EVALUATING IMPACT ON AMPACITY
ACCORDING TO IEC-60287
REGARDING THERMALLY
UNFAVOURABLE PLACEMENT OF
POWER CABLES

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Preface
This master thesis report completes my graduation as a Master of Science in Electrical Engineering at the Royal Institute of Technology (KTH) in Stockholm. It has been a great experience to meet and cooperate with open minded and interesting people within the industry of electrical engineering and at KTH.

Foremost I would like to thank my supervisors at Statkraft and KTH. M.Sc. Kjell Gustafsson at Statkraft and Assoc. Prof. Hans Edin at KTH department Electromagnetic Engineering who has provided suggestions when I have been uncertain.

I would also especially like to thank Christer Liljegren who made it possible to perform important thermal experiments in Mönsterås in Småland. Mikael Karlsson deserves true recognition for his extraordinary skills with a backhoe loader. I would like to thank my girlfriend Fanny Thomsen and my friends Ivan Löfgren and Petri Paananen for their support.

Thank you!

Stockholm, Reimersholme, November 2011

Ludvig Lindström
According to International Electrotechnical Commission’s standard document IEC-60287 the current carrying capabilities of power cables can be mathematically modelled. Current rating of power cables can hence be done without having to perform expensive and timely experiments. This allows different techniques in power cable utilizing and placement to be compared to one another.

In this master thesis two different techniques for placement of power cables are investigated using IEC-60287. A conventional technique where the electric power cable is placed in a cable trench is compared to the method where the power cable is placed in a protective plastic duct. Comparisons have been made in the areas: current carrying capacity, economy and technical simplifications.

Based on the analysis in this report results show that the theoretical current carrying capacity (ampacity) of the power cable placed in a plastic duct is sufficient for usage under given circumstances and that the method allows greater flexibility regarding the interface between contractors.

Conclusions from this master thesis should be used only based on circumstances very similar to the set-up described in this report. Current carrying capabilities of power cables diverges depending on cable model, surrounding media, protective plastics and/or metals and many more properties of the system. Each system demands an investigation of it’s own, but systems containing power cables buried in plastic ducts can with support from this report be closely described.

Keywords  IEC-60287, ampacity, rating, unfavorable thermal environment
Sammanfattning


Analysen visar att de två olika metoderna för kabelplacering skiljer sig främst när det gäller tids-flexibilitet och strömöverföringsförmåga. Metoden där kabeln placeras i ett plaströr inuti vägbanken visar resultat som tyder på att strömöverföringsförmågan är tillräcklig och att metoden dessutom tillåter större flexibilitet när det gäller gränssnitt mellan entreprenörs.

Resultatet och slutsatserna från rapporten skulle kunna användas för att besluta om vilken typ av förläggningsmetod som ska användas i framtida projekt. På grund av sin specifika karaktär bör resultatet användas med eftertanke. Omständigheterna kring framtida kabelförläggningar bör vara snarlika förhållanden beskrivna i denna rapport. Varje system kräver en noggrann undersökning för sig, men vissa riktlinjer dragna i detta examensarbete kan användas generellt.

Nyckelord IEC-60287, överföringsförmåga, märkdata, ofördelaktig termisk miljö
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Chapter 1

Introduction

Wind power farms are growing in size and the demand for coordination in the project execution phase increases steadily. Advanced logistics demand furthermore planning, following the expansion of the wind power farm. More transports, bigger construction areas, more employees, more advanced power control equipment and many more challenges. When farms grow bigger, small improvements in construction methods could prove economically advantageous. The method for placement of power cables in wind power farms have for a long time been done in a way considered to be optimal. Power cables have been placed directly in soil in dug trenches next to the roads leading up to the power plants. A new plan suggests the cables are placed in plastic ducts underneath the road. Perhaps is this new method both quicker and easier as well as safer and cheaper? When farms grow in size, small details grow in importance.

1.1 Background

This report is part of the presentation of the work performed during a master thesis project. This section describes the project and its formalities.

1.1.1 Master thesis

This master thesis has been performed by one person at Statkraft Sverige AB. At KTH\textsuperscript{1}, the department of Electromagnetic Engineering (ETK) is responsible for supervision and support.

The master thesis aims to provide the student with knowledge and experience of independent and reliable work. Due to the scientific and technical nature of the Masters’ Degree Project, academic readers is the main target group. However, it is also desirable that the report is structured in a manner comprehensible to any reader. In table 1.1 reading instructions for the report are presented.

\textsuperscript{1}Royal Institute of Technology
A wind power plant is not considered complete until it is producing electricity. Hence, time is of the essence when constructing a wind power farm. When considering time to completion every step of the construction is important and time saving actions are constantly sought.

One area of construction has been undeveloped for quite some time, but recently development suggestions have emerged. In a wind power farm roads connect all power plants with each other and the main road grid. These roads are used to transport all parts to the power plants, but also for transports regarding maintenance and service. Power cables to, from and in between wind power plants are conventionally placed next to the road in trenches. This method is now challenged by suggestions where power cables are placed in plastic ducts underneath the road (see appendix C). These ducts are placed in the road during road construction and the power cable is pushed into the duct after the road is completed. Hopes are that this new method will be quicker, create flexibility in planning the contractor’s work, cost less and keep ampacity at an acceptable level. International standard IEC-60287 is used to evaluate this method and on-site thermal measurements are performed to gather physical data regarding the thermal resistivity of surrounding materials.

The implementation of power cable placement is a complex task which involves several different contractors. The idea is that if a duct (to slide power cables through) is placed underneath the road, it is possible for the cable installation contractors
1.1. BACKGROUND

to perform the installation with greater flexibility and timeliness. The method also aims to facilitate implementation through greater flexibility in planning.

However, power cables placed inside plastic ducts are subjects to additional thermal stress which can be a problem since the power cable is limited in terms of ability to withstand extreme temperatures. High operating temperatures affects the sheath and most other components of the cable (see section 3.1). Component functionality may be compromised with an increase in thermal stress. Hence, the lifetime of the cable is dependent on that the maximum continuous operating temperature never exceeds that of the manufacturers specification.

If conclusions show that time and money can be saved and that ampacity (current carrying ability) can be maintained at an acceptable level - this is likely to be the technique of the future.

1.1.3 Organization

During the spring of 2011 this project has been carried out at the Swedish/Norwegian energy company Statkraft Sverige AB.

Statkraft Sverige AB

Statkraft Sverige AB is a company within the Norwegian government owned group Statkraft AS. At Statkraft Sverige AB the department Statkraft Sverige Vind is responsible for all constituents in planning and realizing wind power plants and farms.

One of the Masters’ Degree Project supervisors, and employee at Statkraft, MSc Kjell Gustafsson, is responsible for questions concerning the electrical grid. Statkraft is establishing large wind power farms in Sweden and are eager to build these farms in an optimal way. This means Statkraft is trying to:

1. Keep costs at a minimum (quicker installation, enhanced methods)

2. Create flexible project planning (for minimum realization time and as few coincidental contractors as possible)

3. Increase site safety (less interaction between vehicles on road, less coordination between contractors, cable thoroughly protected)

Statkraft is the proposer of this master thesis subject.

KTH

*KTH accounts for one third of Sweden’s capacity for technological research and engineering at university level. Education and research cover a broad spectrum - from natural science to all branches of engineering and architecture, industrial economics*
and social planning.\textsuperscript{2}

\textit{The Electromagnetic Engineering lab (ETK) is one out of the twelve labs in the School of Electrical Engineering at the Royal Institute of Technology. It was formed at the end of 2005 by merging of the divisions of Electrotechnical design (EEK) and Electromagnetic Theory (TET). In 2009, the Electromagnetic Compatibility (EMC) group at Uppsala University was moved to this division.}'\textsuperscript{3}

The second supervisor is Assoc. Prof. Hans Edin at the department of Electromagnetic Engineering, School of Electrical Engineering. He is currently leader of the high voltage engineering and insulation diagnostic group.

### 1.2 Purpose

The purpose of this master thesis is to investigate whether suggested changes to conventional cable laying techniques can contribute to the overall optimization process. Useful contributions are: acceptable ampacity level of power cable, lower installation costs, greater flexibility in project implementation, higher work place safety, minimization of simultaneous contractors on site, greater maintenance flexibility and shorter construction time.

### 1.3 Goals

The goals of this master thesis are divided into three sections: assignment, problem formulation and project question.

#### 1.3.1 Assignment

In this masters’ degree project, these are the key assignments:

- Evaluate the suggested method for power cable placement according to IEC-60287.
- Based on empiric data, evaluate the model describing the material surrounding the power cable.

#### 1.3.2 Problem formulation

According to the project description [12], six questions states the problem.

- Does the suggested new method in power cable placement allow greater flexibility in time planning?

\textsuperscript{2}About KTH, www.kth.se, 2011-06-15
\textsuperscript{3}ETK, www.etk.ee.kth.se, 2011-06-06
1.4. DELIMITATIONS

▷ How does thermal properties of the power cable change with a different cable laying method?

▷ Using the suggested power cable placement method, is the ampacity acceptable?

▷ Is the proposed cable laying technique a suitable solution for Statkraft Sverige AB?

▷ Will the suggested changes lead to measurable benefits?

▷ Should Statkraft Sverige AB use the new suggested method for cable placement?

1.3.3 Project question

Is the suggested change of power cable placement method acceptable regarding data based on IEC-60287, thermal properties of the surroundings and estimations of cost and time requirements?

1.4 Delimitations

This section handles delimitations of the project. The delimitations does not imply restrictions in the use of the report, but should be considered when studying the conclusions. Some conclusions can seem limited or vague, but depends in some cases directly on project delimitations. Delimitations mentioned below are not internally organized.

▷ This masters’ degree project handles ampacity solely as presented in IEC-60287.

▷ Calculations regarding ampacity are performed exclusively on power cables with cross-section and geometry according to figure 3.1 and 3.3 on pages 16 and 18 respectively.

▷ Experiments aiming to investigate thermal properties of the power cable surroundings are limited to basic measurements of temperature and heat conduction.

▷ Thermal properties of surrounding media is investigated at one wind power plant site.

▷ This master thesis does not treat other circumstances than those described in IEC-60287.
Chapter 2

Method

Presentation of results in a structured manner is the key to useful conclusions. The project has therefore been divided into a number of stages that are described in this section.

This master thesis is structured according to an academic technical report.

2.1 Establishment Stage

During this stage the subject of the thesis was closely studied to be able to set goals and delimitations for the project. The goals were then used to plan how the project was to be carried out. The problem formulation is an important part of this stage. Administrative tasks, such as student-supervisor agreements, are also included in this stage. Important documents for the establishment stage are:

- Project plan
- Project description

2.2 Theory

The theory section handles all problem formulations from the project description and the need of data gathering is explained. First of all the international standard (IEC-60287) is described and structured for further use. Secondly the power cable and it’s constituents are explained and the system set-up is shown. The background for the economic review is presented together with time plans for the two investigated power cable laying methods.

2.3 Data gathering

This section describes how data gathering was implemented. Calculations according to IEC 60287 (see chapter 4) are presented. On-site ex-
periment implementations are described. Economic investigations according to the economic review are presented.

2.4 Analysis

Analysis is the single most important part of the report. The analysis is based entirely on results from data gathering and validated only through IEC 60287 ([1], [2], [3]) and in acceptance and ideas from experienced participants (project supervisors et al).

