of its own. It is crucial to understand the relation between earth currents and the voltages between metallic sheaths and the earth. In addition, it is essential to have to the values of resistivity of earth and resistance of the earthing electrode. Following equations for induced sheath voltage gradient may only be utilized for sectionalized cross-bonded systems. (IEEE Std. 575, 2014)

Figure 5.1. illustrates the fault path of the earth fault current for one major sections of a cross-bonded cable system.

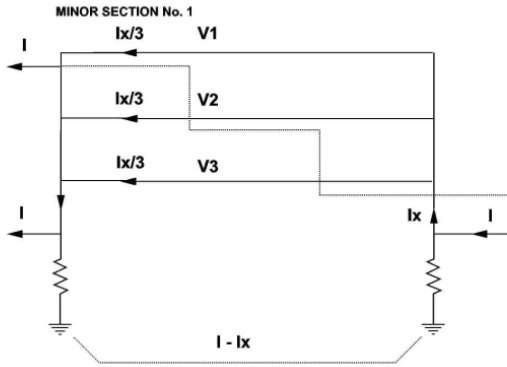


Figure 5.1. One major section of a cross-bonded cable system and the path for earth fault current (IEEE Std. 575, 2014)

Illustrated circuit in the Figure 5.1 is applicable only for trefoil formation during an earth fault. As we can see from the given circuit, the current I_x circulates in all three metallic sheaths and it divides equally between all three metallic shield circuits. The induced voltage gradients for all three metallic sheaths during an earth fault are as follows:

$$E_a = \frac{I_x}{3} \cdot (Z_{ss} + 2Z_{sg}) - I \cdot (Z_{ss} - R_s) \quad (5.12)$$

$$E_b = \frac{I_x}{3} \cdot (Z_{ss} + 2Z_{sg}) - IZ_{sg} \quad (5.13)$$

$$E_c = E_g \quad (5.14)$$

In addition to the induced sheath voltage gradient for each metallic sheath, the voltage between the metallic sheaths at cross-bonding points should be considered and their equations are given as follows:

$$U_{ab} = Il \cdot (Z_{sg} - Z_{ss} + R_s) \quad (5.15)$$

$$U_{bc} = 0 \quad (5.16)$$

$$U_{ac} = Il \cdot (Z_{sg} - Z_{ss} + R_s) \quad (5.17)$$

where Z_{ss} is the self-impedance of the metallic sheath with a earth return [Ω/m], which is given by $Z_{ss} = j\omega \cdot (2 \cdot 10^{-7}) \log_e \left(\frac{2S}{d} \right)$, I is the fault current shown in Figure 5.1 [A], Z_{sg} is the mutual impedance of the metallic sheath with earth return [Ω/m], R_s is the resistance of the metallic sheath [Ω/m], and l is the length of a minor section of the cross-bonded system [m].

However, as the given equations are functions of frequency and ground resistivity, these factors disappear and can be simplified to following form.

$$U_{ab} = l \cdot Z_{ss} \quad (5.18)$$

$$U_{bc} = 0 \quad (5.19)$$

$$U_{ac} = -U_{ab} \quad (5.20)$$

As stated before, given equations may only be utilized for trefoil formation installations and sectionalized cross-bonded systems. In case of a flat formation, more complex numerical methods must be implemented, and these will not be introduced within this thesis. For further information, refer to IEEE Std. 575, 2014.

5.3 Link Boxes

Link boxes and enclosures are meant to house the sheath voltage limiters, link connections, bonding lead connections and ground continuity conductor terminals. Link boxes are manufactured from stainless steel, cast iron, or fiberglass. Link boxes must be able to withstand corrosion and construction and be waterproof if installed to submerging environments. (Argaut & Pierre, 2023)



Figure 5.2. Picture of a bonding lead link box internals.

5.4 Bonding Leads

Bonding leads are used to provide connection between the metallic sheath and link box bonding terminals. Bonding leads must have sufficient dielectric characteristics since they are subjected to overvoltages similarly as the sheath voltage limiters and cable jackets. Insulation material utilized with bonding leads is typically either PVC, XLPE or EPR. Construction of a bonding lead is given by Figure 5.3. (Argaut & Pierre, 2023)

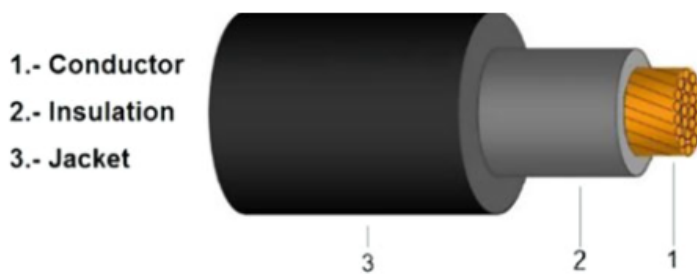


Figure 5.3. Example of a single-core bonding lead (Argaut & Pierre, 2023).

PVC has higher permittivity, which results in lower surge impedance and propagation factor. PE in the other hand, has increased propagation factor, which means that shorter “electrical length” is needed and due to same reason, the surge impedance of PE is higher. In terms of propagation factor and surge impedance EPR is an intermediate material if compared to PVC and PE. Some bonding leads have extruded outer semiconducting layer for testing purposes. Bonding lead positions within cross-bonded cable interface are highlighted in Figure 5.4. (Argaut & Pierre, 2023)

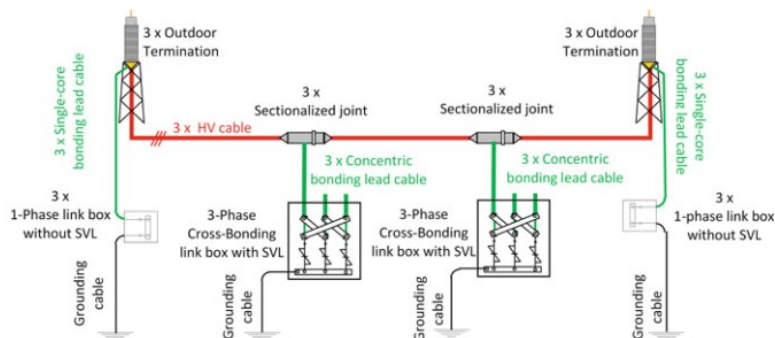


Figure 5.4. Example of a cross-bonded system where bonding leads are identified (Argaut & Pierre, 2023).

If the bonding leads are directly buried to the ground, the bonding leads should have some form of longitudinal water blocking, to avoid the water from inflowing to the high voltage cable joints if the bonding lead or link box suffers from damage, which allows the inflow of water into the link box. (Argaut & Pierre, 2023).

5.5 Selection of Sheath Voltage Limiters

Typically, characteristics of sheath voltage limiters include rated voltage U_r , maximum continuous operating voltage U_c , nominal discharge current, high current impulse withstand, long duration current impulse withstand, short circuit withstand, maximum residual voltage U_{res} , nominal creepage distance, typical temporary overvoltage curve, and discharge class. (Argaut & Pierre, 2023)

The sheath power frequency overvoltage during a fault with a given fault duration should be calculated based on the provided system and power cable parameters. Afterwards the calculated power frequency overvoltage should be compared to overvoltage-versus-time (TOV) characteristics of the chosen SVL. Temporary overvoltage value of the selected SVL should be higher than the calculated power frequency overvoltage. Typical protection margin is between 5 % to 25 %. Method described is the minimum performance criteria for the selection of the SVLs. It is good to note that for this method, the TOV characteristics of the SVL must be available. (Argaut & Pierre, 2023)

If TOV characteristics are not given in the manufacturer's data sheet, different approach can be taken. The SVLs are selected based on its maximum continuous operating voltage U_c . The maximum continuous operating voltage should be higher than the calculated power frequency overvoltage. Natural safety margin between the difference of maximum continuous operating voltage U_c and the rated voltage U_r is given. The rated voltage, U_r should be selected based off the TOV comparison or selected U_c . Typically, the U_r of the SVL is between 3 and 12,5 kV. 3 kV is considered as the minimum value of U_r . In most data sheets of SVL manufacturers, the U_r is 15-25 % higher than the U_c . (Argaut & Pierre, 2023)

Residual voltage U_{res} is one possible approach for selection of SVLs. The residual voltage is the maximum arrester voltage acquired with the tested 8/20 μ s and 10 kA current impulse. The residual voltage of the SVL should be chosen so that it is less than the transient overvoltage withstanding capability of the insulating components of the power cable. These insulating components are metallic sheath interruption joints and cable jackets. Additionally, an energy absorption study may be carried out. However, to perform such study, a specialised EMTP software should be utilized. (Argaut & Pierre, 2023)

5.6 Sheath Voltage Limiters Connection Configurations

Connection configuration of the sheath voltage limiters affects the voltage across the arresters. Following configurations are utilized in the industry. (Argaut & Pierre, 2023)

- Star formation, where the star point is connected to the ground continuity conductor(s).
- Star formation, where the star point is connected directly to ground.
- Delta formation
- Direct placement at crossing of sheath interruption joint – one SVL with higher voltage rating.
- Direct placement at crossing of sheath interruption joint – two SVLs for each side of the joint and a common ground connection between the two.

