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Thermal bottleneck determination in underground power cables methodology and tools to identify the weakest link

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Graduation report

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Summary

When a power cable transports power, heat is generated within the cable and the cable will heat up. The generated heat will flow through the cable to the far environment and will encounter several thermal resistances. The thermal resistance of the environment amounts to 40 – 70% of the total thermal resistance the heat will encounter. Therefore, the influence of the environment on the temperature of the cable is relatively large. Due to varying environmental influences and conditions, the temperature is not equally distributed over the length of a cable. Since the temperature of the cable is limited to a certain maximum, there will be “thermal bottlenecks” present, which limit the current carrying capacity, also known as the “ampacity”, of a cable connection. KEMA developed a new asset management tool, called “dynamic rating”, that uses physical models of these thermal bottlenecks to calculate the maximum temperature in a cable, and adapt the loading to the critical (most limiting) thermal bottleneck. Implementing a dynamic rating system on a cable connection will usually increase the ampacity of that connection and the cable connection can then be utilised toward its maximum loading capability. Therefore one can postpone or cancel investments in new connections and a great amount of money can be saved. In order to implement a dynamic rating system on a cable connection, the critical thermal bottleneck location and its thermal behaviour must be known.

Up till now, the determination of the critical thermal bottleneck location was based on experience of KEMA employees. The goal of this study therefore was: "To develop a methodology to systematically detect, rank and characterize thermal bottlenecks in an underground power cable and develop a ‘tool’ to make this knowledge accessible for KEMA."

For situations where glass fibre measurements are available to measure the temperature of the cable, an “indicator-tool” has been developed that uses three different types of indicators to detect a possible thermal bottleneck location. Relative values of the properties of the environment can be derived from the glass fibre measurements in order to characterize a thermal model of the critical bottleneck location. A database is created to store knowledge about possible bottleneck locations. The database can be extended with knowledge gathered in future research. Sixteen typical possible bottlenecks have been described and implemented in the database and assumptions are made on their property values. These bottlenecks are modelled with a “ranking-tool” using seven typical cable systems. A ranking of these bottlenecks is obtained, and it is shown that the cable system actually has little influence on the ranking of the bottlenecks. If glass fibre measurements are not available, knowledge from the database and ranking, in combination with a route survey, has to be used to detect possible bottleneck locations along the cable route. Finally, a methodology is proposed to identify, characterize and rank possible bottlenecks for cable systems with and without glass fibre measurements and recommendations are made to improve the methodology.
# Table of contents

1 **INTRODUCTION** ........................................................................................................ 1
   1.1 Background ........................................................................................................... 2
   1.2 Goal ..................................................................................................................... 3
   1.3 Narrowing down the scope of the thesis ............................................................... 4
   1.4 Structure of this report ........................................................................................ 4

2 **THEORY OF THERMAL BEHAVIOUR OF POWER CABLES** ......................... 7
   2.1 Cable components ............................................................................................... 8
   2.2 Heat sources ....................................................................................................... 9
      2.2.1 Conductor losses ......................................................................................... 9
      2.2.2 Dielectric losses ....................................................................................... 11
      2.2.3 Sheath losses ............................................................................................ 12
      2.2.4 Armour losses ........................................................................................... 13
   2.3 Installation methods ............................................................................................ 13
      2.3.1 Bonding arrangements .............................................................................. 14
      2.3.2 Circuit formation ....................................................................................... 15
      2.3.3 Depth of installation .................................................................................. 16

3 **IEC 60287 THERMAL MODEL** ......................................................................... 19
   3.1 Electrically equivalent thermal network .......................................................... 20
   3.2 General ampacity formula for continuous loading ............................................. 22
   3.3 Thermal resistances ............................................................................................ 23
      3.3.1 Thermal resistance between conductor and sheath (T₁) ......................... 23
      3.3.2 Thermal resistance between sheath and armour (T₂) ............................... 24
      3.3.3 Thermal resistance of outer cover (T₃) ....................................................... 25
      3.3.4 External thermal resistance (T₄) ............................................................... 25

4 **CRITICAL THERMAL BOTTLENECK DETERMINATION WITH GLASS FIBRE MEASUREMENTS** ........................................................................ 29
   4.1 Properties of a thermal bottleneck ................................................................. 30
   4.2 Difference between a hotspot and a thermal bottleneck ............................... 31
   4.3 Bottleneck indicators for glass fibre temperature measurements .................. 32
      4.3.1 Maximum temperature .............................................................................. 32
      4.3.2 Difference between minimum and maximum temperature .................... 33
      4.3.3 RMS value of the time derivative of the temperature ......................... 35
      4.3.4 Model of the temperature-influence on the cable-surrounding soil ....... 36
      4.3.5 Indicator tool ............................................................................................. 40
   4.4 Case study: Energinet ....................................................................................... 41
TABLE OF CONTENTS

5 CRITICAL THERMAL BOTTLENECK DETERMINATION WITH ROUTE SURVEY AND MODELLING ........................................ 43
5.1 Structure of the Maple program ........................................ 43
5.2 Cable types available in the Maple program ...................... 46
5.3 Bottleneck calculation ............................................. 46
5.3.1 ‘Reference’ situation ........................................... 47
5.3.2 Other surrounding substance .................................... 47
5.3.3 Drying out of the soil around the cable (2-layer model) ...... 48
5.3.4 Dry ground due to external influence ........................... 49
5.3.5 Dike crossings ................................................. 49
5.3.6 Horizontal drillings ............................................ 51
5.3.7 External heat sources ........................................... 53
5.3.8 Other conducting cables nearby ................................. 54
5.4 Results of modelling ................................................ 55

6 PROPOSED METHODOLOGY .............................................. 63

7 CONCLUSIONS AND RECOMMENDATIONS .......................... 67
7.1 Conclusions ....................................................... 67
7.2 Recommendations ................................................ 68

8 REFERENCES .............................................................. 71

APPENDIX A PROPERTIES OF MODELLED CABLE SYSTEMS ....... 73
APPENDIX B ZONE DEFINITION ROUTE GISTRUP-SKUDSHALE .... 85
APPENDIX C LIST OF PROPERTIES FOR A ROUTE SURVEY ....... 87
1 Introduction

Transport of electrical energy in transmission and distribution grids basically uses two types of connections: overhead lines and underground power cables. Overhead lines are well known to everyone since most are visually extremely present. Although underground power cables are more expensive, overhead lines are nowadays more and more replaced by underground power cables due to:

- Technical considerations (deep water crossings, maintenance requirements)
- Better reliability (lines are more susceptible to ice, storm, terrorism)
- Health considerations (magnetic fields, electric fields)
- Environmental considerations (visual impact, urban areas: not enough space for overhead lines)
- Land values and right of ways (the track-width of a cable connection is much less then of an overhead line connection)

This research covers the subject of underground power cables.

When a power cable transports power, dissipation causes the cable to heat up. The higher the temperature, the faster the cable insulation materials degrade. With an increasing degradation, the chances on spontaneous breakdown increase. In order to comply with the design lifetime of 30 years, the temperature of the cable is therefore limited to a certain maximum. This maximum temperature limits the transport capacity of a power cable connection. Since power cables always operate at a previously defined voltage, the current carrying capacity of the connection is limited. The current carrying capacity of a power cable connection is also known as the "ampacity" of a connection.
INTRODUCTION

1.1 Background

In order to increase the ampacity and reliability of underground power cables, a new asset management tool is developed. This cable asset management tool, called ‘dynamic rating’, is based on controlling the thermal and mechanical behaviour of the energy cable system.

As already mentioned, a cable with a certain load generates heat. This heat will flow radially through the cable to the far environment, away from the heat source. The heat will encounter a number of thermal resistances through which the heat flows. These will be explained in chapter 3. Therefore, there will be a temperature difference over each of the thermal resistances similar to the electric equivalent Ohm’s law. As will be shown in chapter 5, the most important thermal resistance is the one corresponding with the cable environment. This gives 40-70% of the total temperature difference between cable conductor temperature and ambient temperature. Thus, the temperature of a cable section is not only depending on its load, but is also influenced by the environment.

Due to varying environmental influences and conditions, the temperature is not equally distributed over the length of a cable. Therefore some parts of the cable are significantly hotter than other parts. These hotter parts are usually called ‘hotspots’ (this name can cause confusion; in section 4.1 this will be explained). The parts that limit the ampacity of the cable connection are called ‘thermal bottlenecks’. Dynamic rating systems use physical models of these thermal bottlenecks to calculate the maximum temperature in a cable, and adapt the loading to the critical (most limiting) thermal bottleneck, which is “the weakest link in the chain”

The ampacity of existing cable connections is usually determined in their original engineering phase. This can, due to the long lifespan of cables, be tens of years ago. At that time the available knowledge regarding ampacity was not as developed as nowadays. Grid owners who use the cable connection operate the system with a large safety margin since they often know little about the possibly changed conditions in the cable condition and environment. Implementing a dynamic rating system on such a cable connection will usually increase the ampacity of that connection and the cable connection can then be utilised toward its maximum loading capability. Therefore one can postpone or cancel investments in new connections and a great amount of money can be saved

Some examples of possible thermal bottlenecks are given below with a schematic picture (Figure 1-2)

1. Soil with deviating properties
2. Crossing through the top of dike
3. Crossing through the bottom of dike
4. Crossing with water, e.g. by a directional drilling
5. Cables in air, e.g. under a bridge
6. Other cables in parallel
1.2 Goal

In order to implement a dynamic rating system, the critical thermal bottleneck of the connection and its properties should be known. With the measured temperature profile (the measured temperature in time at a certain position) of the critical thermal bottleneck, properties of this bottleneck can be derived and the dynamic rating system can be developed. To determine the critical bottleneck location, two methods are available:

- Glass fibre measurements
- Cable route survey with thermocouple measurements

Glass fibre measurements
Newer cables often have glass fibre installed within the cable. Also a glass fibre cable may be laid adjacent to a cable of the circuit, preferably adjacent to the hottest cable. When glass fibre is available, distributed temperature measurements can be performed with a very high resolution. Analysis of these glass fibre measurements will yield the critical thermal bottleneck (more about this in section 4.3).

Cable route survey with thermocouple measurements
If a glass fibre is not available, the cable temperature can be measured with thermocouples. Since it is too elaborate to place a thermocouple on every 2 metres of the connection, it is important to know in advance where it is most likely to find the critical thermal bottleneck. A cable route survey can be used to determine possible bottleneck locations and their properties. If a cable route survey results in a number of possible thermal bottleneck locations, or does not provide enough knowledge of the properties of the bottleneck locations to implement a dynamic rating system, thermocouples can be used to measure at the interesting positions. The measured temperature profiles can then be compared to determine which position has the worst thermal properties. This is the critical thermal bottleneck.
INTRODUCTION

Underground power cables have a very long life span (usually over 30 years). Many existing connections are installed years ago and therefore not equipped with glass fibre, but are nevertheless interesting for dynamic rating systems in order to upgrade their ampacity and postpone or even cancel investments. To save time and money, it is important to know where possible bottlenecks are present and if necessary, where to measure (where to place the thermocouples). Over the years, KEMA employees have developed a lot of experience on this field, but there is no systematic approach yet. To develop this systematic approach is the purpose of this graduation project.

The assignment for this graduation project is:
To develop a methodology to systematically detect, rank and characterize thermal bottlenecks in an underground power cable and develop a ‘tool’ to make this knowledge accessible for KEMA.

1.3 Narrowing down the scope of the thesis

Ampacity calculations are a broad subject. To narrow down the scope of the thesis only a number of possible situations are covered in the study:

- Only a steady state analysis is performed according to IEC 60287. Dynamic calculations according to IEC 60853 are not covered.
- Only 7 typical types of cable systems are considered.
- Out of the three heat transportation mechanisms (conduction, convection and radiation), only conduction is covered. Assumptions are made when convection or radiation starts to play a significant role.
- Not all possible bottlenecks are covered in this study, but a number of typical ones are selected. For each covered bottleneck, assumptions on physical values are made.

1.4 Structure of this report

This report is organized as follows:

Chapter 1: Introduction
The first chapter introduces the reader to the world of electrical energy transmission and distribution. It is explained why it is important to know the thermal bottleneck of a cable connection and the assessment goal is defined.

Chapter 2: Theory of thermal behaviour of power cables
Power cables generate heat when they are in use. The heat sources present in a cable are explained in this chapter. The installation method of a cable circuit can also influence the heat production or transport; this chapter also covers this.
Chapter 3: IEC 60287 thermal model
The international standard IEC 60287 describes how stationary ampacity calculations are carried out. Although the standard is quite comprehensive and detailed, a short introduction is presented. Since this research is based on IEC 60287, an understanding of the basic principles of the standard is necessary.

Chapter 4: Critical thermal bottleneck determination with glass fibre measurements
If glass fibres are available, distributed temperature measurements can be performed to determine the temperature profile in time every couple of metres along the length of the cable connection. These glass fibre measurements have to be analysed to select the possible bottleneck locations and the critical thermal bottleneck. Indicators are developed for this purpose and they will be explained in this chapter. A case study in which these indicators are used is presented.
Previous research uses the definitions "hotspot" and "thermal bottleneck" interchangeably, which might be confusing. This is explained in this chapter.

Chapter 5: Critical thermal bottleneck determination with route survey and modelling
If glass fibre measurements are not available, a route survey can be used to find the critical thermal bottleneck in a cable connection. With a route survey potentially dangerous areas along the cable route are marked as potential bottlenecks. There are numerous possible bottleneck locations. A selection of common ones are introduced and explained in this chapter. In order to perform calculations on these bottlenecks, they should be made specific by choosing well substantiated assumptions on numerical values for the relevant parameters.
To compare the influence of thermal bottlenecks on the ampacity of a cable, a tool is written in Maple 10. The structure of this tool is presented in this chapter. The selected possible bottleneck locations are modelled on various cable systems with the Maple program and the result of this are presented.

Chapter 6: Proposed methodology
In this chapter the procedure that has to be followed to determine and measure the thermal critical bottleneck in an underground power cable connection is described. Glass fibre measurements can also be used to learn new knowledge that can be used with the route survey. This is also explained in this chapter.

Chapter 7: Conclusions and recommendations
In this chapter conclusions are drawn and some recommendations are given.
2 Theory of thermal behaviour of power cables

Power cables are available in various types, e.g. single core cables, multicore cables, paper insulated lead covered (PILC) cables, crosslinked polyethylene (XLPE) cables, self contained fluid filled (SCFF) cables, high pressure fluid filled (HPFF) cables etc. A few examples are presented in Table 2-1. The cable systems can also be installed in various ways. This chapter will not give a detailed description of every possible cable type and installation, but a global introduction in the theory of power cables is presented. Power transport through the cables, by means of a current at a certain voltage, causes the cable temperature to rise. The heat sources present in a cable are also explained in this chapter.

<table>
<thead>
<tr>
<th>Paper insulated lead covered (PILC) cable</th>
<th><img src="image1.png" alt="Image" /></th>
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<tbody>
<tr>
<td>3 cores, for MV</td>
<td>(source: TKF)</td>
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<th>Paper insulated lead covered (PILC) cable</th>
<th><img src="image2.png" alt="Image" /></th>
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<tbody>
<tr>
<td>3 cores, for MV</td>
<td>(source: <a href="http://www.sinafar.com">www.sinafar.com</a>)</td>
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<tr>
<th>Crosslinked polyethylene (XLPE) cable</th>
<th><img src="image3.png" alt="Image" /></th>
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<tbody>
<tr>
<td>1 core, for MV</td>
<td>(source: <a href="http://www.tkf.nl">www.tkf.nl</a>)</td>
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<tr>
<th>Crosslinked polyethylene (XLPE) cable</th>
<th><img src="image4.png" alt="Image" /></th>
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<tbody>
<tr>
<td>3 cores, for MV</td>
<td>(source: <a href="http://www.tkf.nl">www.tkf.nl</a>)</td>
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<tr>
<th>Crosslinked polyethylene (XLPE) cable</th>
<th><img src="image5.png" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td>1 core, for HV</td>
<td>(source: <a href="http://www.borealisgroup.com">www.borealisgroup.com</a>)</td>
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<tr>
<th>Self contained fluid filled (SCFF) cable</th>
<th><img src="image6.png" alt="Image" /></th>
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<tbody>
<tr>
<td>1 core, for HV</td>
<td>(source: <a href="http://www.coppercanada.ca">www.coppercanada.ca</a>)</td>
</tr>
</tbody>
</table>

Table 2-1: Several cable types and their appearance
2.1 Cable components

In order to transport power, power cables have to conduct current and have to withstand a certain voltage. For this reason a cable is at least composed of two components: an electrical conductor and the insulation. In the majority of the power cables, additional concentric layers over the insulation protect the primary electrical insulation against mechanical, electromechanical and chemical damage. With an example of an XLPE cable, this section introduces the most common cable components and their functions.

1. Conductor (aluminium or copper)
2. Conductor shield (semi-conductive)
3. XLPE insulation
4. Insulation shield (semi-conductive)
5. Bedding or swelling tapes (semi-conductive)
6. Layer of aluminium or copper wires (optional) for high short circuit currents
7. Optical fibre (optional)
8. Bedding or swelling tapes (semi-conductive)
9. Metallic shield (e.g. lead)
10. PVC or PE outer sheath

Figure 2-1: Typical XLPE cable layout (source: www.sileccable.com)

Figure 2-1 presents a schematic overview of an XLPE cable. The conductor (1) is usually made of copper or aluminium and can be constructed in various ways, for instance to reduce the skin effect (this will be explained in section 2.2.1). A few examples of conductor constructions are presented in Figure 2-2.

Figure 2-2: Conductor construction methods: a) concentric stranded conductor, b) compacted stranded conductor, c) segmental (Milliken) conductor, d) segmental hollow conductor

The insulation (3) provides the electrical insulation to withstand a certain voltage.
Between conductive (metallic) layers (1, 6 and 9) and insulating layers (3, 10), semi-conductive layers (2, 4, 5 and 8) are used to provide a smooth surface of the insulation. This is needed to straighten out the curvature of for instance a stranded conductor, and for instance small burrs on the conductor will not be harmful because the conductor shield shields them. A smooth surface of the insulation is needed in order to get a good behaviour of the generated electric field. The beddings (5, 8) are needed for the extrusion of the cable. The earthing screen (9) is applied to conduct the capacitive and fault currents, and to provide electrical shielding. It is separated from an optional layer of wires by a semi-conductive layer. These wires can be added to allow higher short circuit currents. Finally, the outer sheath (10) offers mechanical protection.

2.2 Heat sources

Within a power cable, heat is produced by losses. These losses, together with the external heat sources that will be discussed in chapter 4, cause the cable to heat up.

There are four possible heat sources within a power cable:
1. conductor losses
2. dielectric losses
3. sheath losses
4. armour losses

These losses are discussed in the following sections.

2.2.1 Conductor losses

Current flowing trough the conductor causes losses as a result of the electrical resistance of the conductor. These losses can be expressed as:

\[ W_c = I^2 R_{ac,\theta_c} \]

*Equation 2-1*

Where:

- \( W_c \) = conductor losses [W]
- \( I \) = current [A]
- \( R_{ac,\theta_c} \) = AC resistance of the conductor at a certain conductor temperature [Ω]

If the cable is transporting alternating current, there are three effects significant for the electrical resistance of the conductor:
- temperature effects
- skin effect
- proximity effect
These effects are taken into account if the AC resistance of the conductor is calculated with:

\[ R_{\text{ac},T_c} = R_{\text{dc},20} \left[ 1 + \alpha_{\text{20}} (T_c - 20) \right] \left[ 1 + \gamma_s + \gamma_p \right] \]

*Equation 2-2*

Where:

- \( R_{\text{dc},20} \) = DC resistance of the conductor at 20°C [Ω]
- \( \alpha_{\text{20}} \) = temperature coefficient per K at 20°C
- \( T_c \) = conductor temperature [°C]
- \( \gamma_s \) = skin effect factor
- \( \gamma_p \) = proximity effect factor

The factor \( R_{\text{dc},20} \left[ 1 + \alpha_{\text{20}} (T_c - 20) \right] \) actually represents the DC resistance at a certain temperature (\( R_{\text{dc},T} \)).