After performing the analysis, conclusions are presented in the conclusions section. The most important purpose of the conclusions section is to answer the questions from the project goals (in section 1.3 on page 8).

2.5 Presentation

The last stage of the master thesis is to orally present the work that has been performed. Naturally the report is an important part of the presentation, but even more important are the views and ideas of the author and feedback from supervisors and others involved. Suggestions on future work in the area will also be presented. The oral presentation is open and can be visited by anyone with an interest in the subject.
Part I

Theory
Chapter 3

General Theory on Electric Power Transfer in Wind Power Farms

Large wind power plants produce electric power in the vicinity of 1.5 MW up to 5 MW (or in some cases more\(^1\)). Wind power plants deliver their produced power to a transformer. Before feeding the electricity into the public grid, the transformer converts the electricity from the generated voltage to a more suitable high voltage (Page 211 in Developing wind power projects, Wizelius, 2007, [10]).

The power cable that connects the wind power plant with the transformer has to have a power cable ampacity large enough to be able to handle the power produced in the wind power plant. Dimensioning the power cable is done according to the power output of the wind power plant. However, due to increased costs in increased cable dimension, the cable should have an ampacity that is *large enough, but not too large.*

Figure 3.1 and 3.3 describes the geometry of the power cable AXKJ-F 3x95/25. Figure 3.1 shows all constituent parts of the cable and in table 3.1 all parts are described. Figure 3.3 shows the setup with the power cable placed in a protective duct. Figure 3.2 shows a 3D view [11] of the cutaway view in figure 3.1.

### 3.1 Thermal stress

According to the *Arrhenius equation*, at room temperature chemical reactions doubles their reaction rate for every 10 °C increase in temperature [9].

Due to the change in reaction rate, described in the *Arrhenius equation*, power cables deteriorate/age faster under thermal stress. Hence, thermal stress should be avoided to benefit expected lifetime for a power cable.

---

\(^1\)E.g. the Enercon E-126 has a rated power of 7.5 MW.
One of the reasons why a cable is exposed to thermal stress is its geometry and construction. Cables covered with protective plastics or metals isolates and preserves heat better than cables without these protective layers (thermal resistance in equation 3.1 calculated according to IEC-60287-2-1 [2]). A power cable system (power cable, cable protection and surrounding medium) that preserves heat suffers from increased temperature and is hence exposed to thermal stress.

The electrical resistance of the power cable increases with temperature according to equation 4.5 from IEC-60287-1-1 [1]. An increase in electrical resistance leads to an increased loss in electric power (see equation 5.1) in the form of heat. Power cables placed in ground are not only affected, in terms of heat isolation, by
3.2. THERMAL RESISTANCE

Table 3.1. Constituents of power cable in figure 3.1.

<table>
<thead>
<tr>
<th>Serving</th>
<th>Screen</th>
</tr>
</thead>
<tbody>
<tr>
<td>non-extruded layer or assembly of non-extruded layers applied to the exterior of a cable (^2), but can also be called outer sheath;</td>
<td>25 (mm^2) Copper screen;</td>
</tr>
<tr>
<td></td>
<td>PP Polypropylene. Belongs to the group thermoplastic polymers. Keeps the screen fixed during manufacturing;</td>
</tr>
<tr>
<td></td>
<td>C paper Carbon paper. Plastic material covered in carbon particles. Additional screen;</td>
</tr>
<tr>
<td></td>
<td>Semicon Outer and inner semi conductor;</td>
</tr>
<tr>
<td></td>
<td>X Cross-linked polyethylene used for isolation and protection;</td>
</tr>
<tr>
<td></td>
<td>Cond. 95 (mm^2) aluminium conductor;</td>
</tr>
</tbody>
</table>

protective plastic and/or metallic layers. Surrounding medium such as soil, sand, gravel, water, mud or air have a profound effect on heat isolation properties of the system. This will be closer explained in section 3.2.

3.2 Thermal resistance

Heat produced in any system is transferred via mediums surrounding the heat source. Depending on medium properties the heat transfer ability differs between different mediums. Heat transfer can be classified in different groups such as *convection*, *conduction* and *radiation* (see section 1.2 in *Rating of Electric Power Cables...* G J Anders, 2005, [4]). In figure 3.4 heat transfer can be seen as radiation and conduction. Due to the thermal properties of surrounding mediums, the thermal resistance of the system does not only rely on the construction of the power cable (see equation 3.1), but all constituent layers add thermal resistance and even the surrounding soil/sand is important to account for (see equation 3.2 below).

To calculate the ampacity of a power cable according to IEC-60287 many properties of the cable needs clarification, simplification and structuring. This is done in section 4. The thermal resistance of the power cable is one of the constituents needed in the international standard to calculate the ampacity.

The thermal resistance of a power cable can according to IEC-60287-2-1 [2] be described as:

\[ T = T_1 + T_2 + T_3 \]  \hspace{1cm} (3.1)

where

\( T_1 \) is the thermal resistance between one conductor and sheath (see cable description in section 3.1) \([Km/W]\);

\( T_2 \) is the thermal resistance between sheath and armour \([Km/W]\);
$T_3$ is the thermal resistance of outer covering/serving [$Km/W$];

Thermal resistances distinguishes the two methods where the power cables are either placed in a trench or in a duct. The construction of the power cable is the same in both cases. The only thing that differentiates between them is the outer thermal resistance $T_4$. One power cable is placed directly in wet soil, the other in an air filled plastic duct. In the air filled plastic duct the thermal resistance is higher than when soil and gravel surrounds the power cable ($T_{soil} < T_{air}$ [1]). Furthermore, the medium around the power cable and outside the plastic duct have different thermal properties. Since the power cable placed in the duct is better protected than the cable in the trench more coarse soil/gravel can be used. In the method where a duct is used, the material surrounding the system is assumed to have the same or higher thermal resistance than sand or soil. Hence the lowest calculated ampacity is chosen in chapter 10 since a decrease in current carrying capacity can be expected (also found in chapter 10) compared to conventional power cable placement. $T_4$ is
3.3. COMPARISON

Figure 3.4. Simple graphic description of heat transfer fundamentals. Radiation and conduction from singular heat source, without and with barrier.

defined as:

$$T_4 = T'_4 + T''_4 + T'''_4$$  \hspace{1cm} (3.2)

where

$T'_4$ is the thermal resistance of the air space between the cable surface and duct’s internal surface;

$T''_4$ is the thermal resistance of the duct itself;

$T'''_4$ is the external thermal resistance of the duct.

3.3 Comparison

In this master thesis two cable placement techniques are compared. The first is a well known, well used technique, while the other is newly suggested and the thermal properties under consideration.

In figure 3.5 the set-up of both the old and the suggested power cable laying technique can be seen. The power cable is presently placed in a trench on the side of
the road (as seen in figure 3.5) directly in soil. Wet soil, sand and mud surrounds the cable and affects heat transfer. In the suggested method the power cable is placed in a plastic duct underneath the road. A cable placed inside a plastic duct is affected according to described theory on thermal stress and resistance (see section 3.1, 3.2 and chapter 4).

Figure 3.5. Model describing conventional placement of cables and suggested placement of power cables in a plastic duct (bird’s-eye view of the road).
Chapter 4

Theory on Calculating Ampacity According to IEC-60287

Road surface

<table>
<thead>
<tr>
<th>Conditions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_a=20^\circ\text{C}$ ambient soil temperature;</td>
</tr>
<tr>
<td>$\theta=90^\circ\text{C}$ power cable core temperature;</td>
</tr>
<tr>
<td>$\rho_w=1$ Km/W thermal resistivity of wet soil;</td>
</tr>
<tr>
<td>$\rho_d=3$ Km/W thermal resistivity of dry soil;</td>
</tr>
<tr>
<td>$L=1$ m placement depth.</td>
</tr>
</tbody>
</table>

Three phase power cable $\varnothing=64$ mm

Plastic duct $\varnothing=110$ mm

Figure 4.1. Fundamental assumptions such as power cable burial depth etc.

This chapter contains clarifications regarding the use of the international standard IEC-60287. All sections are presented according to the standard documents IEC-60287-1-1 [1], IEC-60287-2-1 [2] and IEC-60287-3-2 [3], with comments where simplifications or alterations have been performed. IEC-60287 is used to establish the permissible current rating (ampacity) of a power cable. The standard contains formulas for calculating losses (ac resistance and dielectric losses), loss factors for power cable constituents (reinforcements etc.) and thermal resistances throughout the entire system (power cable, protective covering and surrounding medium). A full description of prerequisites is found in Appendix A.
CHAPTER 4. THEORY ON CALCULATING AMPACITY ACCORDING TO IEC-60287

The scope of IEC-60287 according to IEC [1]:

'... IEC-60287 is applicable to the conditions of steady-state operation of cables at all alternating voltages, and direct voltages up to 5 kV, buried directly in the ground, in ducts, troughs or in steel pipes, both with and without partial drying-out of the soil, as well as cables in air. The term "steady state" is intended to mean a continuous constant current (100 % load factor) just sufficient to produce asymptotically the maximum conductor temperature, the surrounding ambient conditions being assumed constant."

4.1 Ampacity

The permissible current rating of electric power cables will throughout this master thesis be referred to as ampacity.

Since the ampacity of the power cable is calculated for real conditions, both partial dry-out (section 4.1.2) of the surrounding medium and no dry-out at all (section 4.1.1) is considered. Due to the fact that both scenarios can occur and the least favourable (lowest ampacity) should be counted for, the lowest of the two ampacities is chosen. In this section the main parts of IEC-60287 are described.

In IEC-60287-1-1 [1] the ampacity of an AC cable is derived from the expression for the temperature rise of the cable conductor above ambient temperature:

\[
\Delta \theta = (I^2R + \frac{1}{2}W_d)T_1 + [I^2R(1 + \lambda_1) + W_d]nT_2 + [I^2R(1 + \lambda_1 + \lambda_2) + W_d]n(T_3 + T_4)
\]  
(4.1)

All constituents in equation 4.1 are explained in the following sections. From equation 4.1 the ampacity \(I\) in the equation) can be derived in different ways to adapt to different circumstances. Below, two different ways of using equation 4.1 are presented.

4.1.1 Buried cables where drying-out of the soil does not occur

A power cable buried in an environment where the soil does not become dry. A continuous contribution of dampness can be expected. Wet surroundings have different properties than dry (see section 3.1). The permissible current rating is obtained from 4.1 according to IEC 60287-1-1 [1] as follows:

\[
I = \left[ \frac{\Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{R[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + T_4)]} \right]^{0.5}
\]  
(4.2)
4.2. CALCULATION OF LOSSES

4.1.2 Buried cables where partial drying-out of the soil occurs

In areas where dry-out of surrounding medium can be expected, the ampacity calculations must be adapted. The permissible current rating is obtained from 4.1 according to IEC 60287-1-1 [1] as follows:

\[ I = \left[ \Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + vT_4)] + (v - 1)\Delta \theta_x \right]^{0.5} \]  

(4.3)

4.2 Calculation of losses

The heat produced in a power cable is 100 % losses. Ideally, all power is transferred as electricity and nothing is lost to other forms of energy. In reality, the system have losses that heats the conductor and affects it’s surroundings. This section describes the losses and how it affects the ampacity.