5.7 Sheath Voltage Limiters Installation

As stated before, sheath voltage limiters are typically installed in enclosures and link boxes along the cable route. SVLs installations are without exception located at jointing positions, or at the terminals of the power cable interface. The placement and amount of SVLs should be acquired from the general system study. General outline is that the more SVLs the system has, the less it has SVL failures due to energy sharing between the SVLs. General guidance for SVL locations is as follows. SVLs should always be installed in protected locations, which are, substations and link boxes, or enclosures. If the selected special sheath bonding method is single-point bonding, then SVLs should be installed to the end of the cable interface, which is more subjected to transients such as lightning or switching surges, or which end has better grounding conditions. Placement of SVLs is critical for single-point bonded systems since the “open circuit” terminal is subjected to the highest power frequency and surge overvoltages (Argaut & Pierre, 2023). Figure 5.5. Visualizes the overvoltages measured from the jointing positions during no load 330 kV cable energization (Sheng & All, 2022).

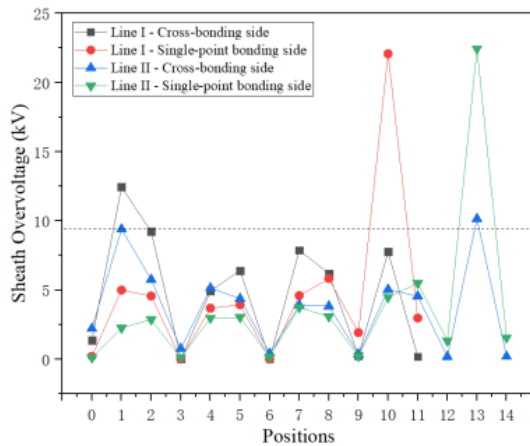


Figure 5.5. Sheath voltage distribution of the 330 kV pure cable lines when energized from different sides (Sheng & All, 2022).

As can be seen from the graph, the highest sheath overvoltages are obtained when the cable circuits are energized from the single-point bonded side. If cable interface introduces mixed special bonding methods, each section and jointing position should be studied from the perspective of sheath overvoltages.

6 Power Cable Ampacity Rating

References for theory, equations, and tables are mainly from IEC 60287-1-1:2023, IEC 60287-2-1:2023, and IEC 60287-3-3:2007 unless otherwise mentioned within the Chapter.

Ampacity rating of a power cable is a factor of many different parameters. The most important, worthwhile mentioning are – The number of power cables utilized in the cable system, Construction of the cable and its' used materials, the surrounding medium of the cable system and the sheath bonding arrangement (Anders, 2005). With high voltage cables, operating voltage is included in the important parameters as the dielectric losses are directly proportional to the square of operating voltage U_0 (IEC 60287-1-1, 2023).

Steady state ampacity calculations involve solving the equation for heat transfer ladder network. Figure 1. Visualizes the heat transfer mechanism in a single-core power cable in a steady state condition where W_c is losses of the core conductor, W_d is the dielectric losses, W_s is the sheath losses, and W_a is the armour losses. T_1 , T_2 , T_3 , and T_4 will be explained later within this chapter. (Anders, 2005)

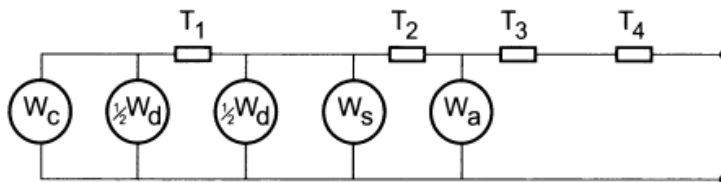


Figure 6.1. Ladder diagram of steady state ampacity rating calculation analogy for single-core power cables (Anders, 2005).

For comparison purposes, heat transfer mechanism for three-core power cable is represented in Figure 6.2.

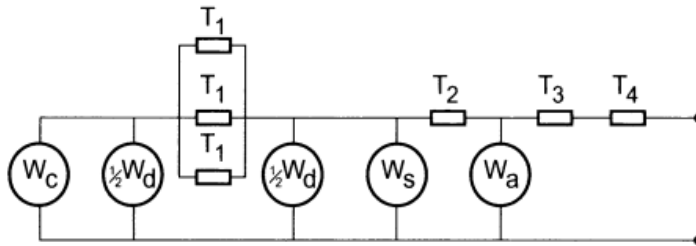


Figure 6.2. Ladder diagram of steady state ampacity rating calculation analogy for three-core power cables (Anders, 2005).

Key difference between single-core and three-core cables is that three-core cables have common sheath, serving and/or armouring, and single-core cables have individual sheath, serving, and/or armouring for each phase conductor (Anders, 2005).

Fundamentally, when maximum permissible ampacity of the power cable is the point of interest, hot spots within the cable route are determined and the equations are modified accordingly based on installation formation, laying depth, and other possible modifications. Identified hot spots could be road crossings, where cables are placed in protective ducts, parallel cable circuits, and adjacent heat sources which could be a district heating pipe.

6.1 Steady State Ampacity

Steady state ampacity determines the loading current, which the power cable can sustain indefinitely without exceeding the allowed maximum temperature of the core conductor, if the environmental conditions remain constant. Typically, steady state ampacity is sufficient method for transmission capacity calculations in most cases. More detailed dynamic ampacity studies are required if steady state method is not sufficient.

Steady state ampacity, where drying of the soil does not occur, is given by Equation 6.1 (IEC 60287-1-1, 2003).

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

where $\Delta\theta$ is permissible temperature rise of conductor above ambient temperature [$^{\circ}\text{C}$], W_d is dielectric losses per unit length per phase [W/m], T_1 thermal resistance per core between conductor and sheath [$\text{K}\cdot\text{m/W}$], T_2 is thermal resistance between sheath and armour [$\text{K}\cdot\text{m/W}$], T_3 is thermal resistance of external serving [$\text{K}\cdot\text{m/W}$], T_4 is thermal resistance of surrounding medium [$\text{K}\cdot\text{m/W}$], n is number of conductors in a cable, R_c is alternating current resistance of conductor at its maximum operating temperature per unit length of the cable [Ω/m], λ_1 and λ_2 are ratio of the total losses in metallic sheaths and armour respectively to the total conductor losses.

If temperature rise of core conductor with given load current is in the scope of interest, Equation 6.1. can be rearranged to Equation 6.2 (IEC 60287-1-1, 2023).

$$\Delta\theta = \left(I^2 R_c + \frac{1}{2} W_d \right) T_1 + n [I^2 R_c (1 + \lambda_1) + W_d] T_2 + n [I^2 R_c (1 + \lambda_1 + \lambda_2) W_d] (T_3 + T_4) \quad (6.2)$$

where I is the RMS current in one conductor [A].

6.2 Thermal Resistance

Total thermal resistance of the power cables consists of four variables - thermal resistance between one conductor and sheath, thermal resistance between sheath and armour, thermal resistance of outer covering, and external thermal resistance. According to IEC 60287-2-1:2023, these variables are also known as T_1 , T_2 , T_3 , and T_4 . The most important of these

variables being T_1 and T_4 . As matter of fact, external thermal resistivity for buried cables is accountable for more than 70 % of the core conductor's temperature rise. Therefore, serving materials are chosen based on the lowest possible thermal resistance, which typically are sand or concrete. (Anders, 2005)

Calculation of single-core power cable's internal thermal resistances is straightforward task. However, three-core power cables require more attention as well as calculation of external thermal resistance. The equations for thermal resistances are product of rigorous mathematical computations and empirical investigations. (Anders, 2005)

6.2.1 Thermal Resistance Between One Conductor and Sheath (T_1)

The thermal resistance between the core conductor and sheath is completely dependent on diameter of the conductor, thickness of the insulation and insulating material of the insulation. Thermal resistance T_1 of a single-core cable is given by Equation 6.3. (IEC 60287-2-1, 2023)

$$T_1 = \frac{\rho_1}{2\pi} \ln \left(1 + \frac{2t_1}{d_c} \right) \quad (6.3)$$

where ρ_1 is the thermal resistivity of insulation [$\text{K}\cdot\text{m}/\text{W}$], t_1 is the thickness of insulation between the conductor and sheath [mm], and d_c is the diameter of the conductor [mm].

In case of a corrugated sheath, t_1 is based on the mean internal diameter of the sheath which is given by Equation 6.4 (IEC 60287-2-1, 2023).

$$t_1 = \left(\frac{D_{it} + D_{oc}}{2} \right) - t_s \quad (6.4)$$

where D_{it} is the diameter of the imaginary cylinder which just touches the inside surface of the troughs of a corrugated sheath [mm], D_{oc} is the diameter of the imaginary coaxial cylinder which just touches the crests of a corrugated sheath [mm], and t_s is thickness of the sheath [mm].

Different material properties in terms of thermal resistivity can be found from Appendix 1.

In case of ampacity calculations, the semiconducting screening materials can be expected to have similar thermal properties as the immediate insulating material (IEC 60287-2-1, 2023).

6.2.2 Thermal Resistance Between Sheath and Armour (T_2)

Typically, armouring is used for offshore power cables and cables, which are operating in heavy duty conditions, e.g., mines and industrial environments. Calculation of thermal resistance between sheath and armour is given by Equation 6.5 (IEC 60287-2-1, 2023).

$$T_2 = \frac{1}{2\pi} \rho_T \ln \left(1 + \frac{2t_2}{D_s} \right) \quad (6.5)$$

where ρ_T is thermal resistivity of material [$\text{K}\cdot\text{m}/\text{W}$], t_2 is thickness of bedding [mm], and D_s is external diameter of metal sheath [mm].