Values \( R_{\text{dc},20} \) and \( \alpha_{\text{20}} \) are usually provided by the manufacturer of the cable. If \( R_{\text{dc},20} \) is not known, it can be calculated using the diameter of the conductor using:

\[ R_{\text{dc},20} = \frac{\rho \cdot \ell}{A} \]

*Equation 2-3*

Where:

- \( \rho \) = the specific electrical resistance of the conductor material [Ωm]
- \( \ell \) = length of the conductor. Ampacity calculations are always carried out per unit of length: here 1 meter will be used [m]
- \( A \) = cross-section of the conductor [m²]

The factors \( \gamma_s \) and \( \gamma_p \) are necessary to take the skin and proximity effects into account. These factors will be calculated with (empirically derived) equations provided by the IEC 60287 standard. This standard is introduced in chapter 3.

With an alternating current, there are alternating magnetic fields in and around the conductor due to the current flowing in that conductor. As a result, the current density will not be uniform. The current will be "pushed" to the outside of the conductor as a result of its own magnetic field (skin effect). Magnetic fields of cables in the neighbourhood can cause the current to slightly shift to one side of the conductor. This is called the proximity effect. With various conductor-constructions (as shown in Figure 2-2) these effects can be suppressed. The effects are visualized in Figure 2-3.
2.2.2 Dielectric losses

The dielectric losses are the losses in the insulation material. The cable insulation, together with the conductor and the earthing sheath, forms a cylindrical capacitor. This cylindrical capacitor is not ideal, but some "resistive" current (current in phase with voltage) is flowing through the cable insulation from the conductor to the earthing sheath. This can be represented by an RC parallel circuit as shown in Figure 2-4.

The insulation resistance $R$ in Figure 2-4 represents various types of losses in the cable insulation. The most common losses (conductive losses, dipole losses, losses due to partial discharges) will be introduced briefly.

Conductive losses
Since the resistance is not infinite, a small current will flow, due to the voltage across the insulation material, through this material. This current causes conductive losses.
Dipole losses
Between the conductor and the earthing sheath an alternating electrical field exists. The dipoles in the insulation material try to follow the changing electric field (they turn), but due to inertia and friction a part of their kinetic energy is lost. These losses are called dipole losses.

Partial discharge losses
A partial discharge is a very small breakdown that can occur in cavities in the insulation material due to diminished withstand voltage of the cavity-material (air). If this happens, charge moves towards the earthing sheath and therefore energy is lost.

The dielectric losses, represented by \( W_d \), can be calculated with the current flowing through resistor \( R \). Usually, the capacitance \( C \) and the power factor \( \tan \delta \) of a power cable can be determined. The dielectric losses can then be calculated with:

\[
W_d = UI_R = UI = U^2 \omega C \tan \delta \quad \text{Equation 2-4}
\]

2.2.3 Sheath losses

As already mentioned in sections 2.3.2 and 2.3.1, generated magnetic fields induce a current flow in the earthing sheath. There are two possible current flow types:

- Circulating currents
- Eddy currents

Circulating currents
Through magnetic induction an AC current flowing through a metal 'loop' will induce a voltage in a parallel metal 'loop'. Therefore, an AC current flowing through the conductor of a power cable will induce a voltage in the earthing sheath of the cable. Likewise, parallel cables will influence each other on all available metal 'loops'. Dependent of the bonding type (section 2.3.1) of the cable circuit, this induced voltage in a certain 'loop' can cause a current to flow it that 'loop', and this induced current can again influence all other metal 'loops' in the neighbourhood. If the induced voltage in a certain 'loop' causes a current to flow, that current will cause losses due to the resistance of the metal.
**Eddy currents**

The Eddy losses occur, in contrast to circulating current, in all types of bonding arrangements. Analogous to the skin effect and the proximity effect (section 2.2.1), alternating magnetic fields due to alternating currents in the conductors cause Eddy currents in the earthing sheath. These Eddy currents cause a relatively small loss.

The calculation of circulating currents and Eddy currents is relatively complex, and not within the scope of this project. Therefore, the sheath losses are expressed with a loss-factor. This loss-factor is the ratio of the heat production in the earthing sheath to the heat production in the conductor:

$$\lambda_{\text{sheath}} = \frac{W_{\text{earthing sheath}}}{W_{\text{conductor}}} \quad \text{Equation 2-5}$$

The value for this loss factor will be calculated with equations provided by the IEC 60287 standard which will be introduced in chapter 3.

**2.2.4 Armour losses**

Similar to the earthing sheath, circulating currents and Eddy currents can occur in the armour of power cables.

One difference between an earthing sheath and armour is that the armour may be made of magnetic materials. In these magnetic materials, an additional form of heat production occurs: hysteresis. This loss is not discussed here.

The armour losses are also expressed with a loss factor:

$$\lambda_{\text{armour}} = \frac{W_{\text{armour}}}{W_{\text{conductor}}} \quad \text{Equation 2-6}$$

This loss factor will also be calculated with equations provided by the IEC 60287 standard. More information about this standard will be given in chapter 3.

**2.3 Installation methods**

Power cables can be installed in many different ways and the installation method influences the ampacity of the cable system. Since it is most common to lay cables directly in the soil at a certain depth, only directly buried cables are covered in this chapter. Cables installed in air are not part of this study, whereas cables installed in pipes, or other environments differing from directly buried, will be treated as possible bottlenecks and will be discussed in section 5.3.
2.3.1 Bonding arrangements

There are various ways to connect a circuit to earth. The manner in which a circuit is earthed is an important parameter when it comes to determining the ampacity. Induced currents in the earthing sheath can generate additional heat. This heat generation is treated in section 2.2.

Three-phase cables usually have a common earthing sheath that is bonded at both ends. All three phases induce voltages in the common earthing sheath and these induced voltages cancel each other out. The influence of the bonding arrangement in three phase cables has therefore no influence on the ampacity.

When working with single core cables, a choice can be made between three bonding types, shown in Figure 2-5:

a) single end bonding
b) both ends bonding
c) crossbonding

![Diagram of bonding arrangements](image)

Figure 2-5: Various bonding arrangements:
a) single end bonding, b) both ends bonding, c) crossbonding
In case of single end bonding, there are only eddy current losses and no circulating currents. Therefore the ampacity is hardly reduced. With this type of bonding there will be an induced voltage at the not earthed end of the sheaths. This induced voltage is normally limited by safety standards.

With both ends bonding there will be no induced voltage at the cable ends, but instead there will be circulating currents. These circulating currents generate additional heat, which reduces the ampacity of the cable circuit. Eddy currents will still be present in this bonding arrangement.

The circulating currents in the earthing sheaths can be significantly reduced with another bonding technique: crossbonding. In this case the circuit is bonded at both ends, but the earthing sheaths are connected in a crosswise fashion. This way the induced currents cancel almost out if the circuit is divided in a multiple of 3 equal lengths. If the lengths are not equal to each other, remaining sheath losses will be larger because the currents are not cancelling out as much as they would do with a multiple of 3 equal lengths. This situation is referred to as unbalanced crossbonding.

2.3.2 Circuit formation

Directly buried cables are usually installed in flat formation or in trefoil formation. These typical installation configurations are depicted in Figure 2-6.

![Typical installation configurations of directly buried cables](image)

Figure 2-6: Typical installation configurations of directly buried cables

Figure 2-6a) and b) show three cables in flat formation, where a difference is made between touching cables and not touching. Figure 2-6 shows a trefoil configuration. Trefoil configurations are usually touching.

The circuit formation influences the circuit ampacity in three ways:
- Induced voltages in earthing sheaths (single end bonding) or sheath currents (both ends bonding)
- Thermal resistance of the environment
- Relative ambient temperature.

The isotherms around a single cable are shown in Figure 2-7. If cables are close to each other, the other cables will also generate heat that has to be transported to the far environment. Therefore the heat will have less possible routes to follow and the smaller the spacing between cables, the higher the relative thermal resistance of the ground will be. The generated heat of the other cables will also cause an increase in the relative ambient temperature. The closer cables are to each other, the more negative the influence on the ampacity of a single cable will be.
Every cable will generate magnetic fields, which will induce voltages in the earthing sheath or sheath currents. This magnetic induction will be larger when cables in a flat formation are closer to each other. In trefoil formation, the influence of magnetic fields is minimized because the generated magnetic fields of the three cables together will partly cancel each other out, which will have a positive influence on the ampacity. The positioning of the cables in a trefoil formation (very close together) will however negatively influence the ampacity.

The choice for a certain circuit formation is not only based on the best circuit ampacity, but also on demands of the customer. The induced voltage and magnetic field at ground level can be subject to safety standards, or for instance the circuit width is limited.

### 2.3.3 Depth of installation

The depth at which a circuit is installed influences the ampacity in two ways. First, the ambient temperature will change. The sun will have less influence on the ambient temperature when a cable is installed at greater depths. Figure 2-8 shows the ambient temperature at a certain depth in the Netherlands as a function of time. For ampacity calculations, the highest temperature at a certain depth is used (worst case scenario).
Up to a depth of 5m, the (worst case) ambient temperature can be assumed to have a linear coupling with the installation depth. At greater depths the ambient temperature will become constant.

The second effect involves the thermal resistance of the cable environment. This thermal resistance increases as the amount of soil surrounding the cable increases, which happens if a cable is installed at greater depths.

Both effects work in opposite directions regarding the cable ampacity, but usually the effect on the thermal resistance of the environment is dominant and the cable ampacity will decrease if a cable is installed at larger depths.
3 IEC 60287 thermal model

The International Electrotechnical Commission (IEC) prepares and publishes international standards for electrical, electronic and related technologies. The IEC 60287 standard describes a method to determine the ampacity of a cable circuit. However, with this standard it is only possible to calculate the “steady state” ampacity. The term “steady state” is intended to meet a continuous constant current (100% load factor) just sufficient to asymptotically produce the maximum allowable conductor temperature, the surrounding ambient conditions being assumed constant. In other words: The maximum steady state load is that load that, given sufficient time, leads to the maximum allowable temperature.

For dynamic load calculations, the IEC 60853 is available. The IEC 60853 introduces the step response of the cable temperature to a step in the load, taking into account the time constants, and provides calculation methods for cyclic rating and the emergency current. This research investigation however is limited to the IEC 60287 calculations.

The formulas in IEC 60287 depend to a great extent on the cable design and the circuit configuration. Since the formulas have often been empirically determined, it is not useful to explain every single formula and its underlying physical factors, which are important for correctly applying the standard. As a result, the standard can sometimes be unclear. The IEC 60287 is also subject to various limitations. Not all situations and cable types are described. To determine the ampacity in those situations assumptions should be made. The formulas used for the cables covered in this research investigation are presented and explained in Appendix A.

IEC 60287 is divided in 3 parts:
- Part 1: Formulas for ratings and power losses
- Part 2: Formulas for thermal resistance
- Part 3: Sections on operating conditions

These parts are again divided into sections. This research investigation basically uses the first section of parts 1 and 2:

IEC 60287-1-1: Electric cables - Calculation of the current rating
  Part 1: Current rating equations (100 % load factor) and calculation of losses
  Section 1: General

IEC 60287-2-1: Electric cables - Calculation of the current rating
  Part 2: Thermal resistance
  Section 1: Calculation of thermal resistance
3.1 Electrically equivalent thermal network

As already mentioned in section 2.2, heat is generated in a power cable when a load is applied to it. This heat can be transferred through the cable to its surroundings in three different ways:

- conduction
- convection
- radiation

For buried cables, conduction is the most important process. Convection and radiation can occur when a cable is installed otherwise, e.g. in pipes (filled with air or water) or in free air. Since this research investigation covers buried cables, only conduction is treated here. In case convection or radiation may play a role, assumptions will be made.

Heat conduction can be described in a way analogous to electrical conduction. Ohm's law can be applied in both situations.

\[ V_1 - V_2 = IR \]

Where:

- \( V_1 - V_2 \) = Voltage difference across electrical resistance [V]
- \( I \) = Electrical current flow through electrical resistance [A]
- \( R \) = Electrical resistance of material through which the current flows [Ω]

The thermal equivalent of Ohm's law, shown in Figure 3-1b, is:

\[ \theta_1 - \theta_2 = WT \]

Where:

- \( \theta_1 - \theta_2 \) = Temperature difference across thermal resistance [°C or °K]
- \( W \) = Heat flow through thermal resistance per unit cable length [W/m]
- \( T \) = Thermal resistance of material through which the current flows per unit cable length [Km/W]

Figure 3-1 shows this analogy. Ohm's law is Figure 3-1a can be applied and this yields:

\[ V_1 - V_2 = IR \]

Equation 3-1

\[ \theta_1 - \theta_2 = WT \]

Equation 3-2
The heat flow is expressed per metre, as ampacity calculations are always given per metre of cable.

In section 2.2 the heat sources (analogous to voltage sources) are already introduced. Assuming the thermal resistance of metals is negligible (compared to the other materials in a cable), the electrically equivalent thermal parameters of the cable components can be formulated mentioned in Table 3-1.

If the longitudinal heatflow in and around a cable is negligible (which is the case if the properties of the cable and surroundings are constant along a long enough cable length), this 1 dimensional model is valid. Otherwise, the longitudinal heatflow must be taken into account.

<table>
<thead>
<tr>
<th>cable part</th>
<th>heat source</th>
<th>thermal resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>conductor</td>
<td>( W_c )</td>
<td>-</td>
</tr>
<tr>
<td>insulation</td>
<td>( W_d )</td>
<td>( T_1 )</td>
</tr>
<tr>
<td>earthing sheath</td>
<td>( W_s )</td>
<td>-</td>
</tr>
<tr>
<td>armour bedding</td>
<td>-</td>
<td>( T_2 )</td>
</tr>
<tr>
<td>armour</td>
<td>( W_a )</td>
<td>-</td>
</tr>
<tr>
<td>outer sheath</td>
<td>-</td>
<td>( T_3 )</td>
</tr>
<tr>
<td>cable surroundings</td>
<td>-</td>
<td>( T_4 )</td>
</tr>
</tbody>
</table>

Table 3-1: Cable components and their representation in the electrically equivalent thermal network

The electrically equivalent thermal network is shown in Figure 3-2.
The dielectric losses \((W_d)\) are positioned halfway the insulation layer, i.e. halfway the dielectric losses. The mentioned temperatures are:

- \(\theta_e\) = ambient ground temperature (ground temperature if the cable wouldn’t be there) [°C]
- \(\theta_j\) = temperature of the outer sheath of the cable [°C]
- \(\theta_a\) = temperature of the cable armour [°C]
- \(\theta_s\) = temperature of the earthing sheath of the cable [°C]
- \(\theta_c\) = temperature of the cable conductor [°C]

### 3.2 General ampacity formula for continuous loading

With the electrically equivalent thermal network for an underground power cable, the following set of equations can be derived:

\[
(W_c + W_d + W_s + W_a)T_4 = \theta_j - \theta_e
\]

\[
(W_c + W_d + W_s)T_3 = \theta_a - \theta_j
\]

\[
(W_c + W_d)T_2 = \theta_s - \theta_a
\]

\[
\left(\frac{W_c + W_d}{2}\right)T_1 = \theta_c - \theta_s
\]

The earthing sheath losses \((W_s)\) and armour losses \((W_a)\) can be expressed in terms of the conductor losses \((W_c)\), see sections 2.2.3 and 2.2.4, where \(\lambda_1\) represents the loss factor for the sheath losses and \(\lambda_2\) represents the loss factor for the armour losses.

With \(W_s = \lambda_1W_c\) and \(W_a = \lambda_2W_c\) Equation 3-3 can be rewritten as:

\[
((1 + \lambda_1 + \lambda_2)W_c + W_d)T_4 = \theta_j - \theta_e
\]

\[
((1 + \lambda_1 + \lambda_2)W_c + W_d)T_3 = \theta_a - \theta_j
\]

\[
((1 + \lambda_1)W_c + W_d)T_2 = \theta_s - \theta_a
\]

\[
\left(\frac{W_c + W_d}{2}\right)T_1 = \theta_c - \theta_s
\]

Adding up the four equations of Equation 3-4 will yield the temperature increase of the conductor compared to the surrounding:

\[
T_1 + (1 + \lambda_1)T_2 + (1 + \lambda_1 + \lambda_2)(T_3 + T_4)W_c + \left[\frac{T_1}{2} + T_2 + T_3 + T_4\right]W_d = \theta_c - \theta_e
\]

Equation 3-5
By filling in $W_c = I^2 R_{ac}$ (Equation 2-1) this yields the central formula of IEC 60287:

$$I = \sqrt{\frac{(\theta_c - \theta_s) - W_d (T_2 + T_3 + T_4)}{R_{ac} (T_1 + (1 + \lambda_1) T_2 + (1 + \lambda_1 + \lambda_2) (T_3 + T_4))}}$$  \hspace{1cm} \text{Equation 3-6}

With $\theta_c$ set on the maximum allowable conductor temperature, the ampacity of a cable circuit can be calculated with this formula.

Calculation of the losses ($W_c$ and $W_d$), alternating current resistance ($R_{ac}$) and loss-ratios ($\lambda_1$ and $\lambda_2$) is covered by IEC 60287-1-1.

The calculation of the thermal resistances ($T_1$, $T_2$, $T_3$ and $T_4$) is covered by IEC 60287-2-1 and explained in the next section.

### 3.3 Thermal resistances

Thermal resistances are very important in ampacity calculations. IEC 60287-2-1 gives equations to calculate these thermal resistances in various situations. Each thermal resistance is dependent of a number of variables. A brief introduction is given in this section.

#### 3.3.1 Thermal resistance between conductor and sheath ($T_1$)

A single core underground power cable consists of several concentric cylindrical layers. The thermal resistance of each layer is derived e.g. by Anders in [4]. Figure 3-3 shows the cylindrical layers of a cable.

![Figure 3-3: Heat conduction in a cylindrically symmetrical construction](image)
The thermal resistance of a layer, for instance the light blue layer, can be expressed as:

$$T_{cs} = \frac{\Delta \theta}{W_{cs}} = \frac{\rho_{cs}}{2\pi} \ln \left( \frac{r_c}{r_s} \right)$$ \hspace{1cm} \textit{Equation 3-7}

With this basic equation the basic formulas for $T_1$, $T_2$ and $T_3$ can be derived.

Every underground power cable has an insulation layer, and the thermal resistance of this layer is represented by $T_1$. It is influenced by:

- thermal resistivity of the insulation material ($\rho_T$)
- thickness of insulation ($t_1$)
- conductor diameter ($d_c$)
- conductor shape (circular, oval, sector-shaped)
- cable layout (single core, belted or oil pressure cable)

If the conductor shape and the cable layout differ from the circular, single core situation, Equation 3-8 will not hold since it is based on circular concentric layers. In those cases IEC 60287 provides other formulas.