4.2.1 AC resistance of conductor

The AC resistance of a conductor consist of the DC resistance, the skin effect and the proximity effect. Working at maximum operating temperature, the AC resistance (per unit length), according to IEC-60287-1-1 section 2.1, is given by:

\[ R = R'(1 + y_s + y_p) \]  

(4.4)

DC resistance of conductor

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

(4.5)

where

\[ R_0 \] is the d.c. resistance of the conductor at 20 °C [Ω/m];

\[ \alpha_{20} \] is the constant mass temperature coefficient for aluminium at 20 °C per Kelvin;

\[ \theta \] is the maximum operating temperature in °C.

Skin effect factor \( y_s \)

At rising frequencies the skin effect effectively limits the cross-sectional area of the conductor [7]. Due to concentration of currents at the surface, the resistance of the conductor increases and hence the ampacity is decreased. The skin effect is a phenomenon that depends on frequency and therefore causes AC resistance to be higher than DC resistance (page 20 in Practical Transformer Handbook, Irving M Gottlieb, 1998, [7]).
The skin effect factor $y_s$ is given by:

$$y_s = \frac{x_s^4}{192 + 0.8 \cdot x_s^4} \quad (4.6)$$

where

$$x_s^2 = \frac{8 \pi f}{R'} \cdot 10^{-7} \cdot k_s \quad (4.7)$$

$f$ is the supply frequency in hertz.

$k_s$ coefficient according to IEC–60287 [1] table 2. Depending on conductor type (e.g. helical) and strand impregnation.

**Proximity effect factor $y_p$ (for three-core cables)**

When circulating currents occur due to alternating magnetic flux caused by current flows in nearby conductor(s), the resistance of the conductor is increased (page 395 in Power System Engineering, R K Rajput, 2006, [8]). This is what is called proximity effect.

Three phase power cables having three conductors gives a proximity effect factor, according to IEC-60287-1-1, of:

$$y_p = \frac{x_p^4}{192 + 0.8x_p^4} \left( \frac{d_c}{s} \right)^2 \left[ 0.312 \cdot \left( \frac{d_c}{s} \right)^2 + \frac{1.18}{x_p^4 \cdot 192 + 0.8x_p^4} + 0.27 \right] \quad (4.8)$$

where

$$x_p^2 = \frac{8 \pi f}{R'} \cdot 10^{-7} \cdot k_p \quad (4.9)$$

$d_c$ is the diameter of conductor [mm];

$s$ is the distance between conductor axes [mm];

$k_p$ coefficient according to IEC–60287 [1] table 2. Depending on conductor type (e.g. helical) and strand impregnation.
4.2. CALCULATION OF LOSSES

4.2.2 Dielectric losses

Cables investigated in this master thesis are insulated with cross-linked polyethylene. This type of dielectric medium, when subject to alternating currents, is run through by charging currents (page 109, Rating of Electric Power Cables:..., George J Anders, 1997, [5]). The work required to move electrons back and forth in the dielectric at the same frequency as the alternating current, generates heat and is a loss of power - this is the dielectric loss [5].

The dielectric loss per unit length in each phase is given by:

$$W_d = \omega C U_0^2 \tan \delta \ [W/m]$$

where

$$\omega = 2\pi f;$$

$$U_0$$ is the voltage to earth [V].

The capacitance for circular conductors is given by:

$$C \approx \frac{\varepsilon}{18 \ln \frac{D_i}{d_c}} \cdot 10^{-9} \ [F/m]$$

where

$$\varepsilon$$ is the relative permittivity of the insulation;

$$D_i$$ is the external diameter of the insulation (excluding screen) [mm];

$$d_c$$ is the diameter of conductor, including screen [mm].

4.2.3 Loss factor for screen

The power loss in the screen ($\lambda_1$), according to IEC-60287-1-1 section 2.2, consists of losses caused by circulating currents ($\lambda_1'$) and eddy currents ($\lambda_1''$), thus:

$$\lambda_1 = \lambda_1' + \lambda_1''$$

where

$$\lambda_1' = \frac{R_S}{R} \left( 1 + \frac{R_S}{X} \right)^2$$

$$X = 2\omega \cdot 10^{-7} \ln \frac{2s}{d}$$

where
CHAPTER 4. THEORY ON CALCULATING AMPACITY ACCORDING TO IEC-60287

\[ X \] is the reactance per unit length of sheath or screen per unit length of cable \([\Omega/m]\);

\[ \omega = 2\pi f \quad [\text{rad/s}] \];

\[ s \] is the distance between conductor axes in the electrical section being considered \([\text{mm}]\);

\[ d \] is the mean diameter of the sheath \([\text{mm}]\);

\[ \lambda_{1''} = 0 \]. The eddy-current loss is ignored according to IEC 60287-1-1 section 2.3.1 \([1]\).

\[ R_s \] is the resistance of the screen per unit length of cable at its maximum operating temperature \([\Omega/m]\).

\[ R_s = R_{S0} \left[ 1 + \alpha_20 (\theta_{SC} - 20) \right] \quad [\Omega/m] \quad (4.15) \]

where

\[ R_{S0} \] is the resistance of the cable screen at 20 °C \([\Omega/m]\).

4.3 Thermal resistance \( T \)

As described in section 3.2 thermal resistance occurs wherever there are mediums limiting heat transfer. Following section explains important parts in calculating what the constituents of a power cable adds in term of thermal resistance.

4.3.1 Thermal resistance of constituent parts of an electric power cable, \( T_1, T_2, T_3 \)

According to IEC-60287-2-1 \([2]\), the thermal resistance, \( T \), is:

\[ T = T_1 + T_2 + T_3 \]

**Thermal resistance between one conductor and sheath \( T_1 \)**

For screened cables with circular conductors the thermal resistance \( T_1 \) is \([2]\):

\[ T_1 = \frac{\rho_T}{2\pi} G \quad (4.16) \]

where

\[ G \] is the geometric factor according to IEC60287 \([2]\);

\[ \rho_T \] is the thermal resistivity of insulation \([Km/W]\);
4.3. THERMAL RESISTANCE T

Thermal resistance between sheath and armour $T_2$

The investigated power cable does not contain armour nor metallic sheath. Hence $T_2$ is not considered.

Thermal resistance of outer covering (serving) $T_3$

$$T_3 = \frac{\rho_T}{2 \pi} \cdot \ln \left(1 + \frac{2t_3}{D_a'}\right)$$  \hspace{1cm} (4.17)

where

$t_3$ is the thickness of serving [mm];

$D_a'$ is the external diameter of the armour [mm];

4.3.2 External thermal resistance $T_4$

The external thermal resistance of a cable in a duct consists of three parts:

$T_4'$ is the thermal resistance of the air space between the cable surface and duct’s internal surface;

$T_4''$ is the thermal resistance of the duct itself;

$T_4'''$ is the external thermal resistance of the duct (sand, soil, gravel, etc.).

$$T_4 = T_4' + T_4'' + T_4'''$$ \hspace{1cm} (4.18)

Thermal resistance between cable and duct $T_4'$

$$T_4' = \frac{U}{1 + 0.1(V + Y\theta_m)D_e}$$ \hspace{1cm} (4.19)

where


$D_e$ is the external diameter of the cable [mm];

$\theta_m$ is the mean temperature of the medium filling the space between cable and duct [°C];
CHAPTER 4. THEORY ON CALCULATING AMPACITY ACCORDING TO IEC-60287

Thermal resistance of the duct $T''_4$

$$T''_4 = \frac{\rho_T}{2\pi} \cdot \ln \left( \frac{D_0}{D_d} \right)$$  \hspace{1cm} (4.20)

where

- $D_0$ is the outside diameter of the duct [\text{mm}];
- $D_d$ is the inside diameter of the duct [\text{mm}];
- $\rho_T$ is the thermal resistivity of duct material [\text{Km/W}]

External thermal resistance of the duct $T''''_4$

$$T''''_4 = \frac{1}{2\pi} \rho_{soil} \cdot \ln (2u)$$  \hspace{1cm} (4.21)

where

- $\rho_{soil}$ is the thermal resistivity of earth around bank [\text{Km/W}];
- $u = \frac{2L}{D_0}$, $L$ is the depth of the laying to centre of duct [\text{mm}].
Chapter 5

Theory on Experiment Implementation

The current ampacity of a power cable is affected by surrounding mediums and the mediums’ thermal resistances (IEC-60287-1-1 section 1.4.1.1 [1] and Rating of Electric Power Cables section 1.3.1, George J Anders, 2005 [4]). This makes the thermal properties of the surroundings interesting when rating power cables.

To find the thermal properties of the surroundings an on-site experiment has been performed. Temperature sensors were placed at different locations in and around dug down cable ducts. A heat cable was installed in the duct and the sensors were used to log how heat spread through the system. This section describes the purpose and set-up of the experiment.

5.1 Experiment purpose

The purposes of performing this experiment are:

- Find temperature transients regarding heat up and cool down\(^1\) of the power cable system\(^2\).
- Observe how heat spreads through system components.
- Investigate damages on ducts placed beneath road surface.
- Gather views on how the new set-up\(^3\) is looked upon.
- Find inaccuracies in measurement equipment.

5.2 Equipment

- Plastic ducts (Polyethylene), 10 m long

---

\(^1\)How quickly is a temperature equilibrium reached at power up and power down?

\(^2\)Power cable, duct and surrounding material

\(^3\)Power cable placed beneath the road surface instead of next to the road.
• Heat cable, 10 m long, 10 [W/m], see calculations in section 5.3
• 4 data loggers (see figure 5.1) for data storage, storage capacity=16000 values
  (≈ 1 temperature sample every 5 minutes for 55 days).
• 6 temperature sensor probes (1.5 m, waterproof flexible thermistor probe)
• Joint foam (used to seal the duct halfway through to avoid heat leakage between measurement points)

5.3 Experiment set-up

3 sets of respectively 8 meters plastic ducts were placed beneath the road surface at an emerging wind power park. The ducts were placed in the road before any heavy transports had begun. All ducts were then left in the road during construction of 3 wind power plants. When the constructions was finished the ducts were dug up and controlled for damages.

At the same time when two of these ducts were dug up, the third duct was left in the road and a heat cable and temperature sensors were installed. Figure 5.2 shows the duct in relation to the road and where the wheel tracks are located. The heat cable was used to simulate the presence of a real power cable working at maximum load. To accurately dimension the heat cable \( P_{\text{heattable}} \approx P_{\text{loss}} \) an approximation of the power cable ampacity, according to the following equation, is demanded:
5.3. EXPERIMENT SET-UP

\[ P_{\text{loss}} = I^2 \cdot R \]  
(5.1)

where

- \( I = 230 \, [A] \), the maximum load of the power cable with conductor at maximum operating temperature \( \theta = 90 \, ^\circ\text{C} \);
- \( R = \frac{0.320}{1000} \cdot (1 + \alpha_{20}(\theta - 20)) = 0.000381445 \, [\Omega/m] \), the dc resistance of the conductor per meter at max operating temperature according to IEC60287-1-1 [1].

which gives

\[ P_{\text{loss}} = 230^2 \cdot 0.000381445 \approx 20.2 \, [W/m] \]

This means that the heat cable, used to simulate the power cable, should be dimensioned to produce 20.2 W/m.