In case of a cable interface, which does not utilize armouring, T_2 can be neglected from the ampacity calculations (IEC 60287-2-1, 2023).

6.2.3 Thermal Resistance of Outer Covering (Serving) (T_3)

Thermal resistance of the outer covering (Serving) is given by Equation 6.6 (IEC 60287-2-1, 2023).

$$T_3 = \frac{1}{2\pi} \rho_T \ln \left(1 + \frac{2t_3}{D'_a} \right) \quad (6.6)$$

where t_3 is thickness of the serving [mm], and D'_a is the external diameter of the armour [mm].

In case of a cable interface, which does not have armouring, D'_a is replaced with the component immediately beneath the armour. This could be sheath, screen or bedding. (IEC 60287-2-1, 2023)

6.2.4 External Thermal Resistance (T_4)

External thermal resistance is responsible for over 70 % of the total losses of the cable interface. Most critical factors are the thermal resistivity of the surrounding medium, and the laying depth of the cable installation. (Anders, 2005)

Simple method for calculating external thermal resistance for one buried single-core cable is given by Equation 6.7 (IEC 60287-2-1, 2023).

$$T_4 = \frac{1}{2\pi} \rho \ln \left(u_1 + \sqrt{u_1^2 - 1} \right) \quad (6.7)$$

where ρ is the thermal resistivity of the soil [K·m/W], $u_1 = \frac{2L}{D_e}$, L is the distance from the surface of the ground to the cable axis [mm], and D_e is the external diameter of the cable [mm].

In most cases, a three-phase system is the point of interest, and therefore the equation for the external thermal resistance must be modified to match different installation formations. External thermal resistance is divided into touching and not touching group of cables and equally loaded and not equally loaded cables. (IEC 60287-2-1, 2023)

External thermal resistance for three cables having approximately equal losses, laid in a horizontal plane, equally spaced apart is given by Equation 6.8 (IEC 60287-2-1, 2023).

$$T_4 = \frac{1}{2\pi} \rho \left\{ \ln \left(u_1 + \sqrt{u_1^2 - 1} \right) + \ln \left[1 + \left(\frac{2L}{s_1} \right)^2 \right] \right\} \quad (6.8)$$

where, s_1 is the axial distance between the cables [mm].

If the external thermal resistance for three cables having unequal sheath losses, laid in a horizontal plane, equally spaced apart, the equation must be modified and incorporated with loss factors for cable system which has unequal sheath losses. The modified equation is given by Equation 6.9. (IEC 60287-2-1, 2023)

$$T_4 = \frac{1}{2\pi} \rho \left\{ \ln \left(u_1 + \sqrt{u_1^2 - 1} \right) + \left[\frac{1 + 0,5(\lambda'_{11} + \lambda'_{12})}{1 + \lambda'_{1m}} \right] \ln \left[1 + \left(\frac{2L}{s_1} \right)^2 \right] \right\} \quad (6.9)$$

where the λ'_{11} is the sheath loss factor for an outer cable of the group, λ'_{12} is the sheath loss factor for the other outer cable of the group, and λ'_{1m} is the sheath loss factor for the middle cable of the group.

Introduced equations apply for flat formation installations since typically, in trefoil formation the cables touch each other. If the cables touching each other is the point of interest within the ampacity study the equation for external thermal resistance must be again modified.

Equation for groups of buried cables touching each other, equally loaded, in flat formation for metallic sheathed cables is given by Equation 6.10 (IEC 60287-2-1, 2023).

$$T_4 = \rho \left(0,475 \ln \left(u_1 + \sqrt{u_1^2 - 1} \right) - 0,346 \right) \quad (6.10)$$

Similarly for non-metallic sheathed cables the external thermal resistance is given by Equation 6.11 (IEC 60287-2-1, 2023).

$$T_4 = \rho \left(0,475 \ln \left(u_1 + \sqrt{u_1^2 - 1} \right) - 0,142 \right) \quad (6.11)$$

External thermal resistance for three single-core cables, trefoil installation, and metallic sheathed cables, is given by Equation 6.12 (IEC 60287-2-1, 2023).

$$T_4 = \frac{1,5}{\pi} \rho \left[\ln \left(u_1 + \sqrt{u_1^2 - 1} \right) - 0,630 \right] \quad (6.12)$$

Similarly for non-metallic sheathed cables the external thermal resistance is given by Equation 6.13 (IEC 60287-2-1, 2023).

$$T_4 = \frac{1}{2\pi} \rho \ln \left[\left(u_1 + \sqrt{u_1^2 - 1} \right) + 2 \ln(u_1) \right] \quad (6.13)$$

Equation for non-metallic sheathed cables is used for sheaths composed of copper wires and for the external thermal resistance of non-metallic touching ducts (IEC 60287-2-1, 2023).

Usually, the power cables are installed inside a protective duct somewhere along the cable route. Places where ducts are utilized, could be road crossings or installations inside the

fenced area of a substation. Therefore, thermal resistance must be calculated for the protective ducts as such installations could be a hot spot for the power cable interface. In most cases, these ducts are manufactured from PE or non-ferro metallic tubes.

Following equations are applicable for cable diameters between 25 mm and 100 mm. Thermal resistance of tube installation is a combination of three integers, which are thermal resistance between cable and duct or pipe (T_4'), thermal resistance of the duct or pipe itself (T_4''), and external thermal resistance of the duct or pipe (T_4'''). The total thermal resistance of ducted installation is given by Equation 6.14. The total thermal resistance is then directly placed into the Equation 6.1. (IEC 60287-2-1, 2023)

$$T_4 = T_4' + T_4'' + T_4''' \quad (6.14)$$

Thermal resistance between cable and duct or pipe is given by Equation 6.15 (IEC 60287-2-1, 2023).

$$T_4' = \frac{U}{1 + 0,1(V + Y \cdot \theta_m)D_e} \quad (6.15)$$

where U , V , and Y are constants, which depend on the installation, see Table 6.1, D_e is the external diameter of the cable [mm], θ_m is the mean temperature of the medium filling the space between the cable and duct [$^{\circ}\text{C}$]. An assumed value for θ_m shall be used initially and the calculation repeated with modified value if necessary.

Table 6.1. Constants for U , Y , and V utilized in Equation 6.15 (IEC 60287-2-1, 2023).

Installation Condition	U	Y	V
In metallic conduit	5,2	1,4	0,011
In fibre duct in air	5,2	0,83	0,006
In fibre duct in concrete	5,2	0,91	0,01
In asbestos cement:			
duct in air	5,2	1,2	0,006
duct in concrete	5,2	1,1	0,011
Gas pressure cable in pipe	0,95	0,46	0,0021
Oil pressure pipe-type cable	0,26	0,0	0,0026
Plastic ducts	1,87	0,312	0,0037
Earthenware ducts	1,87	0,28	0,0036
Water filled plastic ducts	0,1	0,03	0,001

Thermal resistance of the duct or pipe is given by Equation 6.16 (IEC 60287-2-1, 2023).

$$T_4'' = \frac{1}{2\pi} \rho_T \ln \left(\frac{D_o}{D_d} \right) \quad (6.16)$$

where ρ_T is the thermal resistivity of the duct or pipe material [K·m/W], D_o is the outside diameter of the duct or pipe [mm], and D_d is the inside diameter of the duct or pipe [mm].

External thermal resistance of the duct or pipe T_4''' is calculated by replacing the external radius of the cable with the external radius of the duct or pipe, and by utilizing the correct equation. The choice of correct equation is selected based on the installation formation. (IEC 60287-2-1, 2023)

6.3 Sheath Loss Factors

Loss factor of the power cable sheath is a combination of cable construction, cable installation formation, and sheath bonding arrangement. In simplicity, analogy of loss factor

is composed of two integers, which are circulating current and eddy current losses. (IEC 60287-1-1, 2023)

More detailed factors, which influence the loss factor are following. Typically, metallic sheath is formed of helically laid copper wires or welded aluminium, or both. For such implementations sheath resistance might vary. In addition, axial distance between the conductors affects the sheath reactance. Simple analogy is that larger axial distance results in higher sheath reactance. Sheath bonding is critical factor, since it either allows the current to circulate in sheaths, interrupts it, or divides it into sections. Calculation of total sheath loss factor is given by Equation 6.17. (IEC 60287-1-1, 2023)

$$\lambda_1 = \lambda'_1 + \lambda''_1 \quad (6.17)$$

where λ'_1 is the circulating current loss factor of the sheath, and λ''_1 is the eddy current loss factor.

Sheath resistance must be corrected to maximum operating temperature the same way as the core conductor of the power cable. However, calculation of sheath resistance at given operation temperature has iterative nature, as the sheath temperature is a function of the load current. Sheath temperature at maximum operating temperature is given by Equation 6.18. (IEC 60287-1-1, 2023)

$$\theta_{sc} = \theta - (I^2 R_c + 0,5W_d)T_1 \quad (6.18)$$

where θ is the temperature of the sheath above ambient temperature [$^{\circ}\text{C}$], I is the rms load current [A], R_c is the AC resistance of the core conductor at maximum operating temperature [Ω/m], W_d is the dielectric losses of the insulation [W/m], and T_1 is the thermal resistance between sheath and core conductor [$\text{K}\cdot\text{m}/\text{W}$].