For a single core cable with a cylindrical conductor, the thermal resistance $T_1$ is calculated with:

$$T_1 = \frac{\rho_T}{2\pi} \ln \left( 1 + \frac{2t_1}{d_c} \right)$$ \hspace{1cm} \textit{Equation 3-8}

### 3.3.2 Thermal resistance between sheath and armour ($T_2$)

In the previous section the basic equation for the thermal resistance of a cylindrical layer is presented (Equation 3-7). This equation is also used for most of the calculations for $T_2$.

The thermal resistance between sheath and armour is influenced by:

- thermal resistivity of the bedding material ($\rho_T$)
- thickness of bedding ($t_2$)
- sheath diameter ($d_s$)

If a cable does not have a separate armour, there is no bedding and the value for $T_2$ is equal to zero (and the value for $T_1$ as well).

For most cable types $T_2$ is calculated with:

$$T_2 = \frac{\rho_T}{2\pi} \ln \left( 1 + \frac{2t_2}{d_s} \right)$$ \hspace{1cm} \textit{Equation 3-9}
3.3.3 Thermal resistance of outer cover \((T_3)\)

The outer cover of a cable is again a concentric cylindrical layer. Equation 3-7 will be used again. The thermal resistance of the outer covering is influenced by:

- thermal resistivity of outer covering material \((\rho_T)\)
- thickness of the outer covering \((t_3)\)
- External diameter of the layer directly under the outer covering, e.g. the armour \((D_a)\)

This yields the general equation for \(T_3\):

\[
T_3 = \frac{\rho_T}{2\pi \ln \left(1 + \frac{2t_3}{D_a}\right)}
\]

**Equation 3-10**

3.3.4 External thermal resistance \((T_4)\)

The surroundings of the cable are of great importance for the ampacity of a cable. The thermal resistance of the environment \((T_4)\) is usually significantly larger compared to the thermal resistances of the cable itself \((T_1, T_2\) and \(T_3)). Therefore the cable temperature is influenced mainly by the cable’s surroundings.

If the ground surface is treated as an isotherm, the temperature rise \(\Delta \theta_p\) above the ambient temperature at a certain position \(P\) in the (uniform) neighbourhood of the cable can be calculated with:

\[
\Delta \theta_p = \frac{\rho_T}{2\pi} W \ln \left(\frac{d'}{d}\right)
\]

**Equation 3-11**

With (these parameters are also visualized in Figure 3-4):

- \(\rho_T\) = thermal resistivity of the cable surrounding substance [Km/W]
- \(W\) = total amount of heat generated in the cable per unit of length [W/m]
- \(d\) = distance between point \(P\) and the centre of the cable [m]
- \(d'\) = distance between point \(P\) and the centre of the reflection of the cable in the ground surface. [m]

As can be seen in Figure 3-4, the parameters \(d\) and \(d'\) are dependent of the laying depth of the cable \(L\) [m].

For multiple cables, superposition can be used to determine the temperature at a certain point in the neighbourhood of the cables.
Figure 3-4: Determination of temperature rise above the ambient temperature for a cable generating an amount of heat (W) at depth L

The thermal resistance of a single cable in directly buried in uniform soil can be calculated with:

\[ T_4 = \frac{\rho_T}{2\pi} \ln \left( \frac{2L}{D} + \sqrt{\left(\frac{2L}{D}\right)^2 - 1} \right) \]

Equation 3-12

With:
- \( \rho_T \) = thermal resistivity of the cable surrounding substance [Km/W]
- D = External diameter of the cable [m]
- L = Laying depth of the cable [m]

Equation 3-12 is derived from Equation 3-11 by calculating \( \rho \) and \( \rho' \) with the external diameter and the laying depth of the cable.

The temperature in the neighbourhood of the cable depends on the generated heat in the cable, the thermal resistivity of the cable’s surrounding and the laying depth of the cable. If the environment of the cable is not uniform, different values for \( \rho_T \) are present and the previous mentioned calculations become relatively complex. For many situations, IEC 60287 gives a calculation method. However, not all possible situations are described. For example, not all conductor types are described, and various matters are still “under consideration”. If the ampacity of a cable circuit has to be determined in such situations, assumptions have to be made.

This research investigation is restricted to a number of possible cable environments. Calculation methods for these environments, including the assumptions made, are discussed in section 5.3.
In section 5.4 it will be shown that the thermal resistance of the ground \( (T_4) \) is responsible for 40 – 70% of the total thermal resistance the heat will encounter on its route to the far environment. Therefore \( T_4 \) will have a big influence on the cable’s ampacity. For an XLPE 150kV crossbonded system in flat formation, the influence of parameters influencing \( T_4 \) on the ampacity of the system is shown. Figure 3-5 shows the relationship between thermal resistivity and ampacity for 2 possible cable environments, and Figure 3-6 shows the relationship between laying depth and ampacity in a uniform environment. The calculation methods for these figures are given in chapter 5.

![Figure 3-5: The relationship between ampacity and thermal resistivity of the soil for an XLPE 150kV crossbonded system in flat formation](image)

![Figure 3-6: The relationship between ampacity and laying depth for an XLPE 150kV crossbonded system in flat formation](image)
4 Critical thermal bottleneck determination with glass fibre measurements

An underground power cable connection has a maximum ampacity that can be determined, as explained in the previous chapter, with IEC 60287. The cable will cross various surroundings along the route. It can for instance cross a region with varying soil properties or it can cross man-made artefacts as e.g. heat pipes, other cables or dykes. If these areas limit the ampacity of the cable they are thermal bottlenecks. The maximum ampacity of a cable connection is, just like a chain being as strong as its weakest link, determined by its critical thermal bottleneck. When using a static approach (as is IEC 60287) this critical thermal bottleneck is always a single situation along the route.

In order to implement a dynamic rating system on underground power cables, beforehand one should know the thermal bottlenecks that are present along the cable route and determine the critical thermal bottleneck that will limit the ampacity of the total system. Finding this critical thermal bottleneck is of great importance if one wants to correctly model a cable connection, since the model of the total system will be based on the behaviour of the critical thermal bottleneck.

![Figure 4-1: Distributed temperature measurements on the cable route Gistrup – Skudshale (Energinet, Denmark)](image)

When optical fibres are installed within or close to the cable, distributed temperature measurements are possible with a combination of Raman scattering and optical time domain reflectometry (OTDR). Figure 4-1 shows an example of a typical temperature measurement of an underground power cable (more information about this measurement is available in Appendix B). These measurements are taken with a
spatial resolution of 2 metres, an accuracy of 1°C and an interval of 1 hour. To reduce
the possible influence of measuring inaccuracies and noise, the raw data is filtered.
Figures presented in this chapter are filtered with a moving average in time.

A tool is developed to determine the possible bottleneck locations along the measured
cable section. This tool uses ‘indicators’ that are ‘high’ if a position along the cable
route might be a possible bottleneck location. The more indicators are ‘high’ at a
certain position, the more likely the presence of a thermal bottleneck will be at that
position. This tool, which uses ‘indicators’, is introduced in section 4.3.

4.1 Properties of a thermal bottleneck

With Equation 3-5, the influence of the environment on the cable temperature can be
explained. Equation 3-5 can be rewritten to:

\[ \theta_c = \left( 0.5 T_1 + T_2 + T_3 \right) W_d + \left[ T_1 + (1 + \lambda_1) T_2 + (1 + \lambda_1 + \lambda_2) T_3 \right] W_c \]

Equation 4-1

The first part in Equation 4-1 \( (0.5 T_1 + T_2 + T_3) W_d \) depends on the properties of the
cable system (cable properties, laying configuration, operating voltage, etc.) and is
constant along the length of the cable.
The second part \( (T_1 + (1 + \lambda_1) T_2 + (1 + \lambda_1 + \lambda_2) T_3) W_c \) depends on properties of the
cable system (assume constant), and on the heat generated in the conductor \( (W_c) \). This
heat generation depends on the load of the cable. If the load is assumed constant, this
part is constant, too.
The third part \( ((1 + \lambda_1 + \lambda_2) W_c + W_d) T_4 \) depends on the properties of the cable system
(assume constant again), the cable load and the thermal resistance of the environment.
The last part (\( \theta_e \)) is the ambient ground temperature.

Therefore, with a constant load, Equation 4-1 can be reduced to:

\[ \theta_c = a + b T_4 + \theta_e \]

Equation 4-2

With \( a \) and \( b \) positive constants.
From Equation 4-2 it can concluded that, at a constant load, a higher thermal
resistance of the environment \( (T_4) \) or a higher ambient temperature \( (\theta_e) \) at a certain
position along the cable route, will cause a rise in the conductor temperature at that
position.
Sections along the cable route with a high thermal resistance of the ground or a high ambient temperature are therefore possible bottleneck locations. Some examples are:

- High $T_d$:
  - Other surrounding substance with a high thermal resistivity (e.g. clay or peat)
  - Very dry soil
  - Cables in pipes
  - Directional drillings
- High $\theta_c$:
  - Heat sources nearby (e.g. pipes for city heating, oil pipes)
- Other calculation method for the cable temperature (Equation 4-1 will not hold):
  - Parallel cables
  - Cables in air

With distributed temperature measurements along the cable length, possible bottleneck locations can be found. One should however realize that the cable load is not constant during a glass fibre measurement. The slow response of a cable on load changes should be taken into account. The tool, described section 4.3, will have ‘indicators’ to take this dynamic behaviour of the cable into account.

### 4.2 Difference between a hotspot and a thermal bottleneck

The temperature is usually measured over a limited period of time. This means the ‘hot spots’ are only valid during the specified period. Different cable loads at other times (assuming the properties of the environment are constant) might cause different behaviour of the cable temperature and might induce other ‘hot spots’. If for instance the cable load is low during a measured period (average cable temperature is low, e.g. 20°C), and the cable crosses a heat source (e.g. pipes for district heating at 30°C) with very good thermal ground properties, the heat source crossing might be marked as a ‘hot spot’. When the cable load at another time is high (average cable temperature is high, e.g. 40°C) and another measurement is performed the heat source crossing will (due to the very good thermal ground properties) still be close to 30°C and the heat source crossing is a ‘cold spot’. The cable’s ampacity is not limited by the heat source crossing, but there will be another position in the cable section that is the critical thermal bottleneck. As a result of low loads the determination of the thermal bottleneck with the ‘maximum temperature’ used as an indicator (this indicator is explained in the next section) will fail in this situation. This is shown in Figure 4-2, the thermal bottleneck will be in the ‘dry ground’ area. Similar problems may occur when a ‘hot spot’ location is determined with a time average of the measured temperature.
4.3 Bottleneck indicators for glass fibre temperature measurements

In order to determine the possible thermal bottlenecks with a distributed temperature measurement, a tool with various indicators can be developed. This tool will be referred to as the "indicator-tool".

A good indicator should:
- Properly indicate possible thermal bottleneck locations
- Not be influenced by measuring inaccuracies
- Be reproducible

A few indicators are introduced and discussed in the next sections.

4.3.1 Maximum temperature

The most obvious indicator for a possible thermal bottleneck is the maximum temperature. The positions in the cable route where the cable reaches the highest temperatures are 'hot spots' and these might limit the cable's ampacity. In literature this method is most common, see for instance articles [3], [7], [8], [11] and [12].

Figure 4-3 shows the maximum, minimum and average temperatures for a measurement in Denmark (the same measurements as used for the 3D-plot in figure 1), and the indicators for the maximum temperature. The indicator for the maximum temperature is 'high' at most positions in zone 24. The small variations between temperatures at positions close to each other are not necessarily noise, but can be caused by environmental influences.
As already mentioned in section 4.2, this ‘hot spot’ method, or maximum (average) temperature, is a good method, but results should be handled with care (especially when there are ‘low loads’ or changing environmental conditions). The “hot spot” will not always be on the same position as the critical thermal bottleneck.

4.3.2 Difference between minimum and maximum temperature

Another method to find the thermal bottlenecks is to observe the difference between the lowest and the highest value of the temperature ($\Delta T$) within the measured time. At thermal bottleneck locations, the temperature will vary fast. The bigger the difference, the more the cable temperature is influenced by the changes in the load of the cable. This can be explained similar to the derivation of Equation 4-2, but now without the assumption of a constant load. The equation will then be:

$$\theta_c = a + bl^2 + (c + el^2)T_\text{avg} + \theta_e$$  \hspace{1cm} \text{Equation 4-3}

With $a$, $b$, $c$ and $e$ positive constants derived from the properties of the cable system.

If $T_\text{avg}$ and $\theta_c$ are assumed to be independent of time, the time derivative of this equation will be:

$$\frac{d\theta_c}{dt} = 2b\frac{dl}{dt} + 2e\frac{dl}{dt}T_\text{avg}$$  \hspace{1cm} \text{Equation 4-4}

Constants $b$ and $e$, as well as the derivative of the square of the load, will have the same value along the cable length. A high value for the derivative of the cable...
CRITICAL THERMAL BOTTLENECK DETERMINATION WITH GLASS FIBRE MEASUREMENTS

temperature will therefore imply a high value for $T_4$, and a high value for $T_4$ reduces the ampacity of the cable at that position.

Measuring the difference between the lowest temperature reached, and the highest temperature reached during a certain length of time gives a good indication of the variations in cable temperature. Locations with a high value for $\Delta T$ are potentially dangerous because a high load for only a short duration can cause the temperature at these spots to rise to high values or even reach the critical temperature.

Figure 4-4 shows the maximum, minimum, average and Delta temperatures for a measurement in Denmark (the same measurements as used for the 3D-plot in figure 1). The green curve is the $\Delta T$ (Delta temperature).

In 'zone 29' a relatively high outside cable temperature is measured, but the $\Delta T$ is relatively low in that zone. Therefore zone 29 will (according to this measurement) not be marked as a potential bottleneck. Since 'zone 24' has a high maximum temperature and a high $\Delta T$, this location will be the critical thermal bottleneck.

The measured data used for Figure 4-4 has a temperature accuracy of 1°C. To reduce the influence of measuring inaccuracies and noise, it might be wise to take the average of the highest 10 (or another integer) points to determine the maximum temperature reached, and likewise for the minimum temperature reached. One can also choose to filter the measured data with for example a moving average in position. The data used for Figure 4-4 is filtered with a moving average in time.
4.3.3 RMS value of the time derivative of the temperature

A more sophisticated version of the $\Delta T$-indicator mentioned in the previous section is to actually derive the time derivative of the temperature. The basic idea is similar: observe how fast the cable temperature changes in time.

Figure 4-5a shows the current during a measurement period (same measurements as figures Figure 4-1 and Figure 4-4). A typical time-temperature plot on a certain position (in this plot glass fibre position 6193m) is shown in Figure 4-5b. The measured current values are filtered with a moving average in time. The time derivative, and its root mean square (RMS) value (a fixed value for the measured period), are shown in Figure 4-5c.

The RMS value of the time derivative of the temperature ($[dT/dt]_{\text{RMS}}$) has a different value for different positions. When all these values are calculated and plotted against the position it results a plot shown in Figure 4-6 (a position-$[dT/dt]_{\text{RMS}}$ plot). A filtering (like e.g. a moving average) can be useful to make a better visualization of the results possible.

If the $[dT/dt]_{\text{RMS}}$ has a high value at a certain position, the temperature at that position changes fast in time; therefore, this might be a thermal bottleneck.
4.3.4 Model of the temperature-influence on the cable-surrounding soil

This study focuses on the static rating of underground power cables according to the IEC 60287. The indicator in this section is an exception, since it uses a response to a step function described in the IEC 60853. The IEC 60853 treats "calculation of the cyclic and emergency current rating of cables". The calculations carried out in IEC 60853 can be divided into three groups. In the first the response of the conductor temperature is calculated. Next, the response of the cable temperature to the environment is calculated, and finally the emergency and cyclic ratings are calculated.

Figure 3-2 in chapter 3 shows an electrically equivalent thermal network for the generation and transport of heat in a cable that is used in the IEC 60287. A similar electrically equivalent thermal network, shown in Figure 4-7, is used in the IEC 60853, but thermal capacities are taken into account. The thermal capacitance of materials ensures that heat can be stored in a volume of material. As a result, the temperature will slowly increase, as it is being heated up from inside.

Again, heat is generated in the conductor \( W_c \), the dielectric \( W_d \) and the sheath \( W_s \) (and if the cable has armour, a heat source \( W_a \) can be added in a similar way).

Thermal resistances and thermal capacities of the materials involved are represented as resistors \( R_i \) and capacitors \( Q_i \). As stated before, the most important part is the response from the cable jacket temperature to the earth temperature \( \theta_i \) to \( \theta_e \).

IEC 60853 gives a function for the response to a step function for the cable jacket temperature to the earth temperature. If the step response in known, a full dynamic model for the cable jacket temperature to the earth temperature can be derived. For a single cable directly buried in uniform ground the response to a step function is:
\[
\Delta \theta(t) = \frac{\rho W_T}{4\pi} \left[ -Ei\left(\frac{-D_{\text{cable}}^2}{16t \delta}\right) + Ei\left(\frac{-L^2}{t \delta}\right) \right]
\]

Equation 4.5

With \( \delta = \frac{1}{\rho c} \) = the diffusivity of the soil \([\text{m}^2/\text{s}]\)

\( \rho = \) the thermal resistivity of the soil \([\text{Km/W}]\)

\( c = \) the thermal capacity of the soil \([\text{J/Km}]\)

\( L = \) the installation depth of the cable \([\text{m}]\)

\( D_{\text{cable}} = \) the diameter of the cable \([\text{m}]\)

\( Ei(x) = \) the exponential integral

The thermal diffusivity is a kind of time constant for the soil, and is present in the equation in order to take into account the thermal capacitance of the soil.

The total losses in the cable are:

\[
W_T = W_e + W_d + W_r + W_a = W_d + (1 + \lambda_1 + \lambda_2)W_e = W_d + (1 + \lambda_1 + \lambda_2)l^2 R_{AC}
\]

Assuming the majority of the heat is generated in the conductor \((W_d\) is negligible, which is usually true), we obtain:

\[
W_T \approx aW_c = a l^2 R_{AC}
\]

With \( R_{AC} \) = the AC resistance of the conductor

\( l \) = the current through the conductor

\( a \) = a constant

\( R_{AC} \) changes with the conductor temperature, but for this indicator these changes can be neglected and the \( R_{AC} \) at e.g. 50°C can be used.

---

**Figure 4-7:** Electrically equivalent network for the generation and dissipation of heat in a cable.
(source: KEMA course 'power cable ampacity' (2006) by Frank de Wild)
Since measurements are discrete, the difference in the current $I$ between measurement $n$ and measurement $n+1$ can be seen as a step function with a certain negative of positive amplitude. The response of the environment can then be seen as a series of positive and negative step function-responses as given by the IEC60853. This is shown in Figure 4-8.

$D_{\text{cable}}, R_{\text{AC}}, L$ and $I$ are usually known. The only unknown parameters left are then the soil properties $\rho$ and $c$, and the ambient temperature ($\theta_e$) on which the temperature rise will be added. Since $\rho$ and $c$ will vary within a limited range (e.g. $1 \cdot 10^6 \leq c \leq 5 \cdot 10^6$ and $0.5 \leq \rho \leq 5$) one can model the temperature rise with a cable response for various values of $\rho$ and $c$, add this to the ambient temperature, and compare the measured data at a certain position with the modelled data. An example, where the ambient temperature is assumed to be constant along the length of the cable, is given in Figure 4-9.