Figure 5.3 on page 32 shows the temperature sensor set-up. One side of the duct was covered in coarse sand\(^4\) and the other side was covered with material directly from the road (very coarse mix of sand, sandy till\(^5\), mud and stones).

A small hole was drilled on top of the duct and sensors placed according to indicators 4 and 1 in figure 5.3 on page 32. Indicator 2 and 5 in figure 5.3 shows the placement of sensors immediately outside the duct. The sensors placed furthest away from the heat cable and closest to the road surface are indicators 3 and 6.

As mentioned above, joint foam was used to seal the two ends from each other and also to keep the heat cable fixed during the 12 days of data gathering. Three of the data loggers can handle input from 2 sensors each. The fourth has 1 data channel.

On the ninth day the heat cable was shut off and the system was left to cool. After 12 days of continuous measurement the data loggers were collected and the data extracted.

5.3.1 Duct

There were two types of ducts placed in the road. The duct used in this experiment set-up is called SRS110 and is a reinforced 8 mm thick PVC duct. The other duct was a corrugated, but not as sturdy, type called SRN110. Two ducts (one of each type) were placed on a depth of 30 cm and one SRS110 was placed at a depth of 40 cm.

---

\(^4\)According to ISO 14688-1:2002, sand with a grain diameter of between 0.5 mm-1 mm

\(^5\)Unsorted glacial sediment mixed with sand. Swedish: 'sandig morän'.
CHAPTER 5. THEORY ON EXPERIMENT IMPLEMENTATION

Figure 5.2. Model describing placement of plastic duct.

Figure 5.3. Model describing placement of 6 temperature sensors in two different surroundings. Sand on the left, gravel and stones on the right.
Chapter 6

Theory on Time, Cost & Logistics

As stated in section 1.2 and 1.3 Statkraft is interested in finding advantages and disadvantages in different techniques for power cable placement. Areas of interest are economy, safety and planning flexibility. Are there benefits with other methods for electric power cable placement in comparison to methods used today? This section will foremost be based on views from Statkraft employees and contractors working with projects connected to the purpose and goals of this master thesis. Data has been gathered through interviews, collaborations, questionnaires, email conversations and phone calls during the project.

6.1 Time

Time is of the essence when constructing a wind power park. There are many phases of the project that affects the time plan and three examples of important parts\(^1\) are (Chapter 19 in Developing Wind Power Projects, T Wizelius (2008), [10]):

- **Road finished**: When the road, connecting the wind power plant sites with each other and the closest main road, is finished, the construction of the power plant foundation can be initiated;
- **Commissioning**: Not until the wind power plant delivers electricity to the grid, the cost for the wind power plant starts paying back;
- **Flexibility**: Coordination of contractors working on the same site to prevent cross-planning\(^2\) and accidents. What is sought is flexibility in phase implementation and reaching a shorter time of construction.

The table below is used to roughly approximate time consumption in the two methods (existing method and suggested method). All phases defined as ":-:" are phases identical for the two methods or phases not affected by cable placement method.

\(^1\)Reaching an identifiable, important step in a project.
\(^2\)E.g. contractors working at the same place at the same time.
The phases marked '-' will not be considered when comparing the cable placement methods.

Following list describes the table content.

<table>
<thead>
<tr>
<th>Lumbering</th>
<th>Removal of trees and vegetation above ground level.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation, blasting</td>
<td>Removal of stubs, rocks and other irregularities below ground level. An area the width of the road, and desired depth (≈ 1 m), is cleared for the road construction.</td>
</tr>
<tr>
<td>Duct installation</td>
<td>The plastic duct is installed in the bottom of the road-to-be. This part includes the difference in time between the two different cable placement methods.</td>
</tr>
<tr>
<td>Road construction</td>
<td>A road is constructed according to a layer-on-layer principle with different mediums on different depths (method similar to Swedish transport administration, publication 2008:78, page 5 [15]). Differences in road construction are included in duct installation.</td>
</tr>
<tr>
<td>Trench construction</td>
<td>Digging a trench next to the road where the power cable will be placed.</td>
</tr>
<tr>
<td>Cable installation</td>
<td>The electric power cable is placed either in a trench or in a plastic duct underneath the road surface. In the trench scenario, the power cable is wound from the cable reel directly into the trench. When a plastic duct is used, the power cable is pushed through the duct.</td>
</tr>
<tr>
<td>Electric installation</td>
<td>Connecting the power cables to the wind power plant, the transformer and the power grid.</td>
</tr>
</tbody>
</table>

Table 6.1. Example table showing time demand.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Existing method</th>
<th>Suggested method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbering</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Excavation, blasting</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Duct installation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road construction</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Trench construction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cable installation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric installation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Σ</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
6.2. Cost

Material and service costs are the major parts of the total project cost. Both material demand and service need are included in the project plan, but only the material demand is unlikely to change during the project, while the need for services is more flexible. Man hours for contractors are not included in table 6.2 since they are accounted for in table 9.1. The cable pushing equipment mentioned in table 6.2 are the machines required to push/pull the power cable into the plastic duct. One machine is placed at the duct entrance where it pushes the power cable. The second machine is placed at the exit of the duct where the cable is pulled.

Table 6.2. Example table describing the material demand in the different methods.

<table>
<thead>
<tr>
<th>Item</th>
<th>Existing method</th>
<th>Suggested method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>Volume m³</td>
<td>Volume m³</td>
</tr>
<tr>
<td>Plastic duct</td>
<td>Length m</td>
<td>Length m</td>
</tr>
<tr>
<td>Cable pusher</td>
<td>Pcs</td>
<td>Pcs</td>
</tr>
</tbody>
</table>

6.3 Logistics

What are the logistic demands and profits of the different power cable placements?

Table 6.3. Example table describing logistic demands.

<table>
<thead>
<tr>
<th>Service</th>
<th>Existing method</th>
<th>Suggested method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excavation removal</td>
<td>Volume m³</td>
<td>Volume m³</td>
</tr>
<tr>
<td>Sand transports</td>
<td>Volume m³</td>
<td>Volume m³</td>
</tr>
<tr>
<td>Power cable transport</td>
<td>Length m, weight kg</td>
<td>Length m, weight kg</td>
</tr>
<tr>
<td>Duct transport</td>
<td>Length m, weight kg</td>
<td>Length m, weight kg</td>
</tr>
</tbody>
</table>

---

\(^3\) Excavation, transports, duct installation, etc.

\(^4\) According to Kjell Gustafsson [20] and Urban Blom [21]
Part II

Data gathering
Chapter 7

Gathering and Calculation of Ampacity Data

This chapter shows calculations regarding ampacity performed accordingly to IEC-60287 in chapter 4. All calculations are adapted to a three phase power cable placed in a plastic duct (see section 4.3.2 for details). First of all, standard parts\(^1\) of the ampacity is handled. Secondly, the ampacity is calculated for two specific scenarios. For further details on calculations or conditions see Appendix B.

The ambient soil temperature is estimated to 20 °C and hence the difference in temperature in Kelvin, $\Delta \theta$, between soil and aluminium conductor is $(90-20)=70$ K.

Table 7.1. General conditions.

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_0$</td>
<td>$\frac{36}{\sqrt{3}} \cdot 10^3$ V</td>
</tr>
<tr>
<td>$A_{Al}$</td>
<td>95 mm$^2$</td>
</tr>
<tr>
<td>$R_{\text{conductor,Al}}$</td>
<td>0.2975 $\Omega$/km</td>
</tr>
<tr>
<td>$A_{Cu}$</td>
<td>25 mm$^2$</td>
</tr>
<tr>
<td>$R_{\text{screen,Cu}}$</td>
<td>0.6896 $\Omega$/km</td>
</tr>
</tbody>
</table>

See figure 4.1 for additional conditions.

7.1 Ampacity

Calculations have been performed according to two different prerequisites based on IEC-60287. They are:

\(^1\)Calculations common for all cables studied in this report.
1. Buried cables where drying-out of the soil does not occur

2. Buried cables where partial drying-out of the soil occurs

### 7.2 Calculation of losses

See chapter 4 for further description.

#### 7.2.1 AC resistance of conductor

\[ R = R'(1 + y_s + y_p) \] (7.1)

**DC resistance of conductor**

\[ R' = R_0[1 + \alpha_20(\theta - 20)] = 0.00029752[1 + 4.03 \cdot 10^{-3}(90 - 20)] = 0.00038144 \, \Omega \] (7.2)

**Skin effect factor** \( y_s \)

\[
y_s = \frac{x_s^4}{192 + 0.8 \cdot x_s^4} = \frac{0.57397^4}{192 + 0.57397^4} = 0.00056501
\] (7.3)

\[
x_s = \sqrt{\frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_s = \{ k_s = 1 \}} = \sqrt{\frac{8\pi 50}{0.00038144} \cdot 10^{-7}} = 0.57397
\]

**Proximity effect factor** \( y_p \) (for three-core cables)

The proximity effect factor is given by:

\[
y_p = \frac{x_p^4}{192 + 0.8x_p^4} \left[ \frac{d_c}{s} \right]^2 \left[ 0.312 \cdot \left( \frac{d_c}{s} \right)^2 + \frac{1.18}{x_p^4} \left( \frac{d_c}{s} \right)^2 + 0.27 \right] = ... = 0.00025545
\] (7.4)

\[
x_p = \sqrt{\frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_p = \{ k_p = 0.8 \}} = \sqrt{\frac{8\pi 50}{0.00038144} \cdot 0.8 \cdot 10^{-7}} = 0.26355
\]

\[ \rightarrow R = R'(1 + y_s + y_p) = 0.00038144 \cdot (1 + 0.00056501 + 0.00025545) \, \Omega = 0.0038175 \, \Omega
\]

The impact from skin- and proximity effect on the AC resistance is less than 1 %e.
7.3. THERMAL RESISTANCE T

7.2.2 Dielectric losses

The dielectric loss per unit length in each phase is given by:

\[ W_d = \omega C U_0^2 \tan \delta = 2\pi 50 \cdot 0.16392 \cdot 10^{-9} \left(\frac{36}{\sqrt{3}} \cdot 10^3\right)^2 \cdot 0.004 \text{ W/m} = 0.088987 \text{ W/m} \]

(7.5)

7.2.3 Loss factor (\(\lambda_1\)) for screen

\[ \lambda_1 = \lambda_1' + \lambda_1'' \]

(7.6)

\[ \lambda_1' = \frac{R_S}{R} \frac{1}{1 + \left(\frac{R_s}{X}\right)^2} = \frac{0.00085639452}{0.0038175} \frac{1}{1 + \left(0.00085639452\right)^2} = 8.798 \cdot 10^{-5} \]

The eddy-current loss \(\lambda_1''\) is ignored according to IEC 60287-1-1 section 2.3.1 [1].

\[ \lambda_1 = \lambda_1' + \lambda_1'' = 8.798 \cdot 10^{-5} + 0 = 8.798 \cdot 10^{-5} \]

7.3 Thermal resistance T

See section 4.3 for extended explanation of how the thermal resistance T is considered.

\[ T = T_1 + T_2 + T_3 + T_4 \]

7.3.1 Internal thermal resistances, \(T_1\), \(T_2\) and \(T_3\)

Thermal resistance between one conductor and sheath \(T_1\)

\[ T_1 = \frac{PT\cdot PEX}{2\pi} G = \frac{3.5}{2\pi} 1.63 \text{ Km/W} \approx 0.91 \text{ Km/W} \]

(7.7)

\(G\) is a geometric factor based on the diameter of the conductor, thickness of insulation between conductors and thickness of insulation between conductor and sheath. See IEC-60287 [2] figure 3 for details.