From Equation 6.18. the sheath resistance at maximum operating temperature can be calculated from Equation 6.19 (IEC 60287-1-1, 2023).

$$R_s = R_{so}[1 + \alpha_{20}(\theta_{sc} - 20 \text{ K})] \quad (6.19)$$

where R_{so} is the resistance of the cable sheath or screen at 20 °C per unit length of the cable.

In addition to the sheath resistance, sheath reactance must be considered. Reactance of the sheath will vary based on the chosen cable formation arrangement. Sheath reactance calculated for trefoil formation cannot be utilized for flat formation and vice versa but must be calculated separately for each cable formation. (IEC 60287-1-1, 2023)

Sheath reactance for trefoil formation is given by Equation 6.20 (IEC 60287-1-1, 2023).

$$X = 2\omega \cdot 10^{-7} \ln\left(\frac{2s}{d}\right) \quad (6.20)$$

where ω is the angular frequency of the supply [rad/s], s is the axial distance between the phases [mm], and d is the mean diameter of the sheath [mm].

Similarly sheath reactance for flat formation is given by Equation 6.21 (IEC 60287-1-1, 2023).

$$X_1 = 2\omega \cdot 10^{-7} \ln\left(2\sqrt[3]{2}\left(\frac{s}{d}\right)\right) \quad (6.21)$$

For flat formation installations, also mutual reactance per unit length of cable between the sheath of an outer cable and the conductors of the other two, when the cables are in flat formation must be considered and is given by Equation 6.22 (IEC 60287-1-1, 2023).

$$X_m = 2\omega \cdot 10^{-7} \ln(2) \quad (6.22)$$

More detailed information for calculation of metallic sheath loss factor is given in the upcoming subchapters and IEC 60287-1-3, which explains the current sharing phenomena between single-core cables and calculation of circulating current losses in a cable interface with mixed installation formations. Following chapter assumes, that the installation formation remains the same for the whole cable route. (IEC 60287-1-1, 2023)

6.3.1 Circulating Current Losses

In a case where single-core cables are the point of interest, only the losses due to circulating losses are considered. If the cable system under study is either single-point bonded, or cross-bonded, circulating losses can be neglected as no circulating sheath currents are present. Circulating losses must be calculated separately for each cable formation. (IEC 60287-1-1, 2023)

Two single-core cables, and three single-core cables (in trefoil formation), sheaths bonded at both ends of an electrical section (IEC 60287-1-1, 2023).

$$\lambda'_1 = \frac{R_s}{R_c} \cdot \frac{1}{1 + \left(\frac{R_s}{X}\right)^2} \quad (6.23)$$

where R_c is the alternating current resistance at the maximum temperature of the conductor [Ω/m], R_s is the sheath resistance at maximum operating temperature [Ω/m], X is the sheath reactance for trefoil formation [Ω/m].

Three single-core cables in flat formation, with regular transposition, sheaths bonded at both ends of an electrical section (IE 60287-1-1, 2023).

$$\lambda'_1 = \frac{R_s}{R_c} \cdot \frac{1}{1 + \left(\frac{R_s}{X_1}\right)^2} \quad (6.24)$$

where X_1 is the sheath reactance for flat formation [Ω/m].

Three single-core cables in flat formation, without transposition, sheaths bonded at both ends of an electrical section (IEC 60287-1-1, 2023).

The outer cable carrying the lagging phase:

$$\lambda'_{11} = \frac{R_s}{R_c} \left[\frac{0,75C_p^2}{R_s^2 + C_p^2} + \frac{0,25C_Q^2}{R_s^2 + C_p^2} + \frac{2R_sC_pC_QX_m}{\sqrt{3}(R_s^2 + C_p^2)(R_s^2 + C_Q^2)} \right] \quad (6.25)$$

For the other outer cable, the loss factor is given by:

$$\lambda'_{12} = \frac{R_s}{R_c} \left[\frac{0,75C_p^2}{R_s^2 + C_p^2} + \frac{0,25C_Q^2}{R_s^2 + C_p^2} - \frac{2R_sC_pC_QX_m}{\sqrt{3}(R_s^2 + C_p^2)(R_s^2 + C_Q^2)} \right] \quad (6.26)$$

For the middle cable, the loss factor is given by:

$$\lambda'_{1m} = \frac{R_s}{R_c} \cdot \frac{C_Q^2}{R_s^2 + C_Q^2} \quad (6.27)$$

where $C_p = X + X_m$, and $C_Q = X - \frac{X_m}{3}$

If Milliken conductors are used, the loss factor should be multiplied with factor C_F , which is given below, to include the losses due to the eddy current losses. Milliken conductors cause reduced proximity effect and therefore eddy current losses must be included in the calculations. If a round stranded conductors are used, eddy current losses can be neglected for solidly bonded systems. (IEC 60287-1-1, 2023)

$$C_F = \frac{4C_{M1}^2 C_N^2 + (C_{M1} + C_N)^2}{4(C_{M1}^2 + 1)(C_N^2 + 1)} \quad (6.28)$$

where $C_{M1} = C_N = \frac{R_s}{X}$ for cables in trefoil formation

and

$C_{M1} = \frac{R_s}{X+X_m}$ and $C_N = \frac{R_s}{X-\frac{X_m}{3}}$ for cables in flat formation with equidistant spacing

Equations provided above are typically utilized for small cable cross-sections or for medium voltage cables, excluding the effect of Milliken conductors, as the solid bonding is not preferred bonding method for high voltage cables, or cables with high transmission capacity.

6.3.2 Eddy Current Losses

Eddy currents are mainly formed in metallic sheaths of the power cables due to changing magnetic fields. As where only circulating current losses were considered for cable interface where both ends of the metallic sheaths were grounded, similar assumption cannot be made for single-point or cross-bonded cable interfaces. For such cases, eddy current losses must be considered and circulating current losses can be neglected as the metallic sheath does not provide path for the circulating sheath currents. Eddy current losses for single-core cables

with sheaths bonded at single-point or cross-bonded are given by Equation 6.29. (IEC 60287-1-1, 2023)

$$\lambda_1'' = \frac{R_s}{R_C} \left[C_{gs} \lambda_0 (1 + \Delta_1 + \Delta_2) + \frac{(\beta_1 t_s)^4}{12 \cdot 10^{12}} \right] \quad (6.29)$$

where

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

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

ρ_s is the electrical resistivity of the metallic sheath material operating temperature [Ωm], D_s is the external diameter of the sheath [mm], t_s is the thickness of the sheath [mm], ω is the angular frequency of the supply system [rad/s].

Equations for λ_0 , Δ_1 and Δ_2 are given based on the installation formation and they are as follows. Eddy current losses can be neglected if the metallic sheath is constructed from copper wires and copper foil. (IEC 60287-1-1, 2023)

Three single-core cables installed in trefoil formation:

$$\lambda_0 = 3 \cdot \left(\frac{m^2}{1 + m^2} \right) \cdot \left(\frac{d}{2s} \right)^2 \quad (6.30)$$

$$\Delta_1 = 0,86 \cdot m^{3,08} \left(\frac{d}{2s} \right)^{1,4 \cdot m + 0,7} \quad (6.31)$$

$$\Delta_2 = 0 \quad (6.33)$$

Three single-core cables installed in flat formation:

Centre cable:

$$\lambda_0 = 6 \cdot \left(\frac{m^2}{1+m^2} \right) \cdot \left(\frac{d}{2s} \right)^2 \quad (6.34)$$

$$\Delta_1 = 4,7 \cdot m^{0,7} \left(\frac{d}{2s} \right)^{0,16 \cdot m + 2} \quad (6.35)$$

$$\Delta_2 = 0 \quad (6.36)$$

Outer cable leading phase:

$$\lambda_0 = 1,5 \cdot \left(\frac{m^2}{1+m^2} \right) \cdot \left(\frac{d}{2s} \right)^2 \quad (6.37)$$

$$\Delta_1 = 4,7 \cdot m^{0,7} \left(\frac{d}{2s} \right)^{0,16 \cdot m + 2} \quad (6.38)$$

$$\Delta_2 = 21 \cdot m^{3,3} \left(\frac{d}{2s} \right)^{1,47 \cdot m + 5,06} \quad (6.39)$$

Outer cable lagging phase:

$$\lambda_0 = 1,5 \cdot \left(\frac{m^2}{1 + m^2} \right) \cdot \left(\frac{d}{2s} \right)^2 \quad (6.40)$$

$$\Delta_1 = - \frac{0,74 \cdot (m + 2)m^{0,5}}{2 + (m - 0,3)^2} \cdot \left(\frac{d}{2s} \right)^{m+1} \quad (6.41)$$

$$\Delta_2 = 0,92 \cdot m^{3,7} \left(\frac{d}{2s} \right)^{m+2} \quad (6.42)$$

where $m = \frac{\omega}{R_s} \cdot 10^{-7}$

if $m \leq 0,1$, Δ_1 and Δ_2 can be neglected.

Formulations within this chapter are only applicable for single-core cables with metallic sheaths constructed for copper wires and tapes and/or welded aluminium foil. Further formulations for lead sheathed cables and multi- or three-core cables are given in IEC 60287-1-1 05/2023 and will not be introduced within this thesis as they do not belong to the scope of the thesis.