$\theta(t)$

$\theta(t)$

$\theta(t)$

$\theta(t)$

Figure 4-9: Resulting cable temperature is a summation of step responses

$D_{\text{cable}}, R_{\text{AC}}, L$ and $I$ are usually known. The only unknown parameters left are then the soil properties $\rho$ and $c$, and the ambient temperature ($\theta_e$) on which the temperature rise will be added. Since $\rho$ and $c$ will vary within a limited range (e.g. $1 \cdot 10^6 \leq c \leq 5 \cdot 10^6$ and $0.5 \leq \rho \leq 5$) one can model the temperature rise with a cable response for various values of $\rho$ and $c$, add this to the ambient temperature, and compare the measured data at a certain position with the modelled data. An example, where the ambient temperature is assumed to be constant along the length of the cable, is given in Figure 4-9.

Figure 4-9: Modelled temperatures and measured temperature. Compare the measured data with the modelled data (curve fitting).
There are various ways to compare the measured and modelled data and to find the best match. Various methods were tried, and the following method provided good results:

Calculate (at a single position) for all modelled temperatures:

\[
\text{Matchtester} = \left[ 1 - \frac{1}{\text{Average}(T_{\text{measured}}) - \text{Average}(T_{\text{modelled}})} \right] \cdot \left[ 2 - \frac{\text{Correlation}(T_{\text{measured}}, T_{\text{modelled}})}{} \right] \cdot \left[ 1 - \frac{1}{\text{StandardDeviation}(T_{\text{measured}}) - \text{StandardDeviation}(T_{\text{modelled}})} \right]
\]

The better a modelled series matches the measured one on a specified position, the closer the value of 'Matchtester' will get to the value 1 (typically be best match at a certain position had a value between 0.9 and 1). The \( p \), \( c \) and \( \theta_e \) of the modelled series can be seen as a relative \( p \), \( c \) and \( \theta_e \) of the cable surrounding at that position. It is a 'relative' value, because officially the values of \( p \), \( c \) and \( \theta_e \) apply only to the soil. The relative \( p \), \( c \) and \( \theta_e \) values that are generated with this indicator also take crossings, drillings, external heat sources etc into account.

When this modelling is done for all positions, and a filter is applied to the results (e.g. a moving average) the surroundings of the cable on different positions can be compared to each other. This is shown in Figure 4-10, where again the ambient temperature along the length of the cable is assumed to have a constant value. Figure 4-11 shows the relative diffusivity \( \delta \) that can be calculated with the relative \( p \) and \( c \) shown in Figure 4-10.

![Figure 4-10: Modelled relative \( p \) (thermal resistivity) and \( c \) (thermal capacity) plot (moving average over position of 20 points (40m), measurements: 19th October 2006 – 14th November 2006, Route Gistrup – Skudshale, Energinet Denmark), assuming a constant ambient temperature.](attachment:Figure4-10.png)
With the final plots it is possible to identify possible thermal bottleneck locations. A high $\rho$ implies a high average temperature on that position. A low thermal capacitance $c$ causes larger fluctuations (high $d\theta/dt$), since the thermal capacitance is measure for the capability of a material to store heat. Positions with a high value for the relative thermal resistivity and a low value for the relative thermal conductivity are potentially dangerous and might be thermal bottlenecks.

Figure 4-10 and Figure 4-11 are generated assuming a constant ambient temperature along the cable route. If changes in the ambient temperature are taken into account in the modelled temperature data, this can also be matched with the curve-fitting tool. An extra figure for the modelled ambient temperature will then be generated. One should compare the three graphs (modelled $\rho$, modelled $c$ and modelled $\theta_e$) to find the possible bottleneck locations.

### 4.3.5 Indicator tool

With the indicators ‘Maximum temperature’, ‘Difference between minimum and maximum temperature’ and ‘RMS value of the time derivative of the temperature’, introduced in sections 4.3.1, 4.3.2 and 4.3.3, respectively, a tool is written to determine the critical thermal bottleneck for cable circuit where glass fibre measurements are available. Calculations on measurement data are performed with programs written in Maple 10 and the final output figures are generated with Excel.

The indicator ‘Model of the temperature-influence on the cable-surrounding soil’, introduced in the previous section, is not included in the tool since adjustments have to be made to include the influence of variations in the ambient temperature.
4.4 Case study: Energinet

For this study glass fibre measurement of a cable route in Denmark (between Gistrup and Skudshale, owned by Energinet) were available. Previously presented figures with glass fibre measurement data (Figure 4-1, Figure 4-3, Figure 4-4, Figure 4-6, Figure 4-9, Figure 4-10 and Figure 4-11) were generated with this data.

In Figure 4-3, Figure 4-4 and Figure 4-6 indicators are shown for ‘Maximum temperature’, ‘Difference between minimum and maximum temperature’ and ‘RMS value of the time derivative of the temperature’, respectively. Comparing those 3 indicators one can conclude they are all ‘high’ at many positions between glass fibre-positions 6100 and 6600. This is (see Appendix B) a part of a chalk hill.

The results of the indicator ‘Model of the temperature-influence on the cable-surrounding soil’, presented in Figure 4-10 and Figure 4-11, are not used to determinate the bottleneck. This is because only temperatures were modelled for variations in $\rho$ and $c$. Variations in the ambient temperature were not included. To use this indicator, they should be implemented.

Within this measurement also a nice example of the difference between a ‘hot spot’ and a thermal bottleneck is found. This is shown in Figure 4-12. The ‘hot spot at low load’ is at glass fibre-position 7200, which represents a crossing with an undefined pipe. This pipe probably acts as a heat source.

![Figure 4-12: Hotspot vs. critical thermal bottleneck - proven with measurements (Energinet DK)](image)
5 Critical thermal bottleneck determination with route survey and modelling

If an underground cable connection is not equipped with glass fibres, another method has to be used to determine the critical thermal bottleneck. With knowledge of the thermal behaviour of a cable in various surroundings, possible bottleneck locations along the cable route can be selected. Instead of measuring the temperature at all these locations with a thermocouple, the possible bottleneck locations are modelled and a ranking is obtained. With this ranking the critical thermal bottleneck is selected. If a ranking results in multiple critical bottleneck locations, thermocouple measurements at only those locations can be used to determine which one limits the ampacity of the system. This method minimizes the number of thermocouple measurements needed and since these measurements are expensive (due to practical difficulties) it will reduce the cost to find the critical thermal bottleneck. To model and rank these potential thermal bottlenecks, the “ranking-tool” is developed which will be introduced in this chapter. A route survey is necessary to determine which possible bottlenecks are present along the cable route, and they can be ranked with a Maple program that has been written for this purpose.

Calculation of the ampacity of an underground cable connection with IEC 60287 is complicated. Different cable properties and cable surroundings call for different equations. Calculation by hand is difficult, and the help of a computer program is needed. For a research under commission of the Dutch Ministry of Economic Affairs, Prego 22 [9], a program was written to determine the ampacity of an underground cable connection in a few possible environments. This program, written in Maple, is extended to make thermal bottleneck calculations possible.

The structure of the program is explained in section 5.1. Since calculations vary with cable type and cable surrounding, the possibilities of this new program are limited to a number of typical cable systems (these will be introduced in section 5.2) and bottleneck types. For these typical bottleneck types, calculation methods and assumptions on property values are introduced in section 5.3. Results of the program for the typical cable types and bottleneck types are presented and discussed in section 5.4.

5.1 Structure of the Maple program

The starting point of the program is the ampacity calculation for a single position in a cable connection. Constants, cable properties and ground properties of that position are loaded in the active memory. The procedure “Inominaal” uses separate procedures for “T1”, “T2”, “T3”, “T4”, “Rac”, “Wd”, “lambda1” and “lambda2” to calculate the variables needed for the central formula of IEC 60287 (Equation 3-6) and finally calculates the ampacity of the cable at that specific position with the data present in the active memory at that time.
Since the environment of a cable will change over a cable route, several possible thermal bottlenecks are present. With a study of the available information about the environments along the cable route, studying for instance the available maps, performing a site survey and knowledge of the thermal behaviour of the cable in those environments, possible bottleneck locations are selected. Available data about these possible bottleneck locations is used to determine the parameter values necessary to model the bottlenecks. If not enough data is available, assumptions will be made.

The Maple program uses a reference situation. It can be chosen randomly, but it is wise to select a situation that is very common along the cable route. Only the parameter values deviating from the reference situation are necessary to define a bottleneck. A deviating parameter can also have multiple possible values; in that case a parameter range can be defined. The program subsequently changes the values in the active memory to calculate the minimum and maximum possible ampacity for each bottleneck and calculates an ampacity-range for each bottleneck. In this way a derating range for each possible bottleneck is calculated, and this is used to rank the possible bottleneck locations in order to select the most critical thermal bottleneck. A typical output-plot of the program is shown in Figure 5-1. The properties of the reference situation, the bottlenecks and the cable system in Figure 5-1 will be introduced in sections 5.2 and 5.3. In Figure 5-1 it can easily be seen that there is a single situation in which the ampacity is most limited (dry peat). This is the critical thermal bottleneck in the cable circuit. When there are a number of situations present with more or less the same limited ampacity, a thermocouple measurement is recommended on those situations to determine the most critical thermal bottleneck amongst the found number of situations, if at all needed.

Figure 5-1: Typical result of bottleneck calculation with the Maple program

Figure 5-2 shows a flowchart of the Maple program developed. The blue lines represent predefined variables. Red lines show what procedure 'calls' another procedure for sub-calculations. The green lines are the outputs (values) of procedures.
CRITICAL THERMAL BOTTLENECK DETERMINATION WITH ROUTE SURVEY AND MODELLING

Figure 5-2: Flowchart of the Maple program
5.2 Cable types available in the Maple program

As already mentioned before, cable types and installation methods influence the IEC 60287 calculation methods. In the Maple program a number of typical cable systems are pre-programmed. These cable systems represent more than 75% of the cable systems present in the Netherlands.

The following cable systems are introduced:
- 3-core paper insulated lead covered cable (PILC), 10kV, single end or both ends bonded
- 3-core crosslinked polyethylene cable (KUDIKA), 10kV, both ends bonded
- Single core crosslinked polyethylene cable (XLPE), 20kV, in trefoil, both ends bonded
- Single core crosslinked polyethylene cable (XLPE), 150kV, in flat plane, crossbonded
- Single core crosslinked polyethylene cable (XLPE), 380kV, in flat plane, crossbonded
- Pressurized oil cable (SCFF), 150kV, in flat plane, single end bonded
- Pressurized oil cable (SCFF), 150kV, in flat plane, both ends bonded

The equations that are used for these cable systems in the IEC 60287 are provided in Appendix A.

5.3 Bottleneck calculation

With a route survey (field study of the cable route, research on available maps, etc.) possible thermal bottlenecks can be identified for a certain underground cable connection. This will be further explained in chapter 6. In order to determine the critical thermal bottleneck, the possible thermal bottlenecks should be ranked. Since the properties of the cable surroundings are rarely known on beforehand, assumptions are made to model the influence of possible bottleneck locations on the ampacity of an underground cable connection.

Sometimes it is relatively straightforward to use the IEC 60287, as described in chapter 3, to calculate the ampacity in a possible bottleneck situation. If the geometry of the cable surroundings does not change compared to the reference situation, the same equations can be used and only some parameter values change. If however the geometry of the surroundings varies along the cable, different IEC 60287 equations are needed. Assumptions should be made if there are no applicable equations and sometimes to simplify the calculations.

For every new possible bottleneck one should first define the calculation method to determine the parameter values needed to model this possible bottleneck. A number of typical possible bottleneck locations are predefined in a database and implemented in the Maple program. These bottlenecks cover most of the possible bottleneck locations present in the Netherlands and their calculation methods are introduced in this section.
To define deviations as a percentage, a reference situation (100% situation) is proposed in section 5.3.1. The deviations of properties of the selected possible bottlenecks on the ‘reference’ situation are defined in sections 5.3.2 to 5.3.8. Combinations of bottlenecks, e.g. multiple parallel cable circuits installed in directional drillings, cannot be calculated with the proposed Maple program.

### 5.3.1 ‘Reference’ situation

A cable system directly buried in uniform ground is defined as reference situation. Apart from the cable system properties defined in Appendix A the reference properties are defined as:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>symbol</th>
<th>value</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying depth</td>
<td>L</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>Ambient ground temperature</td>
<td>(T_a)</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>1</td>
<td>Km/W</td>
</tr>
</tbody>
</table>

### 5.3.2 Other surrounding substance

A cable system is often installed in various types of soil. The thermal parameters of these types of soil will vary and cause different ampacity values at different positions. To show the influence of the surrounding substance on the ampacity of a cable, four frequently present types of soil in the Netherlands have been selected.

As shown in Figure 5-3 types of soil commonly encountered are: sand (‘zand’), clay (‘klei’), weak ground (‘slappe grond’) and peat (‘hoogveen/laagveen’). Pure soil is a mixture of solid materials, water and air. All these materials have an important effect on the resulting thermal resistance. For instance: A sandy soil can have a value for the

![Figure 5-3: Thermal resistivities of the ground in the Netherlands](image)
thermal resistivity of 0.3 Km/W in a very wet environment whereas the value for the thermal resistivity can reach values up to 5.0 Km/W in an extremely dry environment. Typical ranges of the thermal resistivity of the soil are defined for four possible bottleneck locations that are common in the Netherlands. These bottleneck locations and their property values are:

<table>
<thead>
<tr>
<th>Sand</th>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>0.6 - 1.0</td>
<td>K (\text{m/W})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Clay</th>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>0.8 - 1.2</td>
<td>K (\text{m/W})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weak ground</th>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>1.4 - 2.0</td>
<td>K (\text{m/W})</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Peat</th>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>2.0 - 5.0</td>
<td>K (\text{m/W})</td>
</tr>
</tbody>
</table>

A higher value for the thermal resistivity of the ground will cause a higher value for the thermal resistance of the surroundings \(T_d\). This will yield a lower ampacity for this possible thermal bottleneck.

### 5.3.3 Drying out of the soil around the cable (2-layer model)

In certain types of soil (e.g. sandy soil), water might migrate away from a location if the temperature at that location rises above a certain value. This might happen around power cables directly buried in the soil. If this ‘drying out of the soil’ happens around a directly buried power cable, a layer of dried out soil will appear around the cable. Figure 2-7 shows the isotherms around a directly buried single cable. If drying out of the soil will occur in that situation, the soil will become dry in an area within the isotherm of the temperate above which drying out of the soil will occur. This isotherm is called the ‘critical’ temperature for drying out of the soil. Cables directly buried in the soil can cause the soil surrounding the cable to become dry. The dried out layer around the cable will have a much higher thermal resistivity compared to the soil that will not dry out.

For single circuits IEC 60287 gives calculations methods for this situation, these are explained in Appendix A. Parameters for this possible bottleneck are defined as:

<table>
<thead>
<tr>
<th>Drying out of soil</th>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal resistivity dried out soil</td>
<td>(\rho_{\text{dried, out}})</td>
<td>2.0 - 3.3</td>
<td>K (\text{m/W})</td>
</tr>
<tr>
<td></td>
<td>Thermal resistivity not dried out soil</td>
<td>(\rho_{\text{normal}})</td>
<td>1.0</td>
<td>K (\text{m/W})</td>
</tr>
<tr>
<td></td>
<td>Temperature at which ground starts to dry out</td>
<td>(\theta_{\text{critical}})</td>
<td>25 - 45</td>
<td>°C</td>
</tr>
</tbody>
</table>
The layer with the higher thermal resistivity will cause the thermal resistance of the surroundings \((T_4)\) to rise. This will lead to a decreased ampacity for this possible thermal bottleneck.

### 5.3.4 Dry ground due to external influence

As already mentioned in the previous section, the moisture content of the soil influences the thermal resistivity of that soil and thereby influences the cable ampacity in that area by a change in thermal resistance of the surroundings \((T_4)\). The previous section describes a dried out layer around the cable. In extreme (worst case) situations, all of the surrounding soil can be extremely dry. There can be several reasons for the surrounding soil to have very low moisture content, for instance:

- Large distance to water (e.g. stream, river, lake)
- Low groundwater level
- Trees (especially willow trees, alders and poplars can dry out soil)
- Well-pointing at a construction site nearby

Of the selected soil-types in section 5.3.3, a ‘dry’ variant is defined to model the influence of these possible bottlenecks. Weak ground is not taken into account since this soil type always has a high moisture content. The selected possible bottlenecks and their parameters are:

<table>
<thead>
<tr>
<th>Soil Type</th>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry sand</td>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>2.0 - 3.3</td>
<td>Km/W</td>
</tr>
<tr>
<td>Dry clay</td>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>3.0 - 4.0</td>
<td>Km/W</td>
</tr>
<tr>
<td>Dry peat</td>
<td>Thermal resistivity of the soil</td>
<td>(\rho)</td>
<td>10.0 - 17.0</td>
<td>Km/W</td>
</tr>
</tbody>
</table>

### 5.3.5 Dike crossings

Dikes often consist of a layer of clay over coarse sand. The clay prevents water from entering the dike and thereby enables the dike fulfil to its primary function for longer periods of time. The soil within the dike often has unfavourable thermal properties. Cables installed in the top of the dike (Figure 5-4 left) can cause ‘drying out of the soil’ (section 5.3.3) in already relatively dry ground. Cables installed along the bottom of a dike (Figure 5-4 right) will less likely cause drying out of the soil because at these positions the cable is closer the groundwater. However, cables installed along the bottom of a dike will experience an increased laying depth and a decreased ambient temperature. In section 2.2.3 the relation between the laying depth and the ambient temperature is described: Up to a depth of 5m the ambient temperature \((\theta_a)\) can be assumed to have a linear coupling with the installation depth \((L)\) by means of:
\[ \theta_a = a + bL \]

Typical values for the ground temperature (highest temperature reached in a year) in the Netherlands are: 15°C at a depth of 1m, and 10°C at a depth of 5m. Below 5m the temperature is assumed constant with a value of 10°C. Values for \( a \) and \( b \) are then (up to a depth of 5m): \( a = 16.25 \) and \( b = 1.25 \).

![Figure 5-4: Cables in dikes, through top of dike (left) and along the bottom of the dike (right)](image)

Parameters to model dike-crossings are defined as:

<table>
<thead>
<tr>
<th>Dike crossing through top of dike</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal resistivity dried out soil</td>
<td>( \rho_{dried\text{-}out} )</td>
<td>2.0-3.3</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity not dried out soil</td>
<td>( \rho_{normal} )</td>
<td>1.5</td>
<td>Km/W</td>
</tr>
<tr>
<td>Temperature at which ground starts to dry out</td>
<td>( \theta_{critical} )</td>
<td>30</td>
<td>°C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dike crossing along bottom of dike</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying depth</td>
<td>( L )</td>
<td>3 - 5</td>
<td>m</td>
</tr>
<tr>
<td>Ambient ground temperature factor “( a )”</td>
<td>( a )</td>
<td>16.25</td>
<td></td>
</tr>
<tr>
<td>Ambient ground temperature factor “( b )”</td>
<td>( b )</td>
<td>-1.25</td>
<td></td>
</tr>
<tr>
<td>Thermal resistivity of the soil</td>
<td>( \rho )</td>
<td>1.5</td>
<td>Km/W</td>
</tr>
</tbody>
</table>

The ‘dike crossing through top of dike’ is a combination of the possible bottlenecks ‘other surrounding substance’ and ‘drying out of soil’. Both will influence the thermal resistance of the surroundings \( (T_4) \) and hence influence the cable’s ampacity.