Thermal resistance between sheath and armour \(T_2\)

AXKJ-F 3x95/25 does not contain armour nor metallic sheath. Hence \(T_2\) is not considered.

\[ T_2 = 0 \]

(7.8)
Thermal resistance of outer covering (serving) $T_3$

$$T_3 = \frac{\rho_{T,PE}}{2\pi} \cdot \ln \left(1 + \frac{2 \cdot 3}{D_a'}\right) = \frac{3.5}{2\pi} \cdot \ln \left(1 + \frac{2 \cdot 3}{55.168}\right) = 0.0471 \text{ K m/W} \quad (7.9)$$

7.3.2 External thermal resistance $T_4$

$$T_4 = T'_4 + T''_4 + T'''_4 \quad (7.10)$$

Thermal resistance between cable and duct $T'_4$

$$T'_4 = \frac{U}{1 + 0.1(V + Y\theta_m)D_e} = \frac{1.87}{1 + 0.1(0.312 + 0.0037 \cdot 50)}71 = 0.4129 \text{ K m/W} \quad (7.11)$$

Thermal resistance of the duct $T''_4$

$$T''_4 = \frac{\rho_{T,PE}}{2\pi} \cdot \ln \left(\frac{D_0}{D_d}\right) = \frac{3.5}{2\pi} \cdot \ln \left(\frac{110}{95}\right) \text{ K m/W} = 0.8060 \text{ K m/W} \quad (7.12)$$

External thermal resistance of the duct $T'''_4$

$$T'''_4 = \frac{1}{2\pi} \rho_{sol} \cdot \ln (2u) = \frac{1}{2\pi} 1.0 \cdot \ln (2 \cdot 12.7273) \text{ K m/W} = 0.5152 \text{ K m/W} \quad (7.13)$$

$$T_4 = T'_4 + T''_4 + T'''_4 = 0.47414 + 0.8060 + 0.5152 \text{ K m/W} = 1.7341 \text{ K m/W} \quad (7.14)$$

7.4 Summary

Table 7.2. Common physical quantities for all investigated prerequisites.

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta\theta$</td>
<td>70 K</td>
</tr>
<tr>
<td>$R$</td>
<td>0.0038175 $\Omega$/m</td>
</tr>
<tr>
<td>$W_d$</td>
<td>0.088987 W/m</td>
</tr>
<tr>
<td>$T_1$</td>
<td>0.90798 K m/W</td>
</tr>
<tr>
<td>$T_2$</td>
<td>0 K m/W</td>
</tr>
<tr>
<td>$T_3$</td>
<td>0.0471 K m/W</td>
</tr>
<tr>
<td>$T_4$</td>
<td>1.7341 K m/W</td>
</tr>
<tr>
<td>$n$</td>
<td>3</td>
</tr>
<tr>
<td>$\lambda_1$</td>
<td>8.798 $\cdot 10^{-5}$</td>
</tr>
<tr>
<td>$\lambda_2$</td>
<td>0</td>
</tr>
</tbody>
</table>
7.5. AMPACITY IN TWO CASES

7.4.1 Buried cables where drying-out of the soil does not occur

As declared in chapter 4 the ampacity can be calculated according to:

\[ I = \left( \frac{\Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{R[T_1 + n(1 + \lambda_1 + \lambda_2)(T_3 + T_4)]} \right)^{0.5} \]  \hspace{1cm} (7.15)

7.4.2 Buried cables where partial drying-out of the soil occurs

The permissible current rating is obtained from 4.1 according to [1] as follows:

\[ I = \left( \frac{[\Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + vT_4)] + (v - 1)\Delta \theta_x]}{R[T_1 + n(1 + \lambda_1 + \lambda_2)(T_3 + vT_4)]} \right)^{0.5} \] \hspace{1cm} [A] \hspace{1cm} (7.16)

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Partial dry-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_d )</td>
<td>3 Km/W</td>
</tr>
<tr>
<td>( \rho_w )</td>
<td>1 Km/W</td>
</tr>
<tr>
<td>( v )</td>
<td>3</td>
</tr>
<tr>
<td>( \theta_x )</td>
<td>50 °C</td>
</tr>
<tr>
<td>( \theta_a )</td>
<td>20 °C</td>
</tr>
<tr>
<td>( \Delta \theta_x )</td>
<td>30 K</td>
</tr>
</tbody>
</table>

\( \rho_d, \rho_w \) is the thermal resistivity of the dry/moist soil;

\( v = \rho_d / \rho_w \), the ratio of the thermal resistivities of the dry and moist soil zones;

\( \theta_x \) is the critical temperature rise of the soil and temperature of the boundary between dry and moist zones;

\( \Delta \theta_x = \theta_x - \theta_a \), the critical temperature rise of the soil. \( \theta_a \) is the ambient temperature of the soil.

7.5 Ampacity in two cases

With the power cable placed in a plastic duct at the depth of 1 m, conductor temperature of 90°C and an ambient temperature of 20°C the following data is gathered.
### CHAPTER 7. GATHERING AND CALCULATION OF AMPACITY DATA

<table>
<thead>
<tr>
<th>Specification</th>
<th>Ampacity [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No dry-out</td>
<td>205</td>
</tr>
<tr>
<td>Partial dry-out</td>
<td>180</td>
</tr>
</tbody>
</table>

**Table 7.4.** Electric power cable ampacity in two cases.
Chapter 8

Experiment Data

8.1 Data logg

When all data loggers were collected from the measurement site, the data was downloaded to a computer in the format seen in table 8.1. The data in table 8.1 is unedited, unfiltered and has not been corrected in terms of errors, hence the rough usage of significant figures.

Table 8.1. Table showing sample from gathered temperature data.

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Sensor 1 temperature [°C]</th>
<th>Sensor 2 temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011-05-17</td>
<td>16:34:00.000</td>
<td>16.9956</td>
<td>14.2653</td>
</tr>
<tr>
<td>2011-05-17</td>
<td>16:39:00.000</td>
<td>16.9999</td>
<td>14.2610</td>
</tr>
<tr>
<td>2011-05-17</td>
<td>16:44:00.000</td>
<td>17.0142</td>
<td>14.2639</td>
</tr>
<tr>
<td>2011-05-17</td>
<td>16:49:00.000</td>
<td>17.0286</td>
<td>14.2653</td>
</tr>
<tr>
<td>2011-05-17</td>
<td>16:54:00.000</td>
<td>17.0257</td>
<td>14.2668</td>
</tr>
<tr>
<td>2011-05-17</td>
<td>16:59:00.000</td>
<td>17.0329</td>
<td>14.2682</td>
</tr>
<tr>
<td>2011-05-17</td>
<td>17:04:00.000</td>
<td>17.0344</td>
<td>14.2653</td>
</tr>
<tr>
<td>2011-05-17</td>
<td>17:09:00.000</td>
<td>17.0473</td>
<td>14.2653</td>
</tr>
</tbody>
</table>

As mentioned in 5.3, three of the data loggers stores data from 2 sensors simultaneously. Data from these coincident measurements will be presented together for an accurate comparison.

8.2 Presentation of data

All data gathered from the data loggers (see figure 5.1 on page 30) was checked for errors (e.g. abnormal deviations in temperature from sensor compared to mean measurement values from the same sensor) and is presented in appendix D in figures
D.1, D.2, and D.3. Below in figure 8.1 an example of data visualization is presented. The x-axis shows time in days and the y-axis shows temperature in °C.

Figure 8.1. Example data from probes. Information on probe placement (4, 5 and 6) can be seen in figure 5.3 on page 32.
8.2. PRESENTATION OF DATA

Figure 8.2. Example data from moment of heat cable being shut off. See figure 5.3 for probe placement.
Chapter 9

Gathered Data on Time, Cost & Logistics

9.1 Time

All data in this section is gathered through interviews or questionnaires, each value or table of values will have one or several references to source.
The table below is used to roughly approximate time consumption in the two methods (existing method and suggested method). All phases defined as "-" are phases identical for the two methods or phases not affected by cable placement method.
The phases marked '-' will not be considered when comparing the cable placement methods. 'Hours' in the table are given as man-hours (10 hours can mean 1 person works for 10 hours or 2 persons for 5 hours each). Excavation, blasting is here considered to claim the same amount of time in both methods since the section trench construction accounts for the extra time required to excavate and construct the trench. The same applies to road construction where the difference in time is accounted for in the section duct installation.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Conventional</th>
<th>Duct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumbering</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Excavation, blasting</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Duct installation</td>
<td>0</td>
<td>27</td>
</tr>
<tr>
<td>Road construction</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Trench construction</td>
<td>70</td>
<td>0</td>
</tr>
<tr>
<td>Cable installation</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>Electric installation</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Σ</td>
<td>85</td>
<td>37</td>
</tr>
</tbody>
</table>
9.2 Cost

Material and service costs are the major parts of the total project cost. Both material demand and service need\(^1\) are included in the project plan, but only the material demand is unlikely to change during the project\(^2\) while the need for services is more flexible. Material needs in table 6.2 are approximations. To approximate the need for sand the trench is defined as 0.3 m deep and 0.3 m wide. In 1 km that trench has a volume of 90 m\(^3\). In some areas more sand is needed to fill out gaps - hence the extra 10 m\(^3\). The approximations does not include material for road construction. The demand and cost for renting a dump truck is multiplied with 3 for three trucks\(^3\) and multiplied again with 3 for three days use\(^4\). The cable pushing equipment mentioned in table 9.2 are the machines required to push/pull the power cable into the plastic duct. As mentioned in section 6.2 one machine is placed at the duct entrance where it pushes the power cable. The second machine is placed at the exit of the duct where the cable is pulled. Equipment used to push/pull the power cable can either be bought or rented per day. The cost to buy the complete push/pull equipment is approximately 0.5 MSEK . If the equipment is rented the cost per day is 5000-6000 SEK . The total price lies around 18-19 SEK/m installed power cable\(^5\). During one day a maximum of 4 push/pull operations can be performed.

Table 9.2. Material demand in the different cable placement methods\([18]\).

<table>
<thead>
<tr>
<th>Item</th>
<th>Conventional</th>
<th>Duct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>100 m(^3)</td>
<td>0 m(^3)</td>
</tr>
<tr>
<td>Plastic duct</td>
<td>0 m</td>
<td>1000 m</td>
</tr>
<tr>
<td>Cable pusher</td>
<td>0 pcs</td>
<td>2 pcs</td>
</tr>
</tbody>
</table>

Table 9.3. Costs (\([18]\), \([19]\)).