6.4 Crossing of Thermally Unfavourable Regions

Cable circuits may cross many thermally unfavourable regions within their route. Such regions within urban areas are typically steam pipes, district heating pipes or other cable circuits, which radiate heat or cause drying of the surrounding medium. With such conditions the temperature rise of the conductor may even be as high as 20 % if compared to conductor temperature which is not in the vicinity of external heat sources. Therefore, it is essential to carry out careful study of hot spots within the cable route and take the most critical ones into

account during design phase. Increase of 20 % of conductor temperature may cause shortened life cycle of the cable and even cause insulation damage and therefore cable failure at some point of the life cycle of the cable. (Anders, 2005)

Several parameters of the external heat source affect the temperature rise of the conductor, and the most critical ones are (Anders, 2005):

- Heat dissipation level of the external heat source.
- Distance between the cable and the external heat source at the point of intersection.
- Angle of the intersection.
- The size of the cable.

Visualization of these is shown in Figure 6.3.

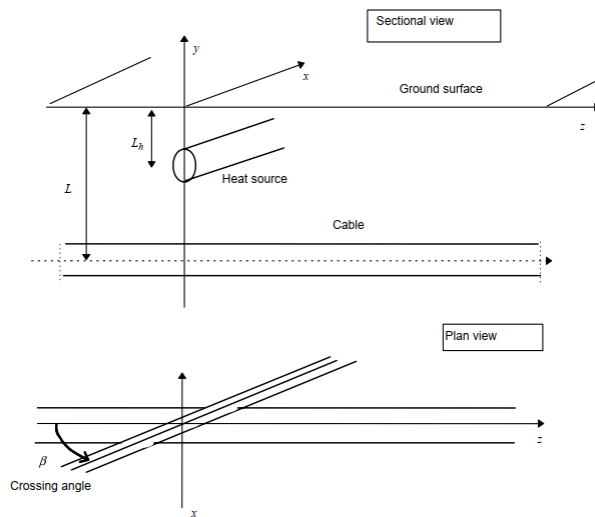


Figure 6.3. Sectional and plan view of the intersection of external heat source and cable circuit (IEC 60287-3-3, 2007).

IEC 60287-3-3 provides numerical calculation methods for the derating factor of the power cables, which cross external heat sources. Maximum permissible rated current of the cable which intersects external heat source is given by Equation 6.43. (IEC 60287-3-3, 2007)

$$DF = \sqrt{1 - \frac{\Delta\theta(0)}{\Delta\theta_{max} - \Delta\theta_d}} \quad (6.43)$$

where $\Delta\theta(0)$ is the temperature rise of the conductor due to the crossing heat source, at the crossing point [K], $\Delta\theta_{max}$ is the maximum permissible conductor temperature rise above ambient temperature [K], and $\Delta\theta_d$ is the conductor temperature rise due to dielectric losses [K].

In case of crossing of a single external heat source, the formulation for $\Delta\theta(0)$ initial condition is as follows and it is obtained by dividing the distance z_{max} into N intervals, each of length Δz (IEC 60287-3-3, 2007):

$$\Delta\theta(0) = \frac{W_h \rho \cdot (e^{\gamma \Delta z} - 1)}{4\pi} \sum_{v=1}^N e^{-\gamma \Delta z} \ln \frac{(L + L_h)^2 + (v \Delta z \sin\beta)^2}{(L - L_h)^2 + (v \Delta z \sin\beta)^2} \quad (6.44)$$

where ρ is the thermal resistivity of soil [K·mW], W_h is the heat generated by the external heat source [W/m], β is the angle of the crossing [°], L is the laying depth of the rated cable [mm], and L_h is the laying depth of the external heat source [mm].

Attenuation factor γ is expressed as (IEC 60287-3-3, 2007):

$$\gamma = \sqrt{(1 - \Delta W \cdot T) \cdot \frac{T_L}{T_r}} \quad (6.45)$$

with

Thermal longitudinal resistance of a conductor T_L is expressed as (IEC 60287-3-3, 2007):

$$T_L = \frac{\rho_{cr}}{A \cdot 10^{-6}} \quad (6.46)$$

where ρ_{cr} is the thermal resistivity of conductor material [K·m/W], and A is the cross-sectional area of the conductor [mm].

Total thermal resistance of cable per conductor T_r is expressed as (IEC 60287-3-3, 2007):

$$T_r = T_1 + n \cdot (T_2 + T_3 + T_4) \quad (6.47)$$

Equivalent thermal resistance of cable per conductor T is expressed as (IEC 60287-3-3, 2007):

$$T = T_1 + n \cdot [(1 + \lambda_1) \cdot T_2 + (1 + \lambda_1 + \lambda_2) \cdot (T_3 + T_4)] \quad (6.48)$$

Conductor temperature rise due to electric losses $\Delta\theta_d$ is expressed as (IEC 60287-3-3, 2007):

$$\Delta\theta_d = W_d \cdot \left[\frac{T_1}{2} + n \cdot (T_2 + T_3 + T_4) \right] \quad (6.49)$$

Incremental heat generated due to change of conductor resistance ΔW is expressed as (IEC 60287-3-3, 2007):

$$\Delta W = \Delta W_0 \cdot \left[1 - \frac{\Delta\theta(0)}{\Delta\theta_{max} - \Delta\theta_d} \right] \quad (6.50)$$

where ΔW_0 is expressed as (IEC 60287-3-3, 2007):

$$\Delta W_0 = \frac{R \alpha_{20} I_{iso}^2}{1 + \alpha_{20} \cdot (\theta_{max} - 20)} \quad (6.51)$$

where α_{20} is the temperature coefficient of electrical resistivity for the conductor material, A is the cross-sectional area of the conductor [mm^2], and I_{iso} is the maximum permissible current of the rated cable when isolated [A].

In most cases a typical value for Δz is 0,01 meters. However, a verification must be carried out, which is: $\gamma \cdot \Delta z < \varepsilon$. Value for ε is typically quite small, $\varepsilon = 0,01$ (IEC 60287-3-3, 2007).

N is expressed as (IEC 60287-3-3, 2007):

$$N = \frac{z_{max}}{\Delta z} \quad (6.52)$$

with $\Delta\theta_{uh}(N \cdot \Delta z) < \varepsilon$.

where z_{max} is a distance and it is a function of the longitudinal thermal resistance of the conductors and the separation between the cable and the external heat source and the heat generated by the crossing source.

Kennelly's principle is applied to calculate the temperature rise in a conductor $\Delta\theta_{uh}(z)$ as a function of distance z from the crossing, which is caused by the crossing external heat source and the calculation method is given by Equation 6.53 (IEC 60287-3-3, 2007).

$$\Delta\theta_{uh}(z) = \frac{\rho}{4\pi} \cdot W_h \cdot \ln \frac{(L + L_h)^2 + z^2 \cdot \sin^2 \beta}{(L - L_h)^2 + z^2 \cdot \sin^2 \beta} \quad (6.53)$$

The attenuation factor γ is dependent on the current in the rated cable, which is the product of the whole calculation method, and therefore an iterative approach to estimate the rated current when the heat source is assumed to be in parallel with to the rated cable must be taken (IEC 60287-3-3, 2007).

The first iterative estimation of $\Delta\theta(0)$ is expressed as follows (IEC 60287-3-3, 2007):

$$\Delta\theta(0) = \frac{\rho}{4\pi} \cdot W_h \cdot \ln \frac{(L + L_h)^2}{(L - L_h)^2} \quad (6.54)$$

Equations above are only applicable for a cable circuit, which intersects a single external heat source. If several external heat sources intersect the cable circuit, a superposition method must be implemented. However, this method will not be introduced within this thesis as it is not part of the scope. For further information, refer to the IEC 60287-3-3 chapter 4.3. (IEC 60287-3-3, 2007)

7 Cable Ampacity Optimization Challenges in Finnish Environment

Chapter seven provides insight into the optimization challenges of high voltage cable's ampacity rating in Finnish environment. Typical derating conditions include crossing of roads and railways and intersection points with external heat sources as district heating pipes or other cable circuits. Optimization of the bonding arrangement, crossing of roads and external heat sources and improvement of soil properties will be discussed.

7.1 Selection of Bonding System and System Design

Essentially, three different bonding options are utilized for the metallic sheaths of 110 kV cables in Finland. These are solid bonding, single-point bonding, and cross-bonding, along with their various modifications and combinations. As a rule of thumb, it can be assumed that short cable connections, where $l < 500$ meters, are grounded from both ends of the cable if the load current is low, or alternatively, the metallic sheaths are earthed from the other end only, if the load current is at higher levels, which is called single-point bonding. Loading current and cable route length are the critical parameters when selecting the appropriate bonding system during the design phase. This is because the magnitude of the load current affects the induced voltage in the metallic sheath, and the magnitude of the open-end standing voltage of the cable's metallic sheath is directly proportional to the length of the cable connection.

In most cases, single-point bonding is utilized within substation area, where cable connections are very short, $l < 100$ meters for each phase. This is due to low induced standing sheath voltage at the open-end of the cable connection even with high ampacity ratings. Such cable installations can be found in substations, which have gas-insulated switchgears (GIS). Cable terminations, which are connected to the GIS, the metallic sheaths are also solidly bonded to the earthing grid. The other end, which is typically connected to transformers, reactors, other equipment, or to an overhead line interface, the metallic sheath will be connected to earth through a sheath voltage limiter. Bonding arrangement described is the

general guideline, which is applied to 110 kV cables within substations owned by transmission system and distribution system operators.