The ‘dike crossing along bottom of dike’ has a change in the value for the thermal resistivity of the soil, which will cause a change in the thermal resistance of the surroundings \( (T_4) \), but also encounters a change in laying depth and ambient ground temperature. The decreased ambient temperature at greater depths would imply a higher ampacity, but the increased laying depth also causes changes in the thermal resistance of the surroundings \( (T_4) \). The increased laying depth will cause a rise of the thermal resistance of the surroundings \( (T_4) \). The (negative) influence of the increased laying depth on the cable’s ampacity will normally be larger compared to the (positive) influence of the decreased ambient temperature and this yields a lower ampacity for this potential thermal bottleneck.
5.3.6 Horizontal drillings

Horizontal drillings are used to bridge sections in the cable route where it is not possible to dig and bury the cable (e.g. road crossings or river/stream crossings). In these situations a pipe will be installed under the section that has to be bridged, and the cable will be pulled through the pipe. In these situations the geometry of the environment is differing from the ‘standard’ situation. IEC 60287 gives calculation methods for cables in pipes; these are explained in Appendix A.

Pipes are usually made of steel or polyethylene (PE). If the pipe is made of steel, the magnetic field caused by the cable will induce currents in the pipe, which will generate extra heat. This extra heat source can significantly reduce the ampacity of the cable circuit. However, if a steel pipe is used, all three cables are usually installed in the same pipe. In this way the magnetic induction leading to heat generation in the steel pipe is minimized. Three cables each installed in a separate steel pipe is not a common installation situation. Therefore this magnetic inductance is not implemented in the Maple program, and steel pipes are not covered in this study.

If PE pipes are used, they often have thick walls to provide the necessary mechanical strength. Compared to soil, PE has a high thermal resistivity, and it will increase the thermal resistance of the cable environment, therefore decreasing the ampacity of the cable circuit. This influence is relatively small, but is still taken into account in the ampacity calculations.

The pipe is usually filled with air, water or bentonite. If the pipe is filled with a solid material like bentonite, IEC 60287 can easily be used with a “3-layer-model”. If the substance in the pipe is a liquid (water or air), one should realize that not only conduction, but also convection may occur (Figure 5-5, and that cables will not ‘float’ in a pipe but will rest on the bottom of a pipe. Calculations are even more difficult then). The liquid will also move along the length of pipe.

![Figure 5-5: Heat exchange in a water filled pipe where the cable is located in the middle of the pipe: water flow (left) and isotherms (right)](image)

Calculations in this research investigation are made assuming only conduction occurring. If convection is present, assumptions will be made on the thermal resistivity in which convection is present to implement the convection in the
calculations and estimate the stationary ampacity. For instance: Heat conduction in air (i.e. when convection is not possible, air is 'standing still') implies a thermal resistivity of 40 Km/W. If convection is expected, the value for the thermal resistivity will be assumed to be between 8 Km/W and 10 Km/W. In an equal manner the thermal resistivity of water will be reduced by convection from 1.7 Km/W (standing still) to 0.5 - 1.0 Km/W (assuming convection).

Horizontal drillings also experience an increased laying depth and a decreased temperature at those depths. The relationship between the installation depth and the ambient temperature is explained in the previous section. If a horizontal drilling bridges a river, one should realize the installation depth is measured from the bottom of the river to the cable.

Two types of possible bottlenecks involving pipes are defined:

<table>
<thead>
<tr>
<th>Pipe filled with air (convection possible)</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying depth</td>
<td>L</td>
<td>10 - 30</td>
<td>m</td>
</tr>
<tr>
<td>Ambient ground temperature</td>
<td>$\theta_a$</td>
<td>10</td>
<td>°C</td>
</tr>
<tr>
<td>Diameter factor (cable vs. inner diameter pipe)</td>
<td>const</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Thickness pipe</td>
<td>$t_{pipe}$</td>
<td>0.02</td>
<td>m</td>
</tr>
<tr>
<td>Thermal resistivity of the pipe filling</td>
<td>$\rho_{filling}$</td>
<td>8.0 - 10.0</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the pipe material</td>
<td>$\rho_{pipe}$</td>
<td>3.0</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the soil surrounding the pipe</td>
<td>$\rho_{outside}$</td>
<td>1.0</td>
<td>Km/W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pipe filled with water (convection possible)</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying depth</td>
<td>L</td>
<td>10 - 30</td>
<td>m</td>
</tr>
<tr>
<td>Ambient ground temperature factor “a”</td>
<td>a</td>
<td>16.25</td>
<td></td>
</tr>
<tr>
<td>Ambient ground temperature factor “b”</td>
<td>b</td>
<td>-1.25</td>
<td></td>
</tr>
<tr>
<td>Diameter factor (cable vs. inner diameter pipe)</td>
<td>const</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Thickness pipe</td>
<td>$t_{pipe}$</td>
<td>0.02</td>
<td>m</td>
</tr>
<tr>
<td>Thermal resistivity of the pipe filling</td>
<td>$\rho_{filling}$</td>
<td>0.5 - 1.0</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the pipe material</td>
<td>$\rho_{pipe}$</td>
<td>3.0</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the soil surrounding the pipe</td>
<td>$\rho_{outside}$</td>
<td>1.0</td>
<td>Km/W</td>
</tr>
</tbody>
</table>

Field measurements often show relatively high temperatures at the entrances and exits of a pipe, especially in the case of water filled deep drillings (Figure 5-6). The reason for this has not clearly been identified yet. A plausible explanation might be that warm water flows, due to longitudinal heat transport, to the outer ends of the pipe, since these are the highest positions in the pipe. If the outer ends of the pipe are above the water table, in worst-case situations the warm water at the outer ends of the pipe might be replaced by air. Due to the longitudinal heat transport in the pipe, this air will also be relatively warm, which can be modelled with an increased ambient temperature. These areas now have unfavourable thermal properties and might represent a possible thermal bottleneck.
A pipe entrance/exits situation with warm air replacing the pipe-filling is modelled with the following parameters:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying depth</td>
<td>( L )</td>
<td>1 – 3</td>
<td>m</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>( \theta_a )</td>
<td>25 - 30</td>
<td>°C</td>
</tr>
<tr>
<td>Diameter factor (cable vs. inner diameter pipe)</td>
<td>const</td>
<td>1.6</td>
<td></td>
</tr>
<tr>
<td>Thickness pipe</td>
<td>( t_{\text{pipe}} )</td>
<td>0.02</td>
<td>m</td>
</tr>
<tr>
<td>Thermal resistivity of the pipe filling</td>
<td>( \rho_{\text{filling}} )</td>
<td>8.0 - 10.0</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the pipe material</td>
<td>( \rho_{\text{pipe}} )</td>
<td>3.0</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the soil surrounding the pipe</td>
<td>( \rho_{\text{outside}} )</td>
<td>1.0</td>
<td>Km/W</td>
</tr>
</tbody>
</table>

The influence of the parameters of the possible thermal bottlenecks defined in this section on the cable ampacity is a combination of influence on the thermal resistance of the surroundings (\( T_s \)), an increased laying depth and a changing ambient temperature.

### 5.3.7 External heat sources

Power cables are not the only heat generating infrastructures buried in the ground. Oil pipes, pipes for city heating, sewers, etc. also might cause the cable surroundings to heat up. Large paved parkings are also known for the relatively warm soil beneath the surface. If a cable crosses these areas there may be a thermal bottleneck. These situations can be modelled with an increased ambient temperature.

One situation is selected where the ambient temperature is increased to 25 - 30°C, compared to the ‘reference’ situation, caused by a nearby heat pipe. The influence of a higher ambient temperature can easily be seen in the central equation of IEC 60287 (Equation 3-6).
5.3.8 Other conducting cables nearby

If the circuit under consideration is in parallel with another cable circuit, the ambient temperature of the ground will rise caused by the heat generated by the other cables. It is possible that cables will not only influence each other on a thermal level, but also induce currents in other cables due to their magnetic fields. If the cables are single end bonded or crossbonded or if the spacing between the cable circuits is large enough, the influence of these magnetic fields can be neglected (as is done in this study).

IEC 60287 gives calculation methods for cables in parallel. In a simplified form (no influence of magnetic fields in neighbouring circuits), these calculation methods are implemented in the Maple program. The calculation methods are explained in Appendix A.

If other cables are not in parallel with the circuit under consideration, but cross the circuit at a certain angle, calculations are more complicated since longitudinal heat flow must be taken into consideration. Anders and Brakelmann [5], [6] have developed calculation methods for these situations, but in this study a worst case assumption is made: Since longitudinal heat flow will only increase the cable's ampacity in a cable crossing situation, cable crossing ampacities will never be lower than cables in parallel at the same (vertical) distance. Therefore cable crossings can be calculated as cables in parallel at a certain vertical distance. In the Maple program, only ampacities for parallel cables at equal depth (horizontal distance) can be calculated, calculations for multiple circuits above each other are not possible. Therefore no bottlenecks for cable crossings are defined.

Two possible thermal bottlenecks with parallel circuits are implemented in the Maple program:

**Parallel circuit PILC 10 kV**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load of circuit in parallel</td>
<td>I</td>
<td>150</td>
<td>A</td>
</tr>
<tr>
<td>Heart-heart distance between circuits</td>
<td>d</td>
<td>0.5 – 2.0</td>
<td>m</td>
</tr>
<tr>
<td>(horizontal, no vertical distance)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Parallel circuit XLPE 150 kV**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>symbol</th>
<th>values</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Load of circuit in parallel</td>
<td>I</td>
<td>800</td>
<td>A</td>
</tr>
<tr>
<td>Heart-heart distance between circuits</td>
<td>d</td>
<td>0.5 – 2.0</td>
<td>m</td>
</tr>
<tr>
<td>(horizontal, no vertical distance)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5.4 Results of modelling

The possible thermal bottlenecks defined in the previous section are calculated with the Maple program previously described. Results are presented and discussed in this section.

To give an idea of the values for the variables in the central formula of IEC 60287, Table 5-1 gives the results for the calculation of the 'reference' situations for all available cables in the Maple program.

<table>
<thead>
<tr>
<th></th>
<th>PILC 10kV</th>
<th>KUDIKA 10kV</th>
<th>XLPE 20kV</th>
<th>XLPE 150kV</th>
<th>XLPE 380kV</th>
<th>SCFF 150kV s.e.b.</th>
<th>SCFF 150kV b.e.b.</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_1</td>
<td>0.663</td>
<td>0.641</td>
<td>0.280</td>
<td>0.430</td>
<td>0.556</td>
<td>0.499</td>
<td>0.499</td>
</tr>
<tr>
<td>T_2</td>
<td>0.113</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>T_3</td>
<td>0.099</td>
<td>0.072</td>
<td>0.190</td>
<td>0.053</td>
<td>0.042</td>
<td>0.133</td>
<td>0.133</td>
</tr>
<tr>
<td>T_4</td>
<td>0.666</td>
<td>0.646</td>
<td>1.801</td>
<td>1.414</td>
<td>1.018</td>
<td>1.111</td>
<td>1.111</td>
</tr>
<tr>
<td>W_0</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.488</td>
<td>12.832</td>
<td>2.978</td>
<td>2.978</td>
</tr>
<tr>
<td>R_xc</td>
<td>1.30E-04</td>
<td>1.52E-04</td>
<td>9.20E-05</td>
<td>3.32E-05</td>
<td>1.48E-05</td>
<td>2.88E-05</td>
<td>2.88E-05</td>
</tr>
<tr>
<td>λ₁</td>
<td>0.019</td>
<td>0.018</td>
<td>0.767</td>
<td>0.099</td>
<td>0.047</td>
<td>0.003</td>
<td>3.238</td>
</tr>
<tr>
<td>λ₂</td>
<td>6.35E-03</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>θ_e</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>θ_c</td>
<td>50</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>90</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>Ampacity</td>
<td>282.83</td>
<td>416.97</td>
<td>463.25</td>
<td>1.046.51</td>
<td>1.530.39</td>
<td>1.141.20</td>
<td>627.87</td>
</tr>
</tbody>
</table>

Table 5-1: Results of the Maple program for calculation of the 'reference' situation. Values of the variables in the central formula of IEC 60287 and the calculated ampacity for the 'reference' situation.

In Table 5-1 it can be seen that T_4 amounts to 40 – 70% of the total thermal resistance. In most cases the majority of the generated heat will therefore be dissipated in the cable environment. Relatively large differences between the various cable systems can be observed in the maximum allowable conductor temperature, the dielectric losses (W_0) and the factor for the sheath losses (λ₁).

Results of the bottleneck calculations per cable are given in Figure 5-7 to Figure 5-13. The red bars in those figures represent the range in which the calculated ampacity for a specific bottleneck varies, relative to the ampacity of the 'reference' situation. The maximum and minimum of the calculated ampacity-range per bottleneck are given in Table 5-2 and Table 5-3, respectively.

It can be seen that in almost every situation the influence of the possible bottlenecks is similar. Some exceptions are worth mentioning:

- The 'XLPE 380kV' shows some deviations, especially for bottlenecks where the thermal resistivity of the soil reaches very high values. This is because the dielectric losses are, because of the high operation voltage, relatively high. If the cable crosses a region with 'dry peat', applying a voltage on the cable would already result in dielectric losses that will cause the cable to exceed the maximum allowable temperature.
- The influence of 'drying out of soil' is, compared to the other cables, much lower for a PILC 10kV system. This is because a PILC cable has a relatively low maximum allowable temperature. Operating the cable at its maximum ampacity (i.e. maximum allowable temperature), the layer of dried out soil around the cable will be smaller compared to other cables with a higher allowable temperature. Since 'dike crossing through top' also uses this dried out layer, this bottleneck will have less influence on a PILC cable.

- The influence of an increase in ambient temperature, for instance with the 'heat pipe', is larger for a PILC 10kV system. This is again caused by the maximum allowable operating temperature. The central formula of the IEC 60287 (Equation 3-6) uses the temperature difference between the maximum allowable temperature and the ambient temperature. This difference will experience relative larger fluctuations caused by the ambient temperature if the maximum allowable temperature is relatively low.

![Figure 5-7: Results of the bottleneck calculation with the Maple program for the PILC 10kV system](image)
Figure 5-8: Results of the bottleneck calculation with the Maple program for the KUDIKA 10kV system

Figure 5-9: Results of the bottleneck calculation with the Maple program for the XLPE 20kV system
CRITICAL THERMAL BOTTLENECK DETERMINATION WITH ROUTE SURVEY AND MODELLING

Figure 5-10: Results of the bottleneck calculation with the Maple program for the XLPE 150kV system

Figure 5-11: Results of the bottleneck calculation with the Maple program for the XLPE 380kV system
Figure 5-12: Results of the bottleneck calculation with the Maple program for the SCFF 150kV single end bonded system

Figure 5-13: Results of the bottleneck calculation with the Maple program for the SCFF 150kV both ends bonded system
## Maximum modelled ampacity for a bottleneck as a percentage of the reference situation

<table>
<thead>
<tr>
<th>bottleneck name</th>
<th>PILC 10kV</th>
<th>KUDIKA 10kV</th>
<th>XLPE 20kV</th>
<th>XLPE 150kV</th>
<th>XLPE 380kV</th>
<th>SCFF 150kV s.e.b.</th>
<th>SCFF 150kV b.e.b.</th>
<th>highest value found</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>114.98%</td>
<td>117.71%</td>
<td>122.85%</td>
<td>120.04%</td>
<td>121.01%</td>
<td>117.04%</td>
<td>122.87%</td>
<td>122.87%</td>
</tr>
<tr>
<td>clay</td>
<td>106.71%</td>
<td>107.78%</td>
<td>109.68%</td>
<td>108.67%</td>
<td>109.46%</td>
<td>107.61%</td>
<td>109.79%</td>
<td>109.79%</td>
</tr>
<tr>
<td>weak ground</td>
<td>89.67%</td>
<td>88.45%</td>
<td>86.47%</td>
<td>87.43%</td>
<td>85.13%</td>
<td>88.35%</td>
<td>86.02%</td>
<td>89.67%</td>
</tr>
<tr>
<td>peat</td>
<td>78.84%</td>
<td>76.80%</td>
<td>73.64%</td>
<td>75.07%</td>
<td>68.75%</td>
<td>76.13%</td>
<td>72.43%</td>
<td>78.84%</td>
</tr>
<tr>
<td>drying out of soil</td>
<td>100.00%</td>
<td>88.48%</td>
<td>84.11%</td>
<td>86.28%</td>
<td>85.73%</td>
<td>90.71%</td>
<td>85.19%</td>
<td>100.00%</td>
</tr>
<tr>
<td>dry sand</td>
<td>78.84%</td>
<td>76.80%</td>
<td>73.64%</td>
<td>75.07%</td>
<td>68.75%</td>
<td>76.13%</td>
<td>72.43%</td>
<td>78.84%</td>
</tr>
<tr>
<td>dry clay</td>
<td>67.15%</td>
<td>64.67%</td>
<td>60.99%</td>
<td>62.45%</td>
<td>49.09%</td>
<td>62.84%</td>
<td>58.58%</td>
<td>67.15%</td>
</tr>
<tr>
<td>dry peat</td>
<td>39.28%</td>
<td>37.12%</td>
<td>34.11%</td>
<td>34.23%</td>
<td>0.00%</td>
<td>28.45%</td>
<td>25.66%</td>
<td>39.28%</td>
</tr>
<tr>
<td>dike crossing through top</td>
<td>84.28%</td>
<td>79.32%</td>
<td>76.07%</td>
<td>77.57%</td>
<td>72.48%</td>
<td>79.13%</td>
<td>75.27%</td>
<td>84.28%</td>
</tr>
<tr>
<td>dike crossing along bottom</td>
<td>83.29%</td>
<td>79.62%</td>
<td>75.97%</td>
<td>75.41%</td>
<td>64.79%</td>
<td>74.42%</td>
<td>70.43%</td>
<td>83.29%</td>
</tr>
<tr>
<td>pipe filled with air</td>
<td>72.28%</td>
<td>69.60%</td>
<td>62.52%</td>
<td>71.99%</td>
<td>55.49%</td>
<td>68.28%</td>
<td>64.14%</td>
<td>72.28%</td>
</tr>
<tr>
<td>pipe filled with water</td>
<td>84.48%</td>
<td>82.76%</td>
<td>80.51%</td>
<td>78.58%</td>
<td>66.73%</td>
<td>75.64%</td>
<td>71.91%</td>
<td>84.48%</td>
</tr>
<tr>
<td>pipe entrance or exit</td>
<td>67.26%</td>
<td>72.05%</td>
<td>65.12%</td>
<td>80.82%</td>
<td>71.69%</td>
<td>77.86%</td>
<td>75.30%</td>
<td>80.82%</td>
</tr>
<tr>
<td>heat pipe</td>
<td>84.52%</td>
<td>93.10%</td>
<td>93.05%</td>
<td>93.04%</td>
<td>90.96%</td>
<td>92.06%</td>
<td>91.10%</td>
<td>93.10%</td>
</tr>
<tr>
<td>parallel circuit PILC 10kV</td>
<td>98.58%</td>
<td>99.38%</td>
<td>97.53%</td>
<td>99.58%</td>
<td>99.47%</td>
<td>99.25%</td>
<td>99.58%</td>
<td>99.58%</td>
</tr>
<tr>
<td>parallel circuit XLPE 150kV</td>
<td>94.76%</td>
<td>97.61%</td>
<td>95.73%</td>
<td>97.79%</td>
<td>97.04%</td>
<td>97.45%</td>
<td>97.24%</td>
<td>97.79%</td>
</tr>
</tbody>
</table>

Table 5-2: Results of the Maple program for calculation of the bottlenecks. Highest calculated ampacity per bottleneck per cable, as a percentage of the ampacity of the 'reference' situation per cable.