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost</th>
<th>Cost/1000 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>203 SEK/m(^3)</td>
<td>203 SEK/m(^3)*100 m(^3)=20300 SEK</td>
</tr>
<tr>
<td>Plastic duct</td>
<td>50 SEK/m</td>
<td>50000 SEK</td>
</tr>
<tr>
<td>Cable pusher</td>
<td>6000 SEK/pcs</td>
<td>6000 SEK</td>
</tr>
<tr>
<td>Man-hour</td>
<td>750 SEK/h</td>
<td>methods differing</td>
</tr>
<tr>
<td>Dump truck</td>
<td>2620 SEK/day</td>
<td>23580 SEK (ex fuel)</td>
</tr>
</tbody>
</table>

---

\(^1\)Excavation, transports, duct installation, etc.
\(^2\)According to Kjell Gustafsson \([20]\) and Urban Blom \([21]\)
\(^3\)Volvo dump truck (13 ton capacity) recommended rental price per day.
\(^4\)Cost/1000 m involves 3 trucks for 3 days
9.3 Logistics

Logistics, time and cost are closely connected to each other. In table 9.5 the need for logistics in each method is described.

<table>
<thead>
<tr>
<th>Service</th>
<th>Transport demand /1000 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conventional</td>
<td>Duct</td>
</tr>
<tr>
<td>Excavation removal</td>
<td>150 m³</td>
</tr>
<tr>
<td>Sand transport</td>
<td>100 m³</td>
</tr>
<tr>
<td>Power cable transport</td>
<td>1000 m, 2840 kg [6]</td>
</tr>
<tr>
<td>Duct transport</td>
<td>0 m, 0 kg</td>
</tr>
</tbody>
</table>

### Table 9.4. Actual material cost per km.

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost in SEK/1000 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>20300</td>
</tr>
<tr>
<td>Plastic duct</td>
<td>50000</td>
</tr>
<tr>
<td>Cable pusher</td>
<td>60000</td>
</tr>
<tr>
<td>Man-hours</td>
<td>63750</td>
</tr>
<tr>
<td>Transport</td>
<td>23580 (ex fuel)</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>107630</strong></td>
</tr>
</tbody>
</table>
Part III

Analysis & Results
Chapter 10

Analysis of Gathered Ampacity Data

According to ABB’s guide to XLPE cables [6], a three-core cable buried at a depth of 1 m in ground (20 °C ambient temperature), with an aluminium conductor cross section of 95 mm$^2$, is rated for 230 A (with a maximum conductor temperature of 90 °C). This rating applies only without the use of ducts.

The calculations performed accordingly to IEC-60287 (chapter 4) are adapted to the special circumstances regarding use of plastic ducts. The ducts adds thermal resistance to the system and slows the cooling of the power cable. The current rating is therefore lower than theoretical values from cable standards.

With the power cable placed in a plastic duct at the depth of 1 m, a conductor temperature of 90°C and an ambient temperature of 20°C the following data was gathered. The rated current (ampacity) for two different set-ups, according to section B.5, are:

1. Ampacity of power cable when no dry-out occurs:
   Equation B.23 shows that the rated current carrying capacity is 195 A.

2. Ampacity of power cable when partial dry-out occur:
   Equation B.24 shows that the rated current carrying capacity is 191 A

10.1 Temperature as a function of ampacity

Figure 10.1 shows how temperature is affected by the current flow in the chosen power cable. As mentioned in section 4.3.2 the thermal resistance of the surrounding medium affects the cable’s ability to transfer power. When soil is dried-out it transfers heat less effectively than in wet condition (section 2.2.7.3 in IEC-60287-2-1 [2]).

As can be seen the temperature starts at 20 °C which is the ambient temperature of the surrounding soil. All values above 90 °C is in the forbidden area where the
power cable must not reach. When placing the power cable in soil without the protective plastic duct the ampacity is 240 A at maximum conductor temperature. Adding the plastic duct to the system gives an ampacity of 205 A at 90 °C.

![Graph showing conductor temperature as function of current.](image)

**Figure 10.1.** Temperature as a function of current.

### 10.2 Summary of ampacity data analysis

The level of electric power production in a wind power plant is 100 % depending on the power in the wind. When there is no wind, the power plant does not produce electric power. At high wind speeds\(^1\) the power plant produces as much power as possible. Wind power plants delivers a non continuous electric power where the current is varying. Calculations performed according to IEC-60287 [1] does not include varying currents, but are based on continuous currents.

Section B.5 states that the ampacity is \(\approx 205\) ampere for a power cable placed in the plastic duct described in section B.3.2. The ampacity factor between the conventional method and the method using a plastic duct is called the reduction factor \(\kappa\). In equation 10.1 \(I_{\text{duct}}\) is the ampacity of the power cable placed in the duct and \(I_{\text{conv}}\) is the ampacity of the power cable placed in a trench the conventional way.

\(^1\)Wind power plants normally work in the range of a few m/s up to approximately 25 m/s [10](p.29)
10.2. SUMMARY OF AMPACITY DATA ANALYSIS

\[ \kappa = \frac{I_{\text{duct}}}{I_{\text{conv}}} = \frac{205}{240} = 0.85 \ldots \approx 0.85 \quad (10.1) \]

The Ampacity is 85 % of maximum possible value for power cables with properties according to the first section in chapter 10.

Table 10.1. Temperature vs. ampacity.

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Ampacity</th>
<th>Conventional</th>
<th>Duct</th>
</tr>
</thead>
<tbody>
<tr>
<td>65 °C</td>
<td>195</td>
<td>164</td>
<td></td>
</tr>
<tr>
<td>70 °C</td>
<td>205</td>
<td>172</td>
<td></td>
</tr>
<tr>
<td>75 °C</td>
<td>215</td>
<td>181</td>
<td></td>
</tr>
<tr>
<td>80 °C</td>
<td>225</td>
<td>189</td>
<td></td>
</tr>
<tr>
<td>85 °C</td>
<td>234</td>
<td>197</td>
<td></td>
</tr>
<tr>
<td>90 °C</td>
<td>240</td>
<td>205</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 11

Analysis of Experimental Data

Thermal properties of the soil and the plastic duct affects the power cable ampacity. Low thermal resistance is desirable for best possible heat transfer, but system constituents adds thermal resistance and can not be neglected.

11.1 Placement

As can be seen in all measurement data (Appendix D figure D.1, D.2, and D.3) the temperature is not only affected by the heat cable, but also by external sources. The sinusoidal changes in temperature can be traced to solar radiation. Nothing else in the area of the duct emits heat and the heat cable has a fixed power. Sensors placed closer to the surface of the road experiences greater temperature changes with solar radiation and air temperatures than sensors deeper down in the road [17]. A deeper placement also means less drying-out of the soil/sand due to external heat (solar radiation). An increased distance to ground level also decimates the cooling effect of heat being transferred by air.

11.2 Surrounding media

Even though two different kinds of filling were used around the duct and power cable no significant difference can be found between them. In one case sand was used and in the other gravel and stones\(^1\). In both cases measurements indicates low thermal resistance. Temperatures inside and outside the duct changes simultaneously. Compare Probe 4 and 5 in figure D.1 in appendix D to see the almost unnoticeable differences.

\(^1\)See section 5.3 for details.
11.3 Temperature

A power cable placed directly in soil without protective duct emits heat immediately into surrounding media. The ability of the system to transfer heat depends entirely on the thermal properties of the soil/sand. Introducing a plastic duct to the system means additional thermal resistance. Heat produced due to losses in the power cable is not transferred as easily as in the case where no protective layers surround the power cable.

11.4 Duct

The soil/gravel surrounding the plastic duct has a thermal resistivity of approximately 1 Km/W [6]. The duct itself has a thermal resistivity of around 6 Km/W. A material with high thermal resistivity has a low ability of heat transfer\(^2\). The impact from the duct’s thermal resistance can be seen in figure D.1 in appendix D and table 11.1 where indications are found supporting the theory that the duct both aggravates heat transfer and prevents further heating. In figure D.1 the difference in temperature between the sensors placed inside the duct and immediately outside can be seen. The thermal resistance of the duct cause a \(\approx 0.4^\circ\text{C}\) higher temperature inside the duct than outside (when external heat sources affect the system less than internal sources). When external heat sources affects the duct and power cable more than the heat cable, the duct works in the opposite way and protects the inside from heating up (in this case \(\approx 0.5^\circ\text{C}\) difference). After digging up both plastic ducts no damages were found on model SRN110 (see section 5.3). Small punctures were found on duct model SRS110 due to the coarse structure of the surrounding gravel.

11.5 Temperature restriction

One of the most important parts of the results from the experiment can be seen in figure 11.1 on page 62 where the continuous line marks temperatures inside the duct surrounded by sand. To understand how heat was conducted throughout the system the heat cable was turned off and the temperature sensors left to observe the result. Between the 20\(^{th}\) and the 21\(^{st}\) of May a sharp change in temperatures can be seen due to this heat restriction. From this one figure it is only possible to get a vague idea of what kind of change has occurred. However, comparing the result in figure 11.1 with the mean temperatures of the surroundings in table 11.1 on page 61 can give additional information regarding the thermal resistivity of the system.

\(^2\)As stated by Fourier’s law, the thermal analogue of Ohm’s law.
11.6. CIRCUMSTANCES

When transients for system heat up/cool down (see figure 11.2) has been accounted for, mean temperature values were calculated. The mean values in table 11.1 are used to confirm changes in temperature throughout the system. During the time the heat cable is on it emits heat and affects the system surrounding it (see section 5.3 details on set-up).

Probes 1, 2 and 3 are placed in the vicinity of the gravel covered duct while probes 4, 5 and 6 are placed close to the sand covered duct. Table 11.1 on page 61 describes mean temperatures based on data gathered by probes 1-6 according to figure 5.3 on page 32. $\bar{\theta}_{on}$ is the temperature when the heat cable is turned on. $\bar{\theta}_{off}$ is the temperature when the heat cable is turned off. $\Delta \bar{\theta}$ is the difference in temperature between $on$ and $off$. Negative difference means that the mean temperature was higher with the heat cable turned off than on. This is an effect of the heat from the sun.

Table 11.1. Mean temperatures with heat cable on and off.

<table>
<thead>
<tr>
<th>Sensor n</th>
<th>$\bar{\theta}_{n,\text{on}}$ [°C]</th>
<th>$\bar{\theta}_{n,\text{off}}$ [°C]</th>
<th>$\Delta \bar{\theta}_n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.5</td>
<td>14.8</td>
<td>0.7</td>
</tr>
<tr>
<td>2</td>
<td>14.5</td>
<td>14.9</td>
<td>-0.4</td>
</tr>
<tr>
<td>3</td>
<td>15.6</td>
<td>17.2</td>
<td>-1.6</td>
</tr>
<tr>
<td>4</td>
<td>16.4</td>
<td>16.3</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>16.0</td>
<td>16.7</td>
<td>-0.7</td>
</tr>
<tr>
<td>6</td>
<td>15.9</td>
<td>17.6</td>
<td>-1.7</td>
</tr>
</tbody>
</table>

11.6 Circumstances

When the experiment equipment (see section 5.2 on page 29) was installed it was done with regards to how the road is normally built. This means that no special regard was shown to sensors and data loggers installed in the road. To prepare the road for heavy traffic, the road surface is flattened with a heavy duty soil compactor.

This means two things:

1. The circumstances for the experiment (properties of the road material, geometry of the cable versus road surface, etc.) were similar to how they would be during a full scale application.

2. The equipment might have been affected by vibrations or other forces from the road preparation machines.

$^3$Extreme values in the beginning of data gathering (when sensors are still not buried) are neglected, see figure 11.2.
However, no indications of errors due to damages on equipment can be found. All data was compared with regards to deviations. Temperature peaks and daily fluctuations were found identical throughout all data logs (see figures D.1 and D.2 in appendix D on page 100).