Single-point is cost effective solution as it is simple in terms of required components and installation costs. A special form of single-point bonding is middle-point bonding, and it can be utilized to extend the maximum length of single-point bonded cable connection. As the name suggests, the cable connection and the continuity of the sheath are interrupted in the middle of the cable connection with a sheath interruption joint. Metallic sheaths are earthed from both sides of the screen interruption joint and at the terminations, the metallic sheaths are earthed through SVL's. Therefore, the length of a cable connection with middle-point bonded metallic sheaths can be almost doubled, as the standing sheath voltages at the open ends are halved if compared to traditional single-point bonding method. Middle-point bonding is a more cost-effective solution if compared to cross-bonded systems, as it allows optimization of cable drum sizing and does not require as many cable joints and other accessories. However, the middle-point bonded system also has a maximum limit length, which limits the cable length to a certain level. This should be carefully studied in terms of standing sheath voltage amplitude during steady state and transient conditions.

Lastly, cross-bonding is utilized for long cable transmission lines as no other option offers such effective neutralization of circulating losses. In addition, cross-bonding does not have the maximum length for the cable route. This is because the cable connection can be constructed in theory from an infinite number of major sections within the cross-bonding system. However, in case of high voltage cables, where $U_n \geq 110$ kV, the capacitive charging current may limit the length of the cable route due to reactive power produced by the operating capacitance of the high voltage cable. As an example, a 64/110 (123) kV high voltage cable with conductor cross-section of 2000 mm², will produce approximately 1,3 MVar's of capacitive reactive power per kilometer. For such cable, the compensation of the produced capacitive reactive power is not necessary as such cable connections tend to be shorter than 20 kilometers in length. However, for a 400 kV high voltage cable, the produced capacitive reactive power per unit length is so large, that it needs compensation equipment every 20 kilometers, or the capacitive reactive power will overload the cable itself (Elovaara & Haarla, 2011).

7.2 Horizontal Drilling and Piping Under Railways and Public Roads

Horizontal Directional Drilling (HDD) is quite new but advancing method. HDD is utilized to cross challenging infrastructures within urban environments. Typically, HDD is applied when crossing highways, railways, district heating pipes, watercourses, substation or even industrial plants. In earlier days, the cable circuit would have to be routed elsewhere, or utilize overhead line to cross urban infrastructure. HDD may provide substantial savings in costs if utilized properly and is the preferred method in urban environment as it minimizes the visual disturbances within the area if compared to a traditional overhead line interface. (Smith, 2021)

Finnish legislation demands certain precautions when high voltage cables are to be installed in the vicinity of or crossing highways and railways. Rule of thumb is that when crossing a road in cityscape, the minimum laying depth of the cable(s) is 1,0 meters. In addition, the cables must be protected with concrete slabs and/or with plastic/steel ducts. The crossing method is selected based on the average daily traffic. If the daily traffic is more than 100 vehicles per day, excavating the road is prohibited according to the Finnish Transport Infrastructure Agency. Therefore, the only viable method for crossing the highways is horizontal directional drilling. Same rule applies for highways. The minimum laying depth from the road surface to the top of the protective duct shall be no less than 1,0 meters. However, for weighty reasons the authority may approve shallower installation depths if sufficient protection is ensured. Following factors also influence the choice of installation depth. (Liikennevirasto, 2018)

- If the protective conduit is pushed under a roadside ditch and road, the bottom of the ditch requires a greater installation depth than the distance from the road surface.
- In HDD and, if necessary, in other methods, a larger installation depth is often chosen to avoid coarse layers in the road construction and to allow for greater positioning tolerances during installation.
- On a case-by-case basis, e.g., a shallower installation depth may be accepted at a rocky area when using excavation-resistant conduit.

If rock or another reason prevents installation to a sufficient depth, another better location is sought. If that is not possible either, a shallower installation depth is used along with the protection defined below. (Ratahallintokeskus, 2004)

The type of protection depends on the laying depth of the cable installation.

- If $h > 0.7$ m: minimum distance of warning tape from the ground surface is 0.2 m and from the cable is 0.2 m.
- If $0.5 < h < 0.7$ m: Class C (L450) protective conduit.
- If $0.3 < h < 0.5$ m: Class B (N450) protective conduit; in yard and park areas, Class A (N750) protective conduit.
- Class A plastic conduit, concrete casting, or other equivalent protection providing resilience to environmental stresses and, if necessary, occasional traffic.

The letters A...C refer to the standard SFS 6000.

Crossing of railways has its own legislations, which are regulated by the Finnish Transport Infrastructure Agency as well. The cables crossing a railway must be installed underground, in a durable duct or conduit, allowing easy replacement of the cable, if necessary, without the need to excavate soil beneath the rails. Common principles for railway crossings include: (Ratahallintokeskus, 2004)

- The protective conduit should generally extend from the edge of the railway structures to the other edge, however, at least 2.9 meters away from the centreline of the tracks, and it should be as perpendicular as possible to the longitudinal direction of the tracks.
- The underpass depth must be at least 1.4 meters below the bottom of the rail and at least 0.8 meters below the ground level outside the rail banking, unless otherwise agreed in special cases. The installation depth elsewhere follows general installation practices.
- The strength class of the plastic protective conduit used for cable underpasses must be A (SN16).

- At the same crossing point, a maximum of two plastic cable conduits may be installed by piercing.
- Three or more cable ducts must be passed under the railway within a concrete or steel protective conduit.

Installation where ducts are placed inside a conduit is quite challenging situation in terms of the cable's ampacity rating. Standards do not provide a calculation method for such installation, nor does it provide any form of guidance. Typically, contractors and cable manufacturers have their own self developed approach for such installations. The more simplified method utilizes formulations within IEC 60287. The 1 pu value for the cable ampacity is first calculated, where the cables are directly buried without any ducts or conduits. Afterwards the ampacity is calculated for the cable where each duct has one cable inside and then the ampacity is calculated where all the cables are inside a single conduit. Two different approaches can be taken. Either the calculated derating factors are multiplied with each other and multiplied with the 1 pu value, or the calculated external thermal resistances for each duct and conduit are summed together. Introduced method is quite straightforward and can be solved with basic numerical operations.

However, if more precise results are needed, then alternative Finite Element Method (FEM) approach should be taken. FEM is widely utilized in fields of heat transfer and electromagnetics, and therefore it is suitable method to study thermodynamics of high voltage cables and their surrounding mediums. In FEM analysis, the object under study is split into smaller and simpler elements for easier analysis. Essentially, FEM provides numerical results for partial differential equations. Suitable programmes to simulate thermodynamics and electromagnetics of high voltage cables are ANSYS and COMSOL. (Lyu, 2022)

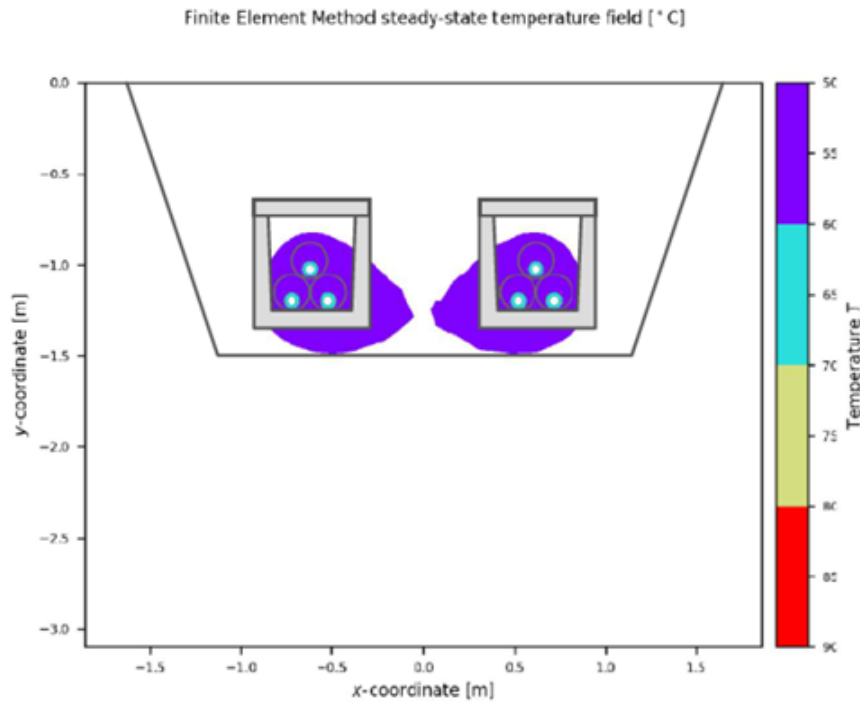


Figure 7.1. Temperature distribution within the surrounding medium of the parallel high voltage cable circuits (Helen Electricity Network Ltd, 2024).

FEM is especially utilized to model the temperature distribution within the surrounding medium of high voltage cables. The results derived from FEM can then be used to determine if drying of the surrounding medium occurs, which could cause significant derating of the cables ampacity ratings.

7.3 Crossings of Public District Heating and Improving the Soil Properties

High voltage cable circuits may cross many unfavorable thermal regions along its route. As explained before, these could be, e.g., district heating pipes, steam pipes, water supply pipes, and parallel cable circuits. The most common of these, which could have significant effect on the high voltage cable's ampacity rating are the district heating pipes. Calculation of the derating factor was introduced in the Chapter 6. District heating pipes are steel pipes with external insulation. Water flowing inside the district heating pipes could reach temperatures of up to 140 °C. Therefore, crossings of district heating pipes should be carefully studied.