## Minimum modelled ampacity for a bottleneck as a percentage of the reference situation

<table>
<thead>
<tr>
<th>bottleneck name</th>
<th>PILC 10kV</th>
<th>KUDIKA 10kV</th>
<th>XLPE 20kV</th>
<th>XLPE 150kV</th>
<th>XLPE 380kV</th>
<th>SCFF 150kV s.e.b.</th>
<th>SCFF 150kV b.e.b.</th>
<th>lowest value found</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
<td>100.00%</td>
</tr>
<tr>
<td>clay</td>
<td>94.42%</td>
<td>93.70%</td>
<td>92.50%</td>
<td>93.10%</td>
<td>92.02%</td>
<td>93.69%</td>
<td>92.30%</td>
<td>92.02%</td>
</tr>
<tr>
<td>weak ground</td>
<td>78.84%</td>
<td>76.80%</td>
<td>73.64%</td>
<td>75.07%</td>
<td>68.75%</td>
<td>76.13%</td>
<td>72.43%</td>
<td>68.75%</td>
</tr>
<tr>
<td>peat</td>
<td>53.95%</td>
<td>51.42%</td>
<td>47.80%</td>
<td>48.87%</td>
<td>16.51%</td>
<td>47.40%</td>
<td>43.39%</td>
<td>16.51%</td>
</tr>
<tr>
<td>drying out of soil</td>
<td>84.17%</td>
<td>72.78%</td>
<td>68.67%</td>
<td>70.50%</td>
<td>62.67%</td>
<td>72.73%</td>
<td>67.77%</td>
<td>62.67%</td>
</tr>
<tr>
<td>dry sand</td>
<td>64.54%</td>
<td>62.02%</td>
<td>58.31%</td>
<td>59.73%</td>
<td>44.14%</td>
<td>59.85%</td>
<td>55.57%</td>
<td>44.14%</td>
</tr>
<tr>
<td>dry clay</td>
<td>59.48%</td>
<td>56.92%</td>
<td>53.21%</td>
<td>54.49%</td>
<td>33.27%</td>
<td>53.96%</td>
<td>49.74%</td>
<td>33.27%</td>
</tr>
<tr>
<td>dry peat</td>
<td>30.51%</td>
<td>28.72%</td>
<td>26.26%</td>
<td>25.46%</td>
<td>0.00%</td>
<td>13.09%</td>
<td>11.74%</td>
<td>0.00%</td>
</tr>
<tr>
<td>dike crossing through top</td>
<td>79.42%</td>
<td>69.06%</td>
<td>64.95%</td>
<td>66.71%</td>
<td>56.65%</td>
<td>68.52%</td>
<td>63.59%</td>
<td>56.65%</td>
</tr>
<tr>
<td>dike crossing along bottom</td>
<td>83.07%</td>
<td>77.82%</td>
<td>73.74%</td>
<td>72.70%</td>
<td>59.50%</td>
<td>71.14%</td>
<td>66.83%</td>
<td>59.50%</td>
</tr>
<tr>
<td>pipe filled with air</td>
<td>67.25%</td>
<td>64.37%</td>
<td>57.02%</td>
<td>65.86%</td>
<td>44.11%</td>
<td>61.40%</td>
<td>57.12%</td>
<td>44.11%</td>
</tr>
<tr>
<td>pipe filled with water</td>
<td>79.18%</td>
<td>76.95%</td>
<td>73.40%</td>
<td>71.98%</td>
<td>55.47%</td>
<td>68.27%</td>
<td>64.13%</td>
<td>55.47%</td>
</tr>
<tr>
<td>pipe entrance or exit</td>
<td>55.20%</td>
<td>62.95%</td>
<td>55.88%</td>
<td>68.56%</td>
<td>51.11%</td>
<td>64.10%</td>
<td>60.76%</td>
<td>51.11%</td>
</tr>
<tr>
<td>heat pipe</td>
<td>75.60%</td>
<td>89.45%</td>
<td>89.38%</td>
<td>89.35%</td>
<td>86.08%</td>
<td>87.82%</td>
<td>87.88%</td>
<td>75.60%</td>
</tr>
<tr>
<td>parallel circuit PILC 10kV</td>
<td>94.28%</td>
<td>97.25%</td>
<td>95.36%</td>
<td>97.34%</td>
<td>93.76%</td>
<td>94.14%</td>
<td>94.50%</td>
<td>93.76%</td>
</tr>
<tr>
<td>parallel circuit XLPE 150kV</td>
<td>75.94%</td>
<td>89.28%</td>
<td>87.17%</td>
<td>88.67%</td>
<td>70.78%</td>
<td>74.66%</td>
<td>74.60%</td>
<td>70.78%</td>
</tr>
</tbody>
</table>

Table 5-3: Results of the Maple program for calculation of the bottlenecks. Lowest calculated ampacity per bottleneck per cable, as a percentage of the ampacity of the 'reference' situation per cable.
To rank the bottlenecks, the average influence of each calculated bottleneck-range is calculated. These values are shown in Table 5-4. The last column in Table 5-4 shows the influence of a bottleneck averaged over all cables (average over the numbers in the same row).

<table>
<thead>
<tr>
<th>bottleneck name</th>
<th>PILC 10kV</th>
<th>KUDIA 10kV</th>
<th>XLPE 20kV</th>
<th>XLPE 150kV</th>
<th>XLPE 380kV</th>
<th>SCFF 150kV s.e.b.</th>
<th>SCFF 150kV b.e.b.</th>
<th>average of range-averaged over all cables</th>
</tr>
</thead>
<tbody>
<tr>
<td>sand</td>
<td>107.49%</td>
<td>108.85%</td>
<td>111.42%</td>
<td>110.02%</td>
<td>110.50%</td>
<td>108.52%</td>
<td>111.43%</td>
<td>109.75%</td>
</tr>
<tr>
<td>clay</td>
<td>100.56%</td>
<td>100.74%</td>
<td>101.09%</td>
<td>100.89%</td>
<td>100.74%</td>
<td>100.65%</td>
<td>101.05%</td>
<td>100.82%</td>
</tr>
<tr>
<td>weak ground</td>
<td>84.26%</td>
<td>82.62%</td>
<td>80.06%</td>
<td>81.25%</td>
<td>76.94%</td>
<td>82.24%</td>
<td>79.23%</td>
<td>80.94%</td>
</tr>
<tr>
<td>peat</td>
<td>66.39%</td>
<td>64.11%</td>
<td>60.72%</td>
<td>61.97%</td>
<td>42.63%</td>
<td>61.76%</td>
<td>57.91%</td>
<td>59.36%</td>
</tr>
<tr>
<td>drying out of soil</td>
<td>92.09%</td>
<td>80.63%</td>
<td>76.39%</td>
<td>78.39%</td>
<td>74.20%</td>
<td>81.72%</td>
<td>76.48%</td>
<td>79.99%</td>
</tr>
<tr>
<td>dry sand</td>
<td>71.69%</td>
<td>69.41%</td>
<td>65.98%</td>
<td>67.40%</td>
<td>56.44%</td>
<td>67.99%</td>
<td>64.00%</td>
<td>66.13%</td>
</tr>
<tr>
<td>dry clay</td>
<td>63.31%</td>
<td>60.80%</td>
<td>57.10%</td>
<td>58.47%</td>
<td>41.18%</td>
<td>58.40%</td>
<td>54.16%</td>
<td>56.20%</td>
</tr>
<tr>
<td>dry peat</td>
<td>34.90%</td>
<td>32.92%</td>
<td>30.18%</td>
<td>29.85%</td>
<td>0.00%</td>
<td>20.77%</td>
<td>18.70%</td>
<td>23.90%</td>
</tr>
<tr>
<td>dike crossing through top</td>
<td>81.85%</td>
<td>74.19%</td>
<td>70.51%</td>
<td>72.14%</td>
<td>64.57%</td>
<td>73.82%</td>
<td>69.43%</td>
<td>72.36%</td>
</tr>
<tr>
<td>dike crossing along bottom</td>
<td>83.18%</td>
<td>78.72%</td>
<td>74.86%</td>
<td>74.05%</td>
<td>62.14%</td>
<td>72.78%</td>
<td>68.63%</td>
<td>73.48%</td>
</tr>
<tr>
<td>pipe filled with air</td>
<td>69.77%</td>
<td>66.99%</td>
<td>59.77%</td>
<td>68.92%</td>
<td>49.80%</td>
<td>64.84%</td>
<td>60.63%</td>
<td>62.96%</td>
</tr>
<tr>
<td>pipe filled with water</td>
<td>81.83%</td>
<td>79.85%</td>
<td>76.96%</td>
<td>75.28%</td>
<td>61.10%</td>
<td>71.96%</td>
<td>68.02%</td>
<td>73.57%</td>
</tr>
<tr>
<td>pipe entrance or exit</td>
<td>61.23%</td>
<td>67.50%</td>
<td>60.50%</td>
<td>74.69%</td>
<td>61.40%</td>
<td>70.98%</td>
<td>68.03%</td>
<td>66.33%</td>
</tr>
<tr>
<td>heat pipe</td>
<td>80.06%</td>
<td>91.27%</td>
<td>91.22%</td>
<td>91.19%</td>
<td>88.52%</td>
<td>89.94%</td>
<td>89.99%</td>
<td>88.88%</td>
</tr>
<tr>
<td>parallel circuit PILC 10kV</td>
<td>96.43%</td>
<td>98.31%</td>
<td>96.44%</td>
<td>98.46%</td>
<td>96.55%</td>
<td>96.80%</td>
<td>96.87%</td>
<td>97.12%</td>
</tr>
<tr>
<td>parallel circuit XLPE 150kV</td>
<td>85.35%</td>
<td>93.45%</td>
<td>91.45%</td>
<td>93.23%</td>
<td>83.91%</td>
<td>86.05%</td>
<td>85.92%</td>
<td>88.48%</td>
</tr>
</tbody>
</table>

Table 5-4: Results of the Maple program for calculation of the bottlenecks. Average calculated ampacity per bottleneck per cable, as a percentage of the ampacity of the 'reference' situation per cable.

The values for 'the average influence of a bottleneck, averaged over all cables' (last column in Table 5-4), 'the lowest found average influence of a bottleneck' (minimum per row for columns 2 to 8 in Table 5-4) and 'the overall lowest value found for a bottleneck' (last column in Table 5-3) are shown in Table 5-5. In Table 5-5 the bottlenecks are sorted on their 'values for the average influence of a bottleneck, averaged over all cables'.

By comparing the last three columns in Table 5-5, it can be concluded the ranking would be almost similar if it was based on the 'lowest average influence' of the 'overall lowest influence'. The only important exception is the 'overall lowest influence' found for 'peat' and 'dry peat'. These exceptions are caused by the dielectric losses occurring in the XPLE 380kV system and are already explained in the start of this section.
The table below shows the results of the Maple program for calculation of the bottlenecks. Final ranking.

<table>
<thead>
<tr>
<th>Bottleneck name</th>
<th>Average influence, averaged over all cables</th>
<th>Lowest average influence</th>
<th>Overall lowest influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry peat</td>
<td>23.90%</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td>dry clay</td>
<td>56.20%</td>
<td>41.18%</td>
<td>33.27%</td>
</tr>
<tr>
<td>peat</td>
<td>59.36%</td>
<td>42.63%</td>
<td>16.51%</td>
</tr>
<tr>
<td>pipe filled with air</td>
<td>62.96%</td>
<td>49.80%</td>
<td>44.11%</td>
</tr>
<tr>
<td>dry sand</td>
<td>66.13%</td>
<td>56.44%</td>
<td>44.14%</td>
</tr>
<tr>
<td>pipe entrance or exit</td>
<td>66.33%</td>
<td>60.50%</td>
<td>51.11%</td>
</tr>
<tr>
<td>dike crossing through top</td>
<td>72.36%</td>
<td>64.57%</td>
<td>56.65%</td>
</tr>
<tr>
<td>dike crossing along bottom</td>
<td>73.48%</td>
<td>62.14%</td>
<td>59.50%</td>
</tr>
<tr>
<td>pipe filled with water</td>
<td>73.57%</td>
<td>61.10%</td>
<td>55.47%</td>
</tr>
<tr>
<td>drying out of soil</td>
<td>79.99%</td>
<td>74.20%</td>
<td>62.67%</td>
</tr>
<tr>
<td>weak ground</td>
<td>80.94%</td>
<td>76.94%</td>
<td>68.75%</td>
</tr>
<tr>
<td>parallel circuit XLPE 150kV</td>
<td>88.48%</td>
<td>83.91%</td>
<td>70.78%</td>
</tr>
<tr>
<td>heat pipe</td>
<td>88.88%</td>
<td>80.06%</td>
<td>75.60%</td>
</tr>
<tr>
<td>parallel circuit PILC 10kV</td>
<td>97.12%</td>
<td>96.43%</td>
<td>93.76%</td>
</tr>
<tr>
<td>clay</td>
<td>100.82%</td>
<td>100.56%</td>
<td>92.02%</td>
</tr>
<tr>
<td>sand</td>
<td>109.75%</td>
<td>107.49%</td>
<td>100.00%</td>
</tr>
</tbody>
</table>

Table 5-5: Results of the Maple program for calculation of the bottlenecks. Final ranking.

It can be concluded that, as long as the dielectric losses are negligible for a certain cable system, the bottleneck ranking is almost equal. Since the thermal resistance of the environment amounts to 40 – 70% of the total thermal resistance, as shown previously in this section, this result was to be expected.

For cables without glass fibre, a route survey will usually result in multiple possible bottleneck locations. The ranking as presented above can be used to select the bottleneck locations that limit the ampacity the most. Only the most ampacity-limiting thermal bottleneck locations then have to be investigated with for instance soil surveys and/or thermocouple measurements, to determine the critical thermal bottleneck location and its properties. The ranking can also be improved by adding more possible bottlenecks and (assumptions on) their property values when new knowledge is obtained in the future, or if the a route survey for a specific cable circuit already provides more detailed information of the property values for the bottlenecks present along the cable route.
6 Proposed methodology

As stated in the introduction of this report, the critical thermal bottleneck of an underground power cable connection and its properties should be known in order to derive a thermal model of the cable for the implementation of a dynamic rating system on the cable connection. Two methods to find the critical thermal bottleneck location have been presented in this report. This chapter describes when and how to choose the appropriate method, and how the knowledge obtained can be shared between the two methods.

Figure 6-1 shows the flowchart for the proposed methodology to obtain the critical thermal bottleneck location of an underground power cable connection and its thermal properties. The goal is to locate the critical bottleneck location of the underground power cable connection, and its thermal properties. With these thermal properties of the critical thermal bottleneck, a model can be derived to implement a dynamic rating system on the cable connection.

The methodology starts with investigating whether a glass fibre cable is present in or close to the cable circuit and whether it is possible to use it for temperature measurements (e.g. it should not be in use for another purpose and if the glass fibre cable is not embedded in the cable itself, laying conditions of the glass fibre cable relative to the power cables should be exactly known in order to determine 'what' is actually measured). If a glass fibre cable is present and available for measurement, a distributed temperature measurement is performed, using sophisticated equipment (as e.g. Raman ODTR, explained in chapter 4). With the indicator-tool discussed in chapter 4, possible bottleneck locations can subsequently be identified and finally the critical thermal bottleneck location can be determined with this tool. To characterize the thermal behaviour of the cable, the properties of the bottleneck must be known. If not enough knowledge can be obtained from the temperature measurements, a thorough route survey with e.g. soil samples on critical thermal bottleneck location will provide more data to model the critical bottleneck location.

The glass fibre measurements can also be used to obtain knowledge of possible thermal bottlenecks. At the possible bottleneck locations, detected with the indicators described in chapter 4, it should be investigated what is the cause of the unfavourable thermal behaviour. A field study (e.g. by studying the available maps, determining ground properties with soil samples, etc.) at the possible thermal bottleneck locations is very useful. If the cause is determined (e.g. soil with bad thermal properties, parallel cables, external heat source of perhaps a yet unknown cause), this knowledge can be stored in a database of 'possible thermal bottleneck locations and their modelling properties'. This database will be used if the critical thermal bottleneck location on an underground power cable connection should be determined without glass fibre measurements. This database corresponds to the database of possible bottleneck locations of chapter 5. In this way, one can learn the behaviour of thermal bottlenecks from the cables equipped with glass fibres, and apply this knowledge to the cables without glass fibres.
If glass fibre measurements are not available, the search for the critical thermal bottleneck will start with a route survey. Again, the location and the thermal properties of the critical thermal bottleneck should be determined. With the developed knowledge (i.e. knowledge of possible bottleneck locations stored in the database introduced in chapter 5) a route survey has to be conducted. In this route survey, all available data, for instance maps of the cable environment, maps of cable installation method, cable types, typical loads, properties of other cables nearby etc. is studied. A list of questions to guide this gathering of information is presented in Appendix C. With the data of the route survey, even if it is minimal information, and the available knowledge in the database the possible bottlenecks are selected. The ranking of the bottlenecks in the database determines the order in which bottlenecks are selected (first, the bottleneck with the most negative influence on the ampacity, if that bottleneck is not present the bottleneck with the second most influence and so on). These possible bottleneck locations are subsequently modelled with the ranking-tool described in chapter 5 and a quantitative ranking is obtained.

If this results in multiple possible locations for the critical thermal bottleneck, a more thorough route survey (with e.g. by studying the situation “on-site” and taking soil samples to determine the thermal properties of the soil surrounding the cable at those locations) is performed in order to narrow the ranges of the parameter variation in the pre-defined bottlenecks. With the more accurate data, the ranking-tool described in chapter 5 can again be used to obtain a more precise ranking of the possible bottleneck locations. In this way, the amount of work needed to find the critical thermal bottleneck is directed to the most important situations in the field.

If the more precise ranking still does result in multiple critical thermal bottleneck locations, the temperature at those (usually very few) locations is measured with a thermocouple. The indicator-tool introduced in chapter 4 will be used to finally determine the critical thermal bottleneck location. If needed, more knowledge of the thermal behaviour on the critical bottleneck location can be derived from the temperature measurements (learning).

The properties of the cable environment will change if the cable surroundings are disturbed by e.g. taking soil samples, a field study of the laying conditions or the installation of a thermocouple. In those situations the cable environment should be restored as much as possible to the original situation in order to do a correct measurement.
PROPOSED METHODOLOGY

Underground power cable connection

Critical thermal bottleneck location known?

Yes

Glass fibre measurements possible?

Yes

Measure cable temperature with glass fibre measurements

Properties of possible bottlenecks

Database of bottleneck locations with properties

Route survey / field study

Possible thermal bottleneck locations

More than one position?

Yes

Thorough route survey (e.g. soil samples to narrow ranges of bottleneck properties)

Use map program to rank locations with more exact bottleneck properties

Critical thermal bottleneck location with properties

No

No

No

No

No

No

No

No

Thermocouple measurements at possible bottleneck locations

More than one location?

Yes

Use indicators to select possible thermal bottlenecks

Possible thermal bottlenecks already known?

Yes

No

No

No

No

Yes

No

No

No

Critical thermal bottleneck location with properties

Use indicators to select critical thermal bottleneck

Enough data to derive model?

Yes

No

Figure 6-1: Flowchart of the proposed methodology to obtain a temperature profile of the critical thermal bottleneck of an underground power cable connection.
7 Conclusions and recommendations

On the basis of the knowledge obtained with this study, conclusions are drawn and presented in this chapter. Recommendations are made for future work.

7.1 Conclusions

The goal of this study was: “To develop a methodology to systematically detect, rank and characterize thermal bottlenecks in an underground power cable and develop a ‘tool’ to make this knowledge accessible for KEMA.” With knowledge of the critical thermal bottleneck location of an underground power cable connection and its thermal properties, a model can be derived to implement a dynamic rating system on a cable.