![Temperature changes during 12 days, surrounded by sand, Probe 4 and 6](image)

**Figure 11.1.** Moment of heat cable being shut off. Probes inside duct and 2 dm above surrounded by sand.

### 11.7 Summary of experimental data analysis

Power cables placed in plastic ducts underneath roads are subjects to different thermal resistances and properties than power cables placed directly in soil in trenches. Shallow placement of power cables allow solar radiation to affect the cable and the ambient temperature of the surroundings. Using a plastic duct to protect the power cable (see section 5.3 on page 30 for further information) allows using additional techniques for cable placement. One of the two buried plastic duct types was undamaged on inspection. The ducts were shallowly placed and expected to have suffered more severe damages. Peak-to-peak temperature values were not expected to be so large in comparison to actual temperature. Cyclic variations in temperature is a result of solar radiation and cannot be avoided, but a more powerful heat cable could have increased the difference between the two. With an input solely from a heat cable would have given a constant temperature.
Figure 11.2. Heat up/cool down transient for system surrounded by sand. The peak represents the installation process when the sensor is placed above ground level (in the sun).
Chapter 12

Analysis of Time, Cost & Logistics Data

In this chapter some of the advantages of each method will be analysed. Time, cost and logistics are all important to accurately evaluate the value in the two competing power cable placement methods. The chapter following after Analysis is the chapter Conclusions & Future which is based on results from the analysis.

12.1 Time

The challenging method for cable placement\(^1\) differs from the existing method when it comes to time extent. In table 9.1 the difference between the two methods can be seen. The method of placing the power cable in a trench implies the construction of the trench and the placement of the cable. In the challenging method however, no trench is constructed, but a duct is placed in the road while constructing it. Vice versa, the trench method does not include any handling of a plastic duct. According to contractors (Mikael Karlsson [18], Christer Liljegren [19] and Statkraft employees Urban Blom [21] and Kjell Gustafsson [20]) the placement of a duct in the road takes less time than the construction of a trench. The duct method takes 37 hours/km power cable (where additional road work is included) compared to 83 hours/km power cable using the conventional method with power cable placed in a trench. Another benefit of the duct method is that the decreased installation time creates more flexibility for power cable establishment during different phases of the project.

12.2 Cost

In table 9.2 the actual material needs are presented. The need for cover-sand is high in the existing method, but on the other hand no duct is used in the trench. 100 m\(^3\) sand is an approximation, but the need for sand is extensive\(^2\). In the suggested

---

\(^1\)Power cable placed in a plastic duct underneath the road instead of directly in the ground in a trench next to the road.

\(^2\)100 m\(^3\) sand cost approximately 200 SEK/m\(^3\)
new method no additional sand is needed\(^3\), but this method demands the use of a plastic duct. To place the power cable inside the plastic duct, special power cable push and pull equipment is used. This equipment is not needed when placing the power cable in a trench.

### 12.3 Logistics

Already mentioned in section 12.2, one of the big differences between the two competing power cable placement methods is that when using a duct the power cable is pushed in after the duct has been buried. To perform the pushing of the power cable special power cable pushing equipment is required. According to Mikael Karlsson [18] pushing the power cable into the duct takes approximately 10 hours per kilometer power cable (including joining). See table 9.1 and 9.5 for details. In the trench scenario 150 m\(^3\) of excavation will have to be removed. At least 12 trips with a 13-ton loader is demanded to cover the demand for sand\(^4\) in the trench. Approximately 220 tons of excavation material is removed in the conventional method. That would require some 17 truck loads to remove. The soil removed when digging the trench can not be used again due to it’s coarse structure (risk of power cable damages).

### 12.4 Summary of time, cost & logistics data analysis

In both time, cost and logistics the two chosen methods differ. Where a duct is used, time is saved when no trench is needed. Higher flexibility is obtained when power cable installation can be performed during greater part of the project. Project costs are decimated when no additional excavation or material is needed for cable installation. Logistics advantages affect both time and cost. The amount of additional transports for sand and excavation material are considerably reduced. Only the sand needed for trench construction weighs approximately 145 tons and it would take one truck\(^5\) 12 trips to move that amount. In the duct method no machines used for cable trench construction will use the finished road.

---

\(^3\)The sand in the road is used to cover the duct  
\(^4\)100 m\(^3\) sand weighs approximately 145 tons.  
\(^5\)13 tons loading capacity.
Chapter 13

Analysis of Method Differences

The two methods for power cable placement are compared in table 13.1. Advantages and disadvantages are presented under each method and are subjectively compared to each other in each comment.
## Table 13.1. Advantages and disadvantages of power cable placement methods.

<table>
<thead>
<tr>
<th>Method</th>
<th>Conventional</th>
<th>Duct</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No duct installation</td>
<td>Trench construction</td>
<td>No trench construction</td>
</tr>
<tr>
<td>Sharing road with contractors inevitable</td>
<td>Cable pushing quicker than cable laying</td>
<td></td>
</tr>
<tr>
<td>Digging/excavating twice</td>
<td>Shorter overall power cable installation</td>
<td></td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No duct costs</td>
<td>Cost for 100 m$^3$ sand and it’s transport</td>
<td>No additional material costs</td>
</tr>
<tr>
<td>Cost for construction and restoration of trench</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large demand of excavation machines</td>
<td>Reuse of coarse excavation material possible</td>
<td>Duct installation equipment cost</td>
</tr>
<tr>
<td>No duct installation equipment cost</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Logistics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No equipment for duct needed</td>
<td>Transport of 100 m$^3$ sand</td>
<td>No additional excavation needed</td>
</tr>
<tr>
<td>150 m$^3$ excavation transport</td>
<td>No additional sand needed</td>
<td></td>
</tr>
<tr>
<td>Road shared with other contractors</td>
<td></td>
<td>No further use of road worth mentioning after duct installation</td>
</tr>
<tr>
<td><strong>Operation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Placed in wet soil - low thermal resistance</td>
<td>Sensitivity to dry - out of soil</td>
<td>Heavy duty protection for power cable</td>
</tr>
<tr>
<td>Favourable conditions for high ampacity</td>
<td>Dry-out decrease power cable lifetime</td>
<td></td>
</tr>
</tbody>
</table>
Part IV

Conclusions & Future Work
Chapter 14

Conclusions

All power cables are limited in terms of ability to withstand high temperatures. High operating temperatures affects the sheath and most other components of the cable. Component functionality may be compromised with an increase in thermal stress. Hence, the lifetime of the cable is dependent on that the maximum continuous operating temperature never exceeds that of the manufacturer's specification. Exceeding the specifications of the manufacturer can lead to hardening of flexible plastics, punctuating of protective layers, deterioration of cable armour, dry out of surrounding soil, etc. All these degradations can lead to the power cable being less resilient to outer forces (e.g. sharp rocks), troubled by short circuits, struck by water leakage, affected by decreasing ampacity and increasing thermal resistance.

If the power cable, on the other hand, is well adapted (rated) to reigning circumstances (dry soil, shifting load, etc.) it is according to section 3.1 less likely to deteriorate and demanded ampacity levels can be maintained.

When using the conventional method for placing power cables in wind power farms the issue of road usage is another of the big challenges. Can the time be divided between different contractors to reach the ultimate solution? As stated in the guidelines [12] for this project, the suggested method for power cable placement aims to decrease unfavourable interaction (simultaneous use of the road) between contractors. As presented in chapter 13 on page 67 the method using plastic ducts buried in the road creates a far more flexible environment for additional contractors using the road.

Since the above conclusion easily can be controlled, it might seem strange that the new method has not been tried earlier. In this case, the ampacity of the power cable placed in the plastic duct is a very important property that is not as easy to measure as the difference in time between two cable placement methods.

One change that could have given better results during thermal resistance measurements was the dimensioning of the heat cable installed in the duct. Even though
the heat cable was dimensioned according to the expected heat profile of the real power cable it gave weak results. The solar radiation affected the duct more than the heat cable. If the heat cable would have generated more heat the properties of the system could have shown more clearly, but would at the same time have shown results non compatible with the real scenario.

### 14.1 Ampacity

When placing a power cable in a plastic duct the thermal resistance of the system\(^1\) increases. With an increase in thermal resistance the current transfer also implies an increase in power cable temperature. Since the temperature affects the aging of the power cable the ampacity is limited to prevent exceeded temperature limits. IEC-60287 were used to confirm whether or not the ampacity adapted to a certain temperature was sufficient. All three investigated cases have led to acceptable current levels within the temperature specifications made by the cable manufacturer. In section 10.2 on page 56 the ampacity 190 A is compared to the specification of a similar power cable buried without a plastic duct. The ampacity reduction factor \(\kappa\) is then 0.82 which means 18 % lower ampacity with the power cable placed inside the duct. The reduction is due to an increase in thermal resistance added by the plastic duct and the medium filling the duct.

### 14.2 Time, cost & logistics

In the comparison between the conventional method and the new method it is clear that the method using a plastic duct has several advantages. First of all the duct method creates a more flexible environment for contractors using the road. Immediately after the road is finished transports of wind power plant material can begin. With the conventional method the road is finished and then used by the cable placement contractors. Contractors using the road for transports to and from the wind power plants are forced to share the road with the teams using the road to dig the trench for the power cable.

According to chapter 9 the duct method demands less **time** than the conventional method. The suggested method (using a duct) saves 46 hours per kilometer finished road and power cable. This time saving is important partly because of it’s effect on cost reduction, but also because of the increased phase implementation flexibility\(^2\). Time is saved partly because the power cable is pushed into the duct, but foremost because almost all usage of the finished road for cable installation is eliminated. Many **hours** of work are also saved when no additional excavation or

---

\(^1\)Electric power cable and plastic duct

\(^2\)E.g. installation of the power cable is simplified and can be performed both quicker and with greater flexibility regarding time.
14.3. WIND POWER FARM

Sand transports are needed (see section 12.3). All transports of additional\(^3\) sand and excavation material is eliminated in the duct method. Costs decrease when no additional material is needed to construct trenches and no additional excavation transports are needed since the duct is placed within the road. The heavy duty quality of the duct makes it possible to reuse the coarse excavated material from road construction. According to table 9.4 the conventional method cost \(\approx 108000\) SEK/km finished road and placed power cable\(^4\). The duct method is approximated to cost 88000 SEK/km finished road and placed power cable. Logistics Usage of the road is more flexible than with the conventional method since the roads are not used for neither trench construction nor power cable placement. This logistic advantage leads to time savings and in the end decreased cost. Placing the duct in the road adds approximately 27 hours of additional delay per kilometer, but minimizes the simultaneous use of the finished road. Placing the cable the conventional way demands approximately 70 hours of simultaneous road usage per kilometer.

14.3 Wind power farm

With regards to analysis and conclusions this section will contain calculations approximating the impact on projects involving several wind power plants. In this case a 10 power plant farm is treated.