However, it is appropriate to mention that the modern district heating pipes do not radiate as much heat as the older ones due to improved insulation properties.

Optimizing the crossing of district heating pipes is challenging. The crossing should be made at approximately a 90-degree angle because this minimizes the impact of heat flux from the district heating pipe. However, it is not always possible to achieve a perfect 90-degree crossing, so alternative methods may need to be considered. Increasing the depth of the crossing is one option. However, increasing the installation depth reduces the ampacity rating of the cable because the calculation of thermal resistance is based on a logarithmic function. Additionally, increasing the installation depth may result in excessive construction costs. Another option is to insulate the cable from the district heating pipe. Insulation is achieved using Finn Foam insulation slabs or other similar insulation materials. However, there is uncertainty about insulating the cable because insulating the cable from the surrounding soil may negatively affect the cable's heating, which can reduce the cable's load capacity.

Due to advanced high voltage cable technology, it is difficult to improve the internal heat conduction properties of today's cables. Therefore, improving the thermal conductivity properties of the surrounding soil is the most effective way to influence the load capacity of cables. The most common backfill materials used are sand, fine gravel, and concrete, as these materials are readily available and their thermal conductivity properties are well-known.

Generally, moist backfills favor the load capacity of cables because the moist soil surrounding the cable conducts heat more efficiently away from the cable. When assessing ampacity ratings according to hot spots, potential drying of the surrounding soil should be considered. If drying of the backfill soil occurs by moisture mitigation, the thermal conductivity of the soil may be reduced by factor of three or higher. The drying of the soil could occur at any point of the cable route, but studies show, that the most likely spot for drying of the soil occurs at the spot where the thermal resistivity is the highest. (Anders, 2005)

A widely utilized option for improving the thermal conductivity of backfill is the use of Weak-Mix. Weak-Mix is a concrete mixture composed of cement, sand, and water. By altering the proportions of these ingredients, it is possible to adjust the moisture content of the mixture according to the environmental conditions of the installation location. Typically,

thermal resistivity of Weak-Mix varies between 0,4 and 1,2 K·m/W. However, in most cases, the thermal resistivity remains below 1,0 K·m/W. (Millar, 2005)

7.4 Case Study

Case study serves the purpose of demonstrating the given equations and theories in practice. This case study is not a real implemented high voltage cable transmission line. However, characteristic environmental conditions of Finland and traditional cable types are being utilized.

The transmission line under study is a 3·2·1 HXCHBMMK-W copper cable with cross-sectional area of 2000 mm². The nominal voltage of the system is 110 kV, and it is a single circuit transmission line, which is buried in plastic ducts. The cable circuit does not have adjacent external heat sources. The bonding method of the metallic sheaths is single-point bonding. Cross-sectional area of the metallic sheath is 35 mm². Cables are installed in trefoil formation. Length of the transmission line is 1 000 meters. Maximum conductor temperature is limited to 65 °C. Laying depth of the cable group is 1 250 mm from the center of the installation formation. More detailed technical data of the cables, grid, and surrounding medium are given in Appendix 5.

By utilizing equations for calculation of thermal resistivity, following results were derived:

- Thermal resistance between one conductor and metallic sheath (T_1) = 0,242 K·m/W
- Thermal resistance between metallic sheath and armour (T_2) = 0,0 K·m/W
- Thermal resistance of the outer covering (serving) (T_3) = 0,046 K·m/W
- External thermal resistance of the duct or pipe (T_4''') = 1,213 K·m/W

In addition, loss factors were calculated for the cable circuit:

- Due to single-point bonding, circulating losses are not present and can be neglected from the calculation.
- Eddy current loss factor for three single-core cables in trefoil formation (λ_1'') = 0,1041

- Armour loss factor (λ_2'') = 0,0 (Layer not present)

Based on the calculated thermal resistivities and loss factors, the steady state ampacity of the power cables can be calculated by substituting the values into Equation 6.1.

Calculation method is simplified in a way that the equation does not consider individual laying depth for all three cables, but it considers laying depth from the center of the trefoil group. The calculated steady state ampacity rating for the cable circuit is 1 416 A, which translates to transmission capacity of 290 MVA at 118 kV operational voltage. For demonstration purposes, iterations with different thermal resistivity of the surrounding soil were carried out.

By reducing the thermal resistivity of surrounding medium, the ampacity rating can be increased significantly. Therefore, usage of Weak Mix is preferred in areas, where the thermal environmental conditions are unfavorable. Ampacity with thermal resistivity of 0,7 K·m/W for all three cables is 1 717 A, which translates to transmission capacity of 350 MVA. However, increase of thermal resistivity reduces the ampacity rating of the power cables. Ampacity rating with thermal resistivity of 1,2 K·m/W for all three cables is 1 285 A, which translates to transmission capacity of 263 MVA. Change of transmission capacity is significant when comparing thermal resistivity of 0,7 K·m/W and 1,2 K·m/W, nearly 90 MVA. Table 7.1 provides calculation example from the Excel sheet.

Table 7.1. Calculation results of the ampacity rating

Trefoil, Single-Point/Cross-Bonded, Buried, In Ducts		
$T_1 =$	0,242	K·m/W
$T_2 =$	0,000	K·m/W
$T_3 =$	0,046	K·m/W
$T_4 =$	1,213	K·m/W
$R_c =$	0,000014	Ω/m
$\lambda_1 =$	0,104101	-
$\lambda_2 =$	0,000000	-
$n =$	1	-
Results		
$I_{RST} =$	<u>1 416</u>	A
$W_c =$	27,8	W/m

If the solid bonding would have been chosen for the cable circuit, the loss factor of the metallic sheath would have been 0,425, which is over four times higher when compared to single-point bonding/cross-bonding. The increase in the loss factor is mainly due to the circulating losses of the metallic sheath. Ampacity rating of similar cable circuit with solid bonding would be approximately 1 000 A, with thermal resistivity of 1,00 of the surrounding medium. If flat, transposed cables, installation formation with solid bonding would have been chosen, the ampacity rating would be similar, but slightly higher if compared to trefoil formation. The case study proves that optimization of thermal resistivity and bonding method of the metallic sheath is crucial part of the design phase of the transmission circuit.

8 Conclusions

The purpose of the thesis was to familiarize the author with calculation methods for ampacity determination of high voltage power cables. Additionally, the goal was to produce a Microsoft Excel based calculation sheet for calculation of ampacity ratings according to IEC 60287 standard for different installation formations of the cables, installation conditions and special metallic sheath bonding methods. The thesis also introduced briefly structure of modern high voltage cables and introduction of sheath voltage limiters and their housing methods. Emphasis was put on the introduction of special sheath bonding methods, and calculation of steady state ratings, loss factors, thermal resistances, and induced sheath voltage gradients as they were key points of the thesis.

With relevant high-quality materials and standards, a comprehensive technical overview of cables and factors affecting the steady-state ampacity rating of high voltage power cables was formed. In addition, a calculation template was developed, which can conveniently calculate the ampacity rating of high voltage power cables in different installation conditions. Optimization of metallic sheath bonding method can also be achieved by comparing the calculated ampacity rating and, for example, the voltage gradients induced in the metallic sheath of the cable during normal operation and fault conditions.

During the thesis work, there were verbal discussions where the appropriate dimensioning method for the ampacity rating of high voltage power cables was considered. The load situations in the power grid are cyclical and change according to time of the day, the network switching conditions, and seasonal temperature of the environment. Based on this information, the sizing method according to IEC 60287 can be questioned since the standard assumes that the cables are at 100% steady-state load for an infinitely long time. In reality, such cable connections that are constantly close to the nominal load capacity are very rare. For this reason, conclusions can be drawn that the majority of 110 kV cables installed in Finland are over dimensioned.

One option is to size the cables according to emergency and cyclic load capacity, rather than according to the absolute instantaneous peak load. Methods for determining emergency and cyclic transmission capacity are guided by IEC 60853. For example, the instantaneous overload capacity for a period of two hours can be significant, up to twice as large as the

steady-state load capacity. Furthermore, the overload capacity for a period of 36 hours can be 30% greater than the steady-state load capacity. However, the emergency and cyclic loading capacity of the cables is dependent on the initial temperature of the core conductor.

By choosing a dimensioning principle based on the intended use, optimizing environmental conditions, and metallic sheath bonding, Transmission and distribution companies and private clients can achieve significant savings in high voltage power cable investments. In addition, contractors should pay attention to determination of ampacity rating, as the appropriate sizing can provide a competitive advantage in project tenders.

Possibility would be to utilize historical data on cyclic network loads according to the seasons to size the cables and to examine, for example, the load levels of existing cables. In addition, the network should be modeled for the future and various switching conditions, such as fault situations and interruptions during maintenance, should be considered, as they affect the loading of different parts of the network.

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Appendix 1. Thermal Resistivity of Different Materials (IEC 60287-2-1, 2023).