Two tools have been developed, the “indicator-tool” (chapter 4) and the “ranking-tool” (chapter 5), and a methodology is proposed (chapter 6). With this methodology, bottlenecks can be identified, characterized and finally ranked in order to determine the critical thermal bottleneck location and its properties.

For situations where glass fibre measurements are available, the “indicator-tool” has been developed that uses three different types of indicators to detect a possible thermal bottleneck location. Relative values of the properties of the environment can be derived from the glass fibre measurements, to characterize a thermal model of the critical bottleneck location. If more data is needed, a thorough route survey on the indicated positions is necessary.

A study towards available literature on the subject showed confusion on the definitions of a “hot spot” and a “thermal bottleneck”. The difference between those terms is explained and it is illustrated with measurement data using the wrong definition may lead to an incorrect selection of the critical location. The developed “indicator-tool” takes appropriate care and therefore usage of this prevents making the wrong choices.

Glass fibre measurements are used to gain knowledge about possible bottleneck locations. A database is created to store this information. This database will be used to find the critical thermal bottleneck if glass fibre measurement are not available.

If glass fibre measurements are not available, knowledge from the database in combination with a route survey has to be used to identify possible bottleneck locations along the cable route. The “ranking-tool” has been developed to model and rank the influence of the possible thermal bottlenecks. A thorough route survey is used to determine the property values of the environment, which are needed to characterize the critical thermal bottleneck location.
Sixteen typical possible bottlenecks have been described and implemented in the ranking-tool. Assumptions are made on their property values (or value ranges). These bottlenecks are modelled using seven typical cable systems. A ranking of those bottlenecks is obtained. It is shown that the cable system actually has little influence on the ranking of the bottlenecks, except for cables with a low maximum allowable temperature or in case of cables with high dielectric losses.

The goal of this study is reached for cables where glass fibre measurements are possible. For cables without glass fibre, the goal is reached for stationary ampacity calculations according to the IEC 60287.

### 7.2 Recommendations

This study is based on the stationary ampacity calculations as given in IEC 60287. It is recommended to perform dynamic calculations as given in IEC 60853 and if necessary, calculation methods should be added to the tools. Dynamic calculations will incorporate thermal capacitances, which will take into account the response of a cable on load variations. This might influence the position of the critical thermal bottleneck location. With a dynamic approach a circuit might even be limited by multiple positions, each with their own dynamic behaviour. It is however expected the location of the critical thermal bottleneck will not change if dynamic calculations are implemented.

Each instance when new knowledge about a possible bottleneck is obtained, this information should be added to the database (chapter 5) to extend and improve the bottleneck ranking for future bottleneck identification in the absence of temperature measurements.

It is recommended to use a guide for route surveys, and extend the list of questions of Appendix C with e.g. the parameters values needed to model each type of bottleneck, when they are needed and the way they can be obtained. It is further recommended to pay special attention to how the surroundings of a cable may be returned in the original condition after it is disturbed (for e.g. for soil sampling or for the installation of a thermocouple).

It is recommended to improve the developed tools:
- The "Model of the temperature-influence on the cable-surrounding soil" (curve-fitting, see section 4.3.4) indicator of the indicator-tool can now only generate modelled temperature profiles for changing values of the relative thermal resistivity and relative thermal conductivity. It should be modified in order to take changes in the ambient temperature into account.
- It is recommended to improve the calculation methods for parallel cables. The influence of parallel cables can now only be calculated if they are all at the same laying depth. If multiple laying depths are possible, worst-case calculations are also possible for cable-crossings. The influence of magnetic field between parallel circuits is also neglected in this study. It is recommended to implement calculation methods for the losses caused by the influence of magnetic fields, in order to take their influence on the ampacity into account (these influences can be relatively large for both ends bonded systems).

- Calculation possibilities for cables in air, tunnels, and other environments are not incorporated in the ranking-tool yet. To extend the usability of the ranking-tool, it is recommended to implement these calculation methods.

- The tools developed in this study are all programmed in Maple and are therefore relatively user-unfriendly. To increase usability of the tools, a user interface, or at least a clear user manual, should be made.

This study focuses on the detection of the critical thermal bottleneck location and its properties, in order to derive a model based on the thermal behaviour of that critical thermal bottleneck. This model is subsequently used to implement a dynamic rating system. Literature shows methods to improve the thermal behaviour of bottleneck locations (e.g. by replacing the soil around the cable by soil with better thermal properties, or by implementing cooling systems), which can be used to migrate the critical thermal bottleneck location. A study towards these methods will be interesting for KEMA since implementation of these methods in a combination with a dynamic rating system might yield even more gain in the dynamic loading capability of a cable circuit.
8 References

[1] International Electrotechnical Commission
ELECTRIC CABLES – CALCULATION OF THE CYCLIC AND EMERGENCY CURRENT RATING OF CABLES – PART I&II&III
IEC Publication 60853, Geneva, Switzerland, 1985

[2] International Electrotechnical Commission
ELECTRIC CABLES – CALCULATION OF THE CURRENT RATING – PART I&II&III
IEC Publication 60287, Geneva, Switzerland, 1994

DISTRIBUTED FIBRE-OPTIC TEMPERATURE SENSORS: TECHNOLOGY AND APPLICATIONS IN THE POWER INDUSTRY

RATING OF ELECTRIC POWER CABLES: AMPACITY COMPUTATIONS FOR TRANSMISSION, DISTRIBUTION, AND INDUSTRIAL APPLICATIONS

CABLE CROSSINGS – DERATING CONSIDERATIONS. II. EXAMPLE OF DERIVATION OF DERATIONG CURVES

CABLE CROSSINGS – DERATING CONSIDERATIONS. II. EXAMPLE OF DERIVATION OF DERATIONG CURVES

INCREASING CABLE RATING BY DISTRIBUTED FIBER OPTIC TEMPERATURE MONITORING AND AMPACITY ANALYSIS

[8] Nokes, G.
OPTIMISING POWER TRANSMISSION AND DISTRIBUTION NETWORKS USING OPTICAL FIBRE DISTRIBUTED TEMPERATURE SENSING SYSTEMS
IEE Seminar on Asset Management of Cable Systems, pp. 4/1-4/9, 1999
REFERENCES

AANPAKKEN VAN BOTTLENECKS IN KABELVERBINDINGEN:
ONMISBAAR BIJ IMPLEMENTATIE VAN DYNAMISCH NETBEHEER
Final Report PREGO 22, KEMA-reference: 70443008-TDT 04-47671A,
KEMA Arnhem, The Netherlands, 2004

[10] Anders, G.J.
RATING OF ELECTRIC POWER CABLES IN UNFAVORABLE
THERMAL ENVIRONMENT
ISBN 0-471-67909-7

HOTSPOT LOCATION AND MITIGATION FOR UNDERGROUND
POWER CABLES
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ASSESSMENT OF UNDERGROUND CABLE RATINGS BASED ON
DISTRIBUTED TEMPERATURE SENSING
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2006
Appendix A  Properties of modelled cable systems

In the Maple program written as "ranking-tool" the following 7 cable systems are defined:
- "PILC, 10kV, 3-core cable, single end or both ends bonded"
- "KUDIKA, 10kV, 3-core cable, both ends bonded"
- "XLPE, 20kV, in trefoil, both ends bonded"
- "XLPE, 150kV, in flat plane, crossbonded"
- "XLPE, 380kV, in flat plane, crossbonded"
- "SCFF, 150kV, in flat plane, single end bonded"
- "SCFF, 150kV, in flat plane, both ends bonded"

The parameter values used for the cable systems are available in the program that is delivered to KEMA. The calculation methods and the IEC 60287 sections that are used are presented in this chapter. For the "XLPE, 150kV, in flat plane, crossbonded" system, the parameter values used and equations are presented as an example.

A.1 Global parameter values

The Maple program uses "reference" values for parameters of environment and laying depth if nothing is adjusted for bottleneck calculation. The following properties and their "reference" values are used for all cable systems:

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laying depth</td>
<td>$L$</td>
<td>1</td>
<td>m</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>$\theta_e$</td>
<td>15</td>
<td>°C</td>
</tr>
<tr>
<td>Thermal resistivity of surrounding soil in a &quot;uniform&quot; situation</td>
<td>$\rho_{T4,\text{uniform}}$</td>
<td>1</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of &quot;wet&quot; soil in a &quot;drying out of soil&quot; situation</td>
<td>$\rho_{T4,\text{drying}<em>\text{-out}</em>\text{-wet}}$</td>
<td>1</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of &quot;dry&quot; soil in a &quot;drying out of soil&quot; situation</td>
<td>$\rho_{T4,\text{drying}<em>\text{-out}</em>\text{-dry}}$</td>
<td>2.5</td>
<td>Km/W</td>
</tr>
<tr>
<td>Critical temperature in a &quot;drying out of soil&quot; situation</td>
<td>$\theta_{\text{drying}_\text{-out}}$</td>
<td>30</td>
<td>°C</td>
</tr>
<tr>
<td>Thermal resistivity of surrounding soil in a &quot;parallel cables&quot; situation</td>
<td>$\rho_{T4,\text{parallel}_\text{-cables}}$</td>
<td>1</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the filling material of the pipe in a &quot;pipe&quot; situation</td>
<td>$\rho_{T4,\text{pipe}_\text{-filling}}$</td>
<td>0.5</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the pipe material in a &quot;pipe&quot; situation</td>
<td>$\rho_{T4,\text{pipe}_\text{-material}}$</td>
<td>6</td>
<td>Km/W</td>
</tr>
<tr>
<td>Thermal resistivity of the soil surrounding the pipe in a &quot;pipe&quot; situation</td>
<td>$\rho_{T4,\text{pipe}_\text{-outside}}$</td>
<td>1</td>
<td>Km/W</td>
</tr>
<tr>
<td>Multiplying factor for the inner pipe diameter compared to the cable diameter in a &quot;pipe&quot; situation</td>
<td>$F_{\text{pipe}}$</td>
<td>1.6</td>
<td></td>
</tr>
</tbody>
</table>
### A.2 Cable parameter values

For the "XLPE, 150kV, in flat plane, crossbonded" system, the property values used are:

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor material</td>
<td></td>
<td>Aluminium, solid</td>
<td></td>
</tr>
<tr>
<td>Insulation material</td>
<td></td>
<td>XLPE</td>
<td></td>
</tr>
<tr>
<td>Earthing sheath material</td>
<td></td>
<td>Lead</td>
<td></td>
</tr>
<tr>
<td>Outer cover material</td>
<td></td>
<td>HDPE</td>
<td></td>
</tr>
<tr>
<td>Voltage to earth</td>
<td>$U_0$</td>
<td>150000/√3</td>
<td>V</td>
</tr>
<tr>
<td>Operating frequency</td>
<td>$f$</td>
<td>50</td>
<td>Hz</td>
</tr>
<tr>
<td>Maximum allowable conductor temperature</td>
<td>$\theta_{c,max}$</td>
<td>90</td>
<td>°C</td>
</tr>
<tr>
<td>Axial separation between two adjacent cables</td>
<td>$s$</td>
<td>0.150</td>
<td>m</td>
</tr>
<tr>
<td>Number of conductors per cable</td>
<td>$n$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Cross-sectional area of conductor</td>
<td>$A_c$</td>
<td>0.0012 m⁴</td>
<td></td>
</tr>
<tr>
<td>Diameter of the conductor</td>
<td>$d_c$</td>
<td>0.0391 m</td>
<td></td>
</tr>
<tr>
<td>Electrical DC resistivity of conductor material at 20°C</td>
<td>$\rho_{E,c,20}$</td>
<td>2.48x10⁻⁸</td>
<td>Ωm</td>
</tr>
<tr>
<td>Constant mass temperature coefficient at 20°C of conductor material</td>
<td>$\alpha_{c,20}$</td>
<td>4.03x10⁻³</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>Thickness of the insulation layer</td>
<td>$t_i$</td>
<td>0.0228</td>
<td>m</td>
</tr>
<tr>
<td>Thermal resistivity of the insulation layer</td>
<td>$\rho_{T1}$</td>
<td>3.5</td>
<td>Km/W</td>
</tr>
<tr>
<td>External diameter of the insulation (excluding screen)</td>
<td>$D_i$</td>
<td>0.0764</td>
<td>m</td>
</tr>
<tr>
<td>Thickness of sheath</td>
<td>$t_s$</td>
<td>0.0027</td>
<td>m</td>
</tr>
<tr>
<td>Electrical resistivity of sheath material at 20°C</td>
<td>$\rho_{E,s,20}$</td>
<td>21.4x10⁻⁸</td>
<td>Ωm</td>
</tr>
<tr>
<td>Cross-sectional area of sheath</td>
<td>$A_s$</td>
<td>0.00178</td>
<td>m²</td>
</tr>
<tr>
<td>Average diameter of sheath</td>
<td>$D_{s,avg}$</td>
<td>0.0873</td>
<td>m</td>
</tr>
<tr>
<td>Constant mass temperature coefficient at 20°C of sheath material</td>
<td>$\alpha_{s,20}$</td>
<td>4x10⁻³</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>Ext. diameter of the layer directly under the outer cover / external diameter of sheath</td>
<td>$D_a$</td>
<td>0.090</td>
<td>m</td>
</tr>
</tbody>
</table>
PROPERTIES OF MODELLED CABLE SYSTEMS

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness of the outer covering</td>
<td>$t_3$</td>
<td>0.0045 m</td>
</tr>
<tr>
<td>Thermal resistivity of outer covering material</td>
<td>$\rho_{T3}$</td>
<td>3.5 Km/W</td>
</tr>
<tr>
<td>Ext. diameter of the cable</td>
<td>$D_e$</td>
<td>0.099 m</td>
</tr>
<tr>
<td>Proximity effect factor conductor</td>
<td>$k_p$</td>
<td>0.8</td>
</tr>
<tr>
<td>Skin effect factor conductor</td>
<td>$k_s$</td>
<td>1</td>
</tr>
<tr>
<td>Loss factor insulation</td>
<td>$\tan\delta$</td>
<td>0.001</td>
</tr>
<tr>
<td>Relative permittivity of the insulation</td>
<td>$\varepsilon$</td>
<td>2.5</td>
</tr>
<tr>
<td>Bonding arrangement</td>
<td>Crossbonded</td>
<td></td>
</tr>
</tbody>
</table>

A.3 Calculation of $T_1$

The cables in the “XLPE, 150kV, in flat plane, crossbonded” system are single core cables. The calculation method for $T_1$ is then given in IEC 60287-2-1 §2.1.1.1:

$$T_1 = \frac{\rho_{T1}}{2\pi} \ln \left[ 1 + \frac{2t_1}{D_e} \right]$$

The cable systems “XLPE, 20kV, in trefoil, both ends bonded”, “XLPE, 150kV, in flat plane, crossbonded”, “XLPE, 380kV, in flat plane, crossbonded”, “SCFF, 150kV, in flat plane, single end bonded” and “SCFF, 150kV, in flat plane, both ends bonded” also use single core cables and use the above equation.

The systems “PILC, 10kV, 3-core cable, single end or both ends bonded” and “KUDIKA, 10kV, 3-core cable, both ends bonded” are multicore cables and calculations methods for those cables are given in IEC 60287-2-1 §2.1.1.2.

A difference is made between the shapes of the conductors.

The cable in the “PILC, 10kV, 3-core cable, single end or both ends bonded” system has sector shaped conductors and the calculation method in that case is given in IEC 60287-2-1 §2.1.1.2.5.

The cable in the “KUDIKA, 10kV, 3-core cable, both ends bonded” system has circular conductors and the calculation method is then given in IEC 60287-2-1 §2.1.1.2.3.

For the calculation of $T_1$, the semiconducting screens around the conductor(s) and insulation are included in $t_1$. In a thermal sense, the semiconducting screens therefore are grouped together with the insulation material.

A.4 Calculation of $T_2$
In all cables in the cable systems, except for the cable in the “PILC, 10kV, 3-core cable, single end or both ends bonded” no armour is present. Therefore no bedding is present, so that the thermal resistance of the bedding is equal to zero:

\[ T_2 = 0 \]

For the cable in the “PILC, 10kV, 3-core cable, single end or both ends bonded” system, which has an armour and therefore a bedding present, calculation methods for \( T_2 \) are given in IEC 60287-2-1 §2.1.2.1.

**A.5 Calculation of \( T_3 \)**

The equation to calculate the thermal resistance of the outer cover is of a cable is given in IEC 60287-2-1 §2.1.3:

\[
T_3 = \frac{\rho T_3}{2\pi} \ln \left[ \frac{2T_3}{D_a} \right]
\]

If cables are in a trefoil formation, as is the case in the “XLPE, 20kV, in trefoil, both ends bonded”, system, IEC 60287-2-1 §2.1.4.3.1 gives a multiplication factor for this thermal resistance.

**A.6 Calculation of \( T_4 \)**

**A.6.1 Calculation of \( T_4 \) in uniform environment**

For cable systems with three cables installed in a “flat plane” with approximately equal losses, an effective \( T_4 \) is calculated for the centre cable of the system. The ampacity will be calculated for this centre cable, since it will have the highest temperature. This calculation method is explained in IEC 60287-2-1 §2.2.3.2.2. The equation, used for, “XLPE, 380kV, in flat plane, crossbonded”, “SCFF, 150kV, in flat plane, single end bonded” and “SCFF, 150kV, in flat plane, both ends bonded” systems is given as:

\[
T_{4,\text{uniform}} = \frac{\rho T_{4,\text{uniform}}}{2\pi} \left( \ln \left[ \frac{2L}{D_e} + \sqrt{\frac{2L}{D_e}} \right] - 1 \right) + \ln \left[ \frac{1}{s} \left( \frac{2L}{s} \right)^2 \right]
\]

For a cable system with a single multicore cable as present in the “PILC, 10kV, 3-core cable, single end or both ends bonded” and “KUDIKA, 10kV, 3-core cable, both ends bonded” systems, calculation methods for the thermal resistance of the environment are given in IEC 60287-2-1 §2.2.2.

For the “XLPE, 20kV, in trefoil, both ends bonded” system, which has three cables installed in a trefoil formation, the calculation method for \( T_4 \) is given in IEC 60287-2-1 §2.2.4.3.1.

**A.6.2 Calculation of \( T_4 \) when “drying out of soil” is present**
Although the environment is varying from “uniform” in this situation, the calculation method for $T_4$ is similar to the “uniform” situation. This is explained in IEC 60287-1-1 §1.4.2. The thermal resistance of the environment will be calculated with the thermal resistivity of the soil outside the dried out zone. The dried out zone will be taken into account in the central equation of the IEC 60287. This is explained in section 5.3.3. Therefore, equations are the same as for the “uniform” situation, for the “XLPE, 150kV, in flat plane, crossbonded” it will thus be:

\[
T_{4,\text{drying out}} = \frac{\rho_{T4,\text{drying out wet}}}{2\pi} \left( \ln \left[ \frac{2L}{D_e} + \sqrt{\left( \frac{2L}{D_e} \right)^2 - 1} \right] + \ln \left[ 1 + \left( \frac{2L}{s} \right)^2 \right] \right)
\]

A.6.3 Calculation of $T_4$ for cables installed in pipes

The calculation method for cables in pipes is explained in IEC 60287-2-1 §2.2.7. $T_4$ is the summation of three parts:

\[
T_{4,\text{pipe}} = T_{4,\text{pipe}}^\prime + T_{4,\text{pipe}}^\prime\prime + T_{4,\text{pipe}}^\prime\prime\prime
\]

Where:

$T_{4,\text{pipe}}^\prime$ represents the thermal resistance of the material between the cable and the pipe,

$T_{4,\text{pipe}}^\prime\prime$ represents the thermal resistance of the pipe itself,

$T_{4,\text{pipe}}^\prime\prime\prime$ represents the thermal resistivity of the soil surrounding the pipe.