Material	Thermal Resistivity [ρ_T] K·m/W
<i>Insulating materials</i>	
Paper insulation in solid type cables	6.0
Paper insulation in oil-filled cables	5.0
Paper insulation in cables with external gas pressure	5.5
Paper insulation in cables with internal gas pressure:	
a) Pre-impregnated	5.5
b) Mass-impregnated	6.0
Polyethylene (PE)	3.5
Cross-linked polyethylene (XLPE)	3.5
Polypropylene laminate plastic (PPLP)	5.5
Polyvinyl chloride (PVC):	
up to and including 3 kV cables	5.0
greater than 3 kV cables	6.0
Ethylene propylene rubber (EPR):	
up to and including 3 kV cables	3.5
greater than 3 kV cables	5.0
Isobutylene isoprene rubber (IIR) "Butyl rubber"	5.0
Other rubbers	5.0
<i>Protective coverings</i>	
Compounded jute and fibrous materials	6.0
Rubber sandwich protection	6.0
Polychloroprene (CR)	5.5
Polyvinyl chloride (PVC):	
up to and including 35 kV cables	5.0
greater than 35 kV cables	6.0
PVC or bitumen on corrugated aluminium sheaths	6.0
Polyethylene (PE)	3.5
<i>Materials for duct installations</i>	
Concrete	1.0
Fibre	4.8
Asbestos	2.0
Earthenware	1.2
Polyvinyl chloride (PVC)	6.0
Polyethylene (PE)	3.5
<i>Other components</i>	
Semi-conducting XLPE and PE	2.5
Semi-conducting ethylene propylene rubber (EPR)	3.5

Appendix 2. Loss Factors and Relative permittivity of the Insulation at Power Frequency
(IEC 60287-1-1, 2023)

Type of Cable	ϵ	$\tan(\delta)$
Cables insulated with impregnated paper		
Solid type, fully impregnated, pre-impregnated or mass-impregnated non-draining	4,0	0,01
Oil-filled, self-contained		
Up to $U_0 = 36$ kV	3,6	0,0035
Up to $U_0 = 87$ kV	3,6	0,0033
Up to $U_0 = 160$ kV	3,5	0,0030
Up to $U_0 = 220$ kV	3,5	0,0028
Oil-pressure, pipe type	3,7	0,0045
External gas-pressure	3,6	0,0040
Internal gas-pressure	3,4	0,0045
PPL		
Equal to, or greater than 63/110 kV cables	2,8	0,0014
Cable with other kinds of insulation		
Butyl rubber	4,0	0,050
EPR		
Up to and including 18/30 (36) kV cables	3,0	0,020
Greater than 18/30 (36) kV cables	3,0	0,005
PVC	8,0	0,1
PE (HD and LD)	2,3	0,001
XLPE		
Up to and including 18/30 (36) kV cables (unfilled)	2,5	0,004
Greater than 18/30 (36) kV cables (unfilled)	2,5	0,001
Greater than 18/30 (36) kV cables (filled)	3,0	0,005

Appendix 3. Factors for argument of Bessel function (IEC 60287-1-1, 2023).

Type of Conductor	Conductor Insulation System	k_s	k_p
<i>Copper</i>			
Round, Solid	All	1	1
Round, Stranded	Fluid, Paper, or PPL	1	0,8
Round, Stranded	Extruded or Mineral	1	1
Round, Milliken	Fluid, Paper, or PPL	0,435	0,37
Round, Milliken, Insulated Wires	Extruded	0,35	0,2
Round, Milliken, Bare Uni-directional Wires	Extruded	0,62	0,37
Round, Milliken, Bare Bi-directional Wires	Extruded	0,8	0,37
Hollow, Helical Stranded	All	-	0,8
Sector-Shaped	Fluid, Paper, or PPL	1	0,8
Sector-Shaped	Extruded or Mineral	1	1
<i>Aluminium</i>			
Round, Solid	All	1	1
Round, Stranded	All	1	0,8
Round, Milliken	All	0,25	0,15
Hollow, Helical Stranded	All	-	0,8

Appendix 4. Data sheet of a HXCHBMMK-W 1x2000/35 mm², 64/110 (123) kV power cable (Prysmian Group Finland Oy, 2020).



Linking
the Future

Prysmian Group Finland Oy

SPECIFICATION
27.10.2020

S016602b
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Page 1(2)

Type designation: HXCHBMMK-W 1x2000/35 110kV

(Design code 71004211)

High voltage power cable

General

Rated voltage	64/110 (123) kV
Standard	Construction and tests i.a.w. SFS 5702 and IEC 60840 (where applicable)
Reference standards	IEC 60228
Temperature rating	Max. conductor operating temperature: 90°C Max. permissible conductor temperature at short-circuit for max. 5 s.: 250°C

Construction

Conductor	<i>Round, segmental stranded and compacted longitudinally watertight copper conductor. Watertightening by swellable material in the wire interstices.</i>		
	Nominal cross-sectional area	mm ²	2000
	Number of segments		5
	Approximate diameter	mm	55.2
	DC resistance at 20°C (max.)	ohm/km	0.0090
Conductor screen	<i>Semi-conducting copolymer compound</i>		
Insulation	<i>XLPE compound</i>		
	Nominal thickness	mm	15.0
	Minimum point thickness	mm	13.5
	Approximate diameter	mm	90
Insulation screen	<i>Semi-conducting copolymer compound</i>		
Extrusion process	<i>Triple-extrusion, completely dry curing and cooling process</i>		
Bedding	<i>Semi-conducting water-swellaable tape</i>		
Metallic screen	<i>A layer of copper wire helix and a copper contact tape counter helix</i>		
	Cross-sectional area (nom.)	mm ²	35
	DC resistance at 20°C (max.)	ohm/km	0.524
Separation tape	<i>Semi-conducting water-swellaable tape and semi-conducting binder tape</i>		
Metallic foil	<i>Longitudinal aluminium tape tightly bonded to sheath</i>		
	Nominal thickness	mm	0.2
Sheath #1	<i>Natural coloured UV-resistant HDPE compound</i>		
	Nominal thickness	mm	4.1
Sheath #2	<i>Black semi-conducting PE compound, bonded to the sheath # 1</i>		
	Approximate thickness	mm	0.5
Complete cable			
	Approximate diameter	mm	107
	Approximate weight	kg/km	24600

Type designation: HXCHBMMK-W 1x2000/35 110kV

(Design code 71004211)

High voltage power cable

Marking

Marks of origin Embossed on the outer sheath: manufacturer, year and week of manufacturing.
Printed on the outer sheath: manufacturer, type designation, year and week of manufacturing, length marking in metres.

Electrical data

Phase inductance in trefoil ¹ (appr.)	mH/km	0.32
Operating capacitance (appr.)	µF/km	0.34
Thermal short-circuit current (max.) for phase conductor for 1.0 s ²	kA	285
Thermal short-circuit current (max.) for metallic screen + foil for 1.0 s ³	kA	14.5
Max. electrical stress	kV/mm	5.1
Impulse voltage withstand level	kV	550

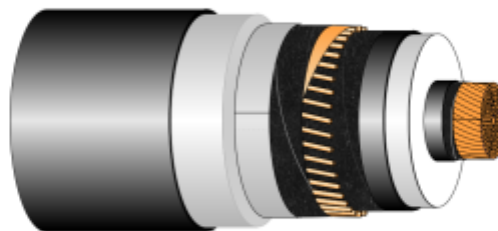
Mechanical data

Bending radius, during pulling (min.)	m	2.14
Bending radius, final position (min.)	m	1.50
Lowest recommended installation temperature	°C	-15
Pulling tension with pulling eye (max.)	kN	100

Type tests

Type tests shall be agreed separately.

Sketch



¹ Cables touching each other.

² Initial temperature of conductor before short-circuit 90°C, final temperature after short-circuit 250°C.

³ Initial temperature of metallic screen and foil before short-circuit 70°C, final temperature after short-circuit 250°C / 180°C.

Appendix 5. Initial calculation data of ampacity calculations.

Grid data:

Parameter	Value	Unit
Maximum 3-phase short-circuit current, I_{k3}''	35,0	kA
Maximum 2-phase short-circuit current, I_{k2}''	30,0	kA
Earth fault current, $3I_0$	4,0	kA
Operational voltage (1 pu), U	118	kV

High voltage cable data:

Parameter	Value	Unit
Electrical Data:		
DC resistance of the core at 20 °C, R_0	0,0090	Ω/km
AC resistance of the core at 65 °C, R_c	0,0138	Ω/km
Capacitance of the cable, C	0,34	$\mu\text{F}/\text{km}$
Loss factor of the insulation, $\tan\delta$	0,001	-
Dielectric losses of each phase, W_d	495,7	W/km
Inductance of the cable, L_c	0,32	mH/km
Resistance of the metallic sheath at 20 °C, R_{s0}	0,524	Ω/km
Resistance of the metallic sheath at 65 °C, R_s	0,619	Ω/km
Structural Data:		
Diameter of the conductor, d_c	55,2	mm
Mean diameter of the metallic sheath, d	92,5	mm
External diameter of the complete cable, D_s	107,0	mm
Nominal thickness of insulation, t_i	15,0	mm
Thickness of the metallic sheath, t_s	2,7	mm
Thickness of the serving, t_3	4,6	mm

Data of surrounding medium:

Parameter	Value	Unit
Temperature of the soil, T_s	15,0	°C
Thermal resistivity of the soil, ρ	1,00	K·m/W
Laying depth of the cables, L_Δ	1 300	mm
Outside diameter of the duct, D_o	200,0	mm
Inside diameter of the duct, D_i	180,0	mm
Thermal resistivity of the duct, ρ_d	3,50	K·m/W