For the calculation of $T_{4,\text{pipe}}^\prime$, IEC 60287-2-1 §2.2.7.1 gives calculation methods. However, these calculation methods use predefined factors (to incorporate e.g. convection, radiation and the laying position of the cable in the pipe) for only a number of situations. To calculate a value for the situations in this study it is assumed the cable is positioned in the centre of the pipe, and assumptions are made on the thermal resistivity of the pipe filling to take the effect of convection into account. In this study, $T_{4,\text{pipe}}^\prime$ is calculated with the equations of IEC 60287-2-1 §2.2.7.2:

\[
D_{\text{pipe outside}} = F_{\text{pipe}} D_e + 2t_{\text{pipe}}
\]

\[
D_{\text{pipe inside}} = F_{\text{pipe}} D_e
\]

\[
T_{4,\text{pipe}}^\prime = \frac{\rho_{T4,\text{pipe filling}}}{2\pi} \ln \left[ \frac{D_{\text{pipe inside}}}{D_e} \right]
\]

Previous mentioned equations are for valid if there is only one cable per pipe (thus for the systems: “PILC, 10kV, 3-core cable, single end or both ends bonded” and “KUDIKA, 10kV, 3-core cable, both ends bonded”, “XLPE, 150kV, in flat plane, crossbonded”)

METHODOLOGY AND TOOLS TO IDENTIFY THE WEAKEST LINK 77
The "XLPE, 20kV, in trefoil, both ends bonded" system is assumed to be installed with all three cables in one single pipe. An extra multiplication factor (value 2.15) is used in this situation. This is explained in IEC 60287-2-1 §2.2.7.1.

The calculation of the thermal resistance of the pipe itself is explained in IEC 60287-2-1 §2.2.7.2. It uses the thermal resistivity of the pipe material. For all cable systems the used equation is:

\[
T_{4,\text{pipe}} = \frac{\rho_{T4,\text{pipe,material}}}{2\pi} \ln \left[ \frac{D_{\text{pipe, outside}}}{D_{\text{pipe, inside}}} \right]
\]

The calculation of the thermal resistance of the soil surrounding the pipe, \( T_{4,\text{pipe}} \), is similar to the calculation of the thermal resistance of the environment in a "uniform" situation, but with the outer diameter of the pipe instead of the outer diameter of the cable. For the "XLPE, 380kV, in flat plane, crossbonded", "SCFF, 150kV, in flat plane, single end bonded" and "SCFF, 150kV, in flat plane, both ends bonded" systems this will be (according to IEC 60287-2-1 §2.2.7.3):

\[
T_{4,\text{pipe}} = \frac{\rho_{T4,\text{pipe, outside}}}{2\pi} \left( \ln \left[ \frac{2L}{D_{\text{pipe, outside}}} + \sqrt{\left( \frac{2L}{D_{\text{pipe, outside}}} \right)^2 - 1} \right] + \ln \left[ 1 + \left( \frac{2L}{s} \right)^2 \right] \right)
\]

For the systems "PILC, 10kV, 3-core cable, single end or both ends bonded", "KUDIKA, 10kV, 3-core cable, both ends bonded" and "XLPE, 20kV, in trefoil, both ends bonded" the equations for a single cable (with instead of the cable diameter the outer diameter of the pipe) is used according to IEC 60287-2-1 §2.2.2.
A.6.4 Calculation of $T_4$ when there are other cables in parallel

If a situation with parallel cables is observed, the centre cable of the system (with three cables) under consideration will not necessarily be the hottest. Therefore all cables of the circuit under consideration and the cables of the parallel circuits are considered separately. The thermal resistance of the environment for single cables is therefore used in these situations. For all cable systems, IEC 60287-2-1 §2.2.2 is used:

$$T_{4,\text{parallel\_cables}} = \frac{\rho_{T_4,\text{parallel\_cables}}}{2\pi \ln \left( \frac{2L}{D_c} + \sqrt{\left( \frac{2L}{D_c} \right)^2 - 1} \right)}$$

No correction factors are used for the influence of cables on the thermal resistivity of the ground.

A.7 Calculation of $R_{ac}$

The electrical DC resistance of the conductor of a certain cable at $20^\circ$C is calculated with:

$$R_{DC,c,20} = \frac{\rho_{E,c,20}}{A_c}$$

With the equation given in IEC 60287-1-1 §2.1.1 the DC resistance for other temperatures is calculated:

$$R_{DC,c,\theta} = R_{DC,c,20} \left( 1 + \alpha_{c,20} (\theta - 20) \right)$$

The AC resistance of a conductor also includes the skin effects and the proximity effects. The proximity effect (for all cable systems) is calculated with IEC 60287-1-1 §2.1.4.1:

$$x_p^2 = \frac{8\pi}{R_{DC,c,\theta}} 10^{-7} k_p$$

$$\gamma_p = \frac{x_p^4}{192 + 0.8x_p^4} \left( \frac{d_c}{s} \right)^2 \left[ 0.312 \left( \frac{d_c}{s} \right)^2 + \frac{1.18}{x_p^4} \frac{\left( \frac{d_c}{s} \right)^2}{192 + 0.8x_p^4 + 0.27} \right]$$

For sector shaped conductors, as are present in the “PILC, 10kV, 3-core cable, single end or both ends bonded” system, calculation for $\gamma_p$ is adjusted according to IEC 60287-1-1 §2.1.4.2.
The skin effect uses (for all cable systems) the calculation methods of IEC 60287-1-1 §2.1.2:

\[ x_s^2 = \frac{8\pi f}{R_{DC,c,\theta_s}} \times 10^{-2} k_s \]

\[ \gamma_s = \frac{x_s^4}{192 + 0.8x_s^4} \]

Finally, the AC resistance of the conductor at a certain temperature is calculated with IEC 60287-1-1 §2.1:

\[ R_{AC,c,\theta} = R_{DC,c,\theta} \left[ 1 + \gamma_s + \gamma_p \right] \]

A.8 Calculation of \( W_d \)

Dielectric losses are only taken into account if the value for \( U_0 \) is larger than 35kV. This is the case for the “XLPE, 150kV, in flat plane, crossbonded”, “XLPE, 380kV, in flat plane, crossbonded”, “SCFF, 150kV, in flat plane, single end bonded” and “SCFF, 150kV, in flat plane, both ends bonded” systems. For those systems the calculation of the dielectric losses in a cable is explained in IEC 60287-1-1 §2.2:

\[ C = \frac{\varepsilon}{18 \ln \left( \frac{D_i}{d_c} \right)} \times 10^{-9} \]

In an electrical sense, the semiconducting layers are not part of the cable capacity. \( D_i \) in this case is therefore the diameter across the insulation underneath the insulation screen. This differs from the calculation of \( T_i \) where the thickness of the semiconducting layers is included in \( t_j \).

The dielectric losses are then calculated with (IEC 60287-1-1 §2.2):

\[ W_d = 2\pi C U_0^2 (\tan \delta) \]

A.9 Calculation of \( \lambda_1 \)

In the “XLPE, 150kV, in flat plane, crossbonded” system, the earthing sheaths in the cable are crossbonded. This means there are no circulating currents in the earthing sheath. The sheath losses are therefore entirely determined by the eddy currents in the lead sheath. The losses for the centre cable are the largest, and these are calculated with IEC 60287-1-1 §2.3.6.1:

\[ R_{AC,c,\theta} = \frac{\rho_{E,s,20}}{A_s} \left[ 1 + \alpha_{s,20} (\theta_s - 20) \right] \]
\[ \omega = 2\pi f \]

\[ \beta_1 = \sqrt{\frac{4\pi \omega}{10^7 \rho_{E,s,20}}} \]

\[ g_s = 1 + \left( \frac{t_s}{D_a} \right)^{1.74} (\beta_1 D_a - 1.6) \]

\[ m = \frac{\omega}{R_{AC,s,\theta_i}} 10^{-7} \]

\[ \lambda_0 = 6 \frac{m^2}{1 + m^2} \left( \frac{D_{s,avg}}{2s} \right)^2 \]

\[ \Delta_1 = 0.86m^{0.08} \left( \frac{D_{s,avg}}{2s} \right)^{(1.4m+0.7)} \]

\[ \Delta_2 = 0 \]

\[ \lambda_1 = \frac{R_{AC,s,\theta_i}}{R_{AC,c,\theta_i}} \left[ g_s \lambda_{0,c} \left( 1 + \Delta_{l,c} + \Delta_{z,c} \right) + \frac{(\beta_1 t_s)^2}{12} \right] \]

The AC resistance of the earthing sheath depends on its temperature, but to calculate the temperature of the earthing sheath, the sheath losses have to be known. Iterative calculation is used to solve this problem.

As shown for the “XLPE, 150kV, in flat plane, crossbonded” system, the calculation method for \( \lambda_1 \) is rather complex and lengthy. The paragraphs used for the other systems are:

For the “PILC, 10kV, 3-core cable, single end or both ends bonded” system, IEC 60287-1-1 §2.3.8 and §2.3.3 are used.
For the “KUDIKA, 10kV, 3-core cable, both ends bonded” system, IEC 60287-1-1 §2.3.8 is used.
The “XLPE, 20kV, in trefoil, both ends bonded” system uses the equations presented in IEC 60287-1-1 §2.3.1.
The “XLPE, 380kV, in flat plane, crossbonded” and “SCFF, 150kV, in flat plane, single end bonded” systems use the same calculation methods as the “XLPE, 150kV, in flat plane, crossbonded” system, which is presented above.
For the “SCFF, 150kV, in flat plane, both ends bonded” system, IEC 60287-1-1 §2.3.3 is used.

**A.10 Calculation of \( \lambda_2 \)**
All presented cable systems, except the "PILC, 10kV, 3-core cable, single end or both ends bonded" system, have no armour. Therefore:

\[ \lambda_2 = 0 \]

For the "PILC, 10kV, 3-core cable, single end or both ends bonded" system, IEC 60287-1-1 §2.4.2.4 is used to calculate \( \lambda_2 \).

**A.11 Final ampacity calculation**

With the calculation methods explained in the sections above, the ampacity of the systems is calculated for various environmental geometries.

**A.11.1 Calculation of ampacity in uniform environment**

For calculation of the ampacity of a circuit, the central equation of the IEC 60287 is used. This equation, which is used for all cable systems, is introduced in IEC 60287-1-1 §1.4.1.1:

\[
I_{\text{uniform}} = \left[ \frac{(\theta_c - \theta_e) - W_d \left[ 0.5T_1 + n(T_2 + T_3 + T_{\text{uniform}}) \right]}{R_{uc}[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + T_{\text{uniform}})]} \right]^{0.5}
\]

\( \theta_{c,\text{max}} \) is used as value for \( \theta_c \) (also in the calculation of \( R_{AC,c,\theta} \)) is used as value for \( \theta_c \) to calculate the ampacity of a system.

**A.11.2 Calculation of ampacity when "drying out of soil" is present**

Changes in the external thermal resistance, consequent to the formation of a dry zone around a cable or circuit are taken into account in the central formula of the IEC 60287. A more detailed explanation can be found in IEC 60287-1-1 §1.4.2.1

\[
v = \frac{\rho_{T_4,drying\_out\_dry}}{\rho_{T_4,drying\_out\_wet}}
\]

\[
I_{\text{drying\_out}} = \left[ \frac{(\theta_c - \theta_e) - W_d \left[ 0.5T_1 + n(T_2 + T_3 + v T_{\text{drying\_out}}) \right]}{R_{uc}[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + v T_{\text{drying\_out}})]} \right]^{0.5}
\]

Again, \( \theta_{c,\text{max}} \) is used as value for \( \theta_c \) (also in the calculation of \( R_{AC,c,\theta} \)) to calculate the ampacity of a system. The critical temperature for the soil to dry out is represented by \( \theta_{\text{drying\_out}} \). The isotherm for \( \theta_{\text{drying\_out}} \) should be outside the cable. If the isotherm for \( \theta_{\text{drying\_out}} \) is within the cable, the ampacity is calculated with \( v = 1 \).

**A.11.3 Calculation of ampacity for cables installed in pipes**
Calculation of the ampacity of a system installed in a pipe or in pipes is calculated with the same equation as cables installed in a “uniform” environment, only now the $T_4$ calculated for the system in a “pipe”. For all systems IEC 60287-1-1 §1.4.1.1 is used:

$$I_{\text{pipe}} = \left[ \frac{(\theta_e - \theta_c) - W_d \left[ 0.5T_1 + n(T_2 + T_3 + T_{4,\text{pipe}}) \right]}{R_{ac} \left[ T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + T_{4,\text{pipe}}) \right]} \right]^{0.5}$$

$\theta_{c,\text{max}}$ is used as value for $\theta_c$ (also in the calculation of $R_{AC,c,\theta_e}$) to calculate the ampacity of a system.

### A.11.4 Calculation of ampacity when there are other cables in parallel

To calculate the ampacity of the circuit under consideration in case of parallel cables, a “start” ampacity is estimated and the resulting conductor temperatures are calculated.

First the total heat losses per cable with the given load per cable are calculated with:

$$W_{\text{total},k} = n_k \left( W_{d,k} + I_k^2 R_{AC,c,\theta_e,k} \left[ 1 + \lambda_{1,k} + \lambda_{2,k} \right] \right)$$

Where $n_k$ is the number of conductors in the cable $k$.

Then the methodology described in IEC 60287-2-1 §2.2.3.1 is used to calculate the increase in ambient temperature around cable $p$ caused by cable $k$:

$$\Delta \theta_{e,kp} = \frac{\rho T_{4,\text{parallel cables}}}{2\pi} W_k \ln \left( \frac{d_{pk}}{d_{pk}} \right)$$

This is done for every cable and ‘new’ ambient temperature around every cable can be calculated, taking the influence of the other cables into account.

Finally, the resulting conductor temperature per cable is calculated with:

$$\theta_{c,k} = \left[ \theta_{e,\text{new},k} + W_{d,k} \left[ 0.5T_{1,k} + n_k \left( T_{2,k} + T_{3,k} + T_{4,\text{parallel cables},k} \right) \right] \right]$$

$$+ I_k^2 R_{AC,c,\theta_e,k} \left[ T_{1,k} + n_k \left( \left( 1 + \lambda_{1,k} \right) T_{2,k} + \left( 1 + \lambda_{1,k} + \lambda_{2,k} \right) (T_{3,k} + T_{4,\text{parallel cables},k}) \right) \right]$$

If the hottest cable of the circuit under consideration is lower then the maximum allowable temperature, the “start” ampacity is increased and calculations are repeated. Likewise, if the hottest cable temperature of the circuit under consideration exceeds the maximum allowable temperature, the “start” ampacity is decreased and calculations are repeated. The “start” ampacity is adjusted until the hottest cable of the...
circuit under consideration is very close (difference < 0.1°C) to the maximum allowable conductor temperature. This usually takes 5 to 10 iterations.

In this calculation method for parallel cables is assumed the influence of magnetic fields between cables of different cable systems can be neglected. \( \lambda_1 \) and \( \lambda_2 \) are only calculated per cable system.

The calculation method is only implemented for cables installed at the same laying depth. A start is made to make calculations for cables at different laying depths possible, but these are not yet to be trusted.
Appendix B  Zone definition route Gistrup-Skudshale

<table>
<thead>
<tr>
<th>Zone No.</th>
<th>From pos.</th>
<th>To pos.</th>
<th>Distance</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>1</td>
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<td>To 400 kV cable</td>
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<td>365</td>
<td>474</td>
<td>109</td>
<td>Directional drilling (road crossing)</td>
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<td>493</td>
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</tr>
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<td>967</td>
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<td>60</td>
<td>Pipe (coming road)</td>
</tr>
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<td>1027</td>
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</tr>
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<td>120</td>
<td>Directional drilling (road crossing)</td>
</tr>
<tr>
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</tr>
<tr>
<td>9</td>
<td>1392</td>
<td>1451</td>
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<td>Directional drilling (sewer pipe crossing)</td>
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<td>1683</td>
<td>10</td>
<td>Pipe (oil pipe crossing)</td>
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<td>571</td>
<td>Chalk hill (Kongshøj)</td>
</tr>
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<td>Fibre-optic cables splice box</td>
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<td>494</td>
<td>Chalk hill (Kongshøj)</td>
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<td>Directional drilling (crossing with water pipes)</td>
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<td>7186</td>
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<td>To 400 kV cable termination</td>
</tr>
</tbody>
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*Table B-1,*
Zone definition route Gistrup-Skudshale, Energinet DK

METHODOLOGY AND TOOLS TO IDENTIFY THE WEAKEST LINK 85
Appendix C List of properties for a route survey

A route survey starts with the gathering of as much information as possible. This list gives a good description of the properties of which information should be known in order to select the critical thermal bottleneck. A distinction is made between properties of the cable itself, properties of the cable system, properties of the environment of the system and operational management of the cable.

C.1.1 Properties of the cable
- Cable specifications:
  o Manufacturer
  o Cable type
  o Cable design (drawing with sizes of the layers present in the cable)
  o Used materials

C.1.2 Properties of the cable system
- Position of the cable circuit in the ENECO network. This position can be indicated on a map of the network
- Maps
  o Global map of the cable route
  o Detailed maps of the cable route
- Details of laying conditions along the cable route:
  o Laying depth
  o Installation methods
- Drawings
  o Vertical cross-section of cable route
  o Original “as build” drawings
  o Drawings of changes made in the cable route
  o Drawings of the present cable route
  o Longitudinal profile of the cable route
- Pictures
  o Pictures of the installation of the circuit
- Materials
  o Specification of joints and cable terminations
- Bonding arrangements
  o Single end or both ends bonded
  o Crossbonding
- Ampacity calculations
  o Ampacity calculations as performed by the manufacturer or ENECO for the original cable connection
  o Ampacity calculations as performed by the manufacturer, ENECO or a third party after changes were made to the cable connection
- Measuring possibilities
  o Possible presence of thermocouples
  o Possible presence of glass fibres available for temperature measurements
- Reports
  o If available: reports of performed temperature measurements
C.1.3 Properties of the environment of the system

- Thermal properties
  - Thermal properties of the soil and/or backfill material along the cable route
  - If measured: thermal resistivities of the soil
  - If measured: ambient ground temperature
  - Reports of performed soil surveys
- Other infrastructure
  - Presence of parallel or crossing cable circuits
  - Presence of other infrastructures in the neighborhood of the cable (oil pipes, city heating, sewers, etc.)
- Presence of trees within a distance of 4 metres of the cable route
  - Willows
  - Poplars
  - Alders
- Level of underground water
  - Measured levels of underground water
  - Possible decreased level caused by well pointing (construction site)
- Man made artefacts
  - Directional drillings
  - Cables in pipes
  - Dike crossings
  - Road crossings
  - Crossing with slip roads
  - Crossing with water

C.1.4 Operational management of the cable

- Load flows through the circuit
  - History of load flows
  - Present load flow
  - Expected load flow / expected increase in load flow
- Presence of higher harmonic current components
- Operation voltage
- Cos $\phi$ of the load
- Ampacity limiting factors (e.g. other components than the cable itself)
- Record of cable failures and their reports
- State/condition of the components
  - State/condition of the cables
  - State/condition of the joints
  - State/condition of the cable terminations