A farm with 10 power plants demand an area of approximately 1150x1230 m\(^2\) (based on Wind farm configuration on page 236 in Wind Power Projects (2008), T Wizelius [10]). Assuming the wind farm is located close to the public grid (\(\approx 3\) km) it is possible to calculate the need for logistics as well as time demand and cost. Given that the farm is constructed in an optimal way a total of \(\approx 8\) km power cable\(^5\) is demanded. Table 14.1 shows the total cost of a 10 wind power plants farm (regarding power cable placement). The power cable placement methods differ in time demand and based on the 10 power plant suggestion the conventional method would require \((83-37)\ h*8\ km=368\) man-hours more than the duct-method.

14.4 Summary

Based of results gathered according to chapter 4, 5 and 6, analysed in chapter 10 the method where the power cable is placed underneath the road in a plastic duct is considered advantageous compared to conventional methods. Using a duct offers improved solutions in areas such as logistics, cost and time demand.

---

\(^3\)Sand and excavation material is still transported in both methods when the road is constructed.  
\(^4\)The cost is defined as 'cost above mutual cost' where the construction of the road is a common cost for both methods.  
\(^5\)1 km connecting power plants three and three, 1 km to join all plants and 3 km to extend the power cable towards connection on public grid.
Table 14.1. Approximations regarding a wind power farm with 10 power plants.

<table>
<thead>
<tr>
<th>Item</th>
<th>Conventional</th>
<th>Duct</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>162400</td>
<td>0</td>
</tr>
<tr>
<td>Plastic duct</td>
<td>0</td>
<td>400000</td>
</tr>
<tr>
<td>Cable pusher</td>
<td>0</td>
<td>48000</td>
</tr>
<tr>
<td>Man-hours</td>
<td>510000</td>
<td>220000</td>
</tr>
<tr>
<td>Transport</td>
<td>188640 (ex fuel)</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>861040</td>
<td>670000</td>
</tr>
</tbody>
</table>

The protection from the plastic duct allows the power cable to be placed in an apparent exposed position. Rocks and other coarse road fillings does not affect the plastic duct or power cable in an observable way. Cables placed in a trench next to the road (without duct) are highly dependant on a surrounding of sand and the absence of rocks and stones. The depth of the placement is crucial for power cable capacity (ampacity) in both the conventional method and the method using a plastic duct. Ambient temperature of the air above ground and solar radiation affects the temperature of the power cable can be avoided by deeper placement. The surrounding material also affects the ampacity and can be selected to compensate for disadvantages created by shallow placement. Materials with low thermal resistance should be chosen.

When implementing the method using plastic ducts there are advantages regarding both costs and construction time. A faster construction time is not obvious to be a certain gain. If cost increases and logistics grow more complex a quick construction time does not always lead to sought benefits. But if time savings is combined with enhancements in at least one of the areas cost or logistics advantages could be found. Complex logistic planning is one of the issues that can be avoided (or at least simplified) with this new method for power cable placement. The fact that one contractor less will use the road after it’s finishing solves many unnecessary conflicts and/or contractor "clashes". Plans of road usage are simplified with the new method.
Chapter 15

Discussion

Due to constant increasing metal costs current carrying capacity (ampacity) will always be a problem when dimensioning a power cable. An easy solution is naturally to use a cable with dimensions big enough to handle all eventual power production. As long as cost is an constituent in project management the dimension of the power cable will be smallest possible to ensure power transfer capabilities.

Cooling

Cooling inside the power cable or duct is an alternative to keep temperatures to an acceptable level. Adding cooling systems adds cost, logistics planning and maintenance issues to the project.

Power Limits

The size of the power plant (in terms of power) is important when handling issues regarding ampacity. Small power plants have need for power cables handling lower ampacities (lower ampacity=cable dimension smaller).

External Influence

If the power cable is placed in material with low thermal resistance the heat produced in the conductor will easier be transferred away from the cable and maintaining the ampacity at an acceptable level. Low thermal resistance materials are more expensive and all additional changes of the surroundings adds cost to the project.
Chapter 16

Future

This report handles a fraction of all possible methods and techniques for placing and evaluating power cable capacity and logistics and cost planning. Based on the knowledge gained from this project some suggestions will be presented for future work or supplementary investigations. To make a decision whether or not a specific technique or method should be used it needs evaluation. The method should be tested small scale and integrated slowly for best result. The suggested method mentioned in this report will be further tested and evaluated before implementation.

For more trustworthy complements to calculations performed according to international standard IEC-60287, temperature changes due to screen currents should be investigated. What level of current can be found in the screen and how does it affect the overall ampacity?

A full scale test should be performed where the load differs. In this report the load is constant which might affect results where the power plant delivers different power levels. During a full scale test different loads should be applied and the performance monitored.
Bibliography

16.1 International Standards


[3] IEC 60287-3-2; Electric cables - Calculation of the current rating - Part 3-2: Sections on operating conditions - Economic optimization of power cable size. International Electrotechnical Commission, 1995-06

16.2 Books & Publications


BIBLIOGRAPHY


16.3 Internet


16.4 Meetings & Interviews


Appendix A

Detailed Description of IEC-60287

The following appendix is in its entirety a summary of the exact wording of IEC-60287. See chapter E for acknowledgement. In IEC-60287-1-1 [1] the ampacity of an AC cable is derived from the expression for the temperature rise of the cable conductor above ambient temperature:

\[
\Delta \theta = (I^2 R + \frac{1}{2} W_d) T_1 + [I^2 R(1 + \lambda_1) + W_d] n T_2 + [I^2 R(1 + \lambda_1 + \lambda_2) + W_d] n (T_3 + T_4) 
\]  

(A.1)

where

- \( I \) is the current flowing in one conductor [A];
- \( \Delta \theta \) is the conductor temperature rise above the ambient temperature [K];

NOTE The ambient temperature is the temperature of the surrounding medium under normal conditions, at a situation in which cables are installed, or are to be installed, including the effect of any local source of heat, but not the increase of temperature in the immediate neighbourhood of the cables due to heat arising therefrom.

- \( R \) is the alternating current resistance per unit length of the conductor at maximum operating temperature [\( \Omega/m \)];
- \( W_d \) is the dielectric loss per unit length for the insulation surrounding the conductor [W/m];
- \( T_1 \) is the thermal resistance per unit length between one conductor and the sheath [Km/W];
- \( T_2 \) is the thermal resistance per unit length of the bedding between sheath and armour [Km/W];
- \( T_3 \) is the thermal resistance per unit length of the external serving of the cable [Km/W];
APPENDIX A. DETAILED DESCRIPTION OF IEC-60287

\( T_4 \) is the thermal resistance per unit length between the cable surface and the surrounding medium \([Km/W]\);

\( n \) is the number of load-carrying conductors in the cable (conductors of equal size and carrying the same load);

\( \lambda_1 \) is the ratio of losses in the metal sheath to total losses in all conductors in that cable;

\( \lambda_2 \) is the ratio of losses in the armouring to total losses in all conductors in that cable.

A.0.1 Buried cables where drying-out of the soil does not occur

The permissible current rating is obtained from 4.1 according to IEC 60287-1-1 [1] as follows:

\[
I = \left[ \frac{\Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{R[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + T_4)]} \right]^{0.5} \quad [A] \quad (A.2)
\]

A.0.2 Buried cables where partial drying-out of the soil occurs

The permissible current rating is obtained from 4.1 according to IEC 60287-1-1 [1] as follows:

\[
I = \left[ \frac{\Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + vT_4)] + (v - 1)\Delta \theta_x}{R[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + vT_4)]} \right]^{0.5} \quad [A] \quad (A.3)
\]

where

\( v \) is the ratio of the thermal resistivities of the dry and moist soil zones \((v = \rho_d/\rho_w)\);

\( \rho_d \) is the thermal resistivity of the dry soil \([Km/W]\);

\( \rho_w \) is the thermal resistivity of the moist soil \([Km/W]\);

\( \theta_x \) is the critical temperature rise of the soil and temperature of the boundary between dry and moist zones \(\circ C\);

\( \theta_a \) is the ambient temperature \(\circ C\);

\( \Delta \theta_x \) is the critical temperature rise of the soil. This is the temperature rise of the boundary between the dry and moist zones above the ambient temperature of the soil \((\theta_x - \theta_a) \) \([K]\);
A.1. CALCULATION OF LOSSES

θ and ρd shall be determined from a knowledge of the soil conditions.

NOTE The soil parameters may be agreed between power cable manufacturer and purchaser.

A.1 Calculation of losses

A.1.1 AC resistance of conductor

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

\[ R = R' (1 + y_s + y_p) \] [Ω] \hspace{1cm} (A.4)

where

- \( R \) is the current resistance of conductor at maximum operating temperature [Ω/m];
- \( R' \) is the d.c. resistance of conductor at maximum operating temperature [Ω/m];
- \( y_s \) is the skin effect factor;
- \( y_p \) is the proximity effect factor.

DC resistance of conductor

\[ R' = R_0 [1 + \alpha_{20}(\theta - 20)] \] [Ω] \hspace{1cm} (A.5)

where

- \( R_0 \) is the d.c. resistance of the conductor at 20 °C [Ω/m];

**NOTE** \( R_0 \) is calculated using the equation for resistance of a conductor of uniform cross section: \( R_0 = \rho \frac{L}{A} \)

where

- \( \rho \) is the resistivity of aluminium at 20 °C [Ω ⋅ m];
- \( L \) is the length of the conductor in [m];
- \( A \) is the cross section area of the conductor in [m²].

- \( \alpha_{20} \) is the constant mass temperature coefficient for aluminium at 20 °C per Kelvin;
- \( \theta \) is the maximum operating temperature in °C.
APPENDIX A. DETAILED DESCRIPTION OF IEC-60287

Skin effect factor $y_s$

The skin effect factor $y_s$ is given by:

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

where

\[
x_s^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_s
\]

$f$ is the supply frequency in hertz.

Proximity effect factor $y_p$ (for three-core cables)

The proximity effect factor is given by:

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

where

\[
x_p^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_p
\]

$d_c$ is the diameter of conductor [mm];

$s$ is the distance between conductor axes [mm].

A.1.2 Dielectric losses

The dielectric loss per unit length in each phase is given by:

\[
W_d = \omega C U_0^2 \tan \delta \ [W/m]
\]

where

\[
\omega = 2\pi f;
\]

$C$ is the capacitance per unit length [F/m];

$U_0$ is the voltage to earth [V].
A.1. CALCULATION OF LOSSES

The capacitance for circular conductors is given by:

\[ C = \frac{\varepsilon}{18 \ln \frac{D_i}{d_c}} \cdot 10^{-9} \, [F/m] \]  

(A.11)

where

\( \varepsilon \) is the relative permittivity of the insulation;

\( D_i \) is the external diameter of the insulation (excluding screen) [mm];

\( d_c \) is the diameter of conductor, including screen, if any [mm].

A.1.3 Loss factor for sheath and screen

The power loss in the sheath or screen (\( \lambda_1 \)) consists of losses caused by circulating currents (\( \lambda_1' \)) and eddy currents (\( \lambda_1'' \)), thus:

\[ \lambda_1 = \lambda_1' + \lambda_1'' \]  

(A.12)

The formulae given in this section express the loss in terms of the total power loss in the conductor(s).

\[ R_S = R_{S0} [1 + \alpha_{20}(\theta_{SC} - 20)] \, [\Omega/m] \]  

(A.13)

where

\( R_{S0} \) is the resistance of the cable sheath or screen at 20 °C [\( \Omega/m \)].

\[ \lambda_1' = \frac{R_S}{R} \frac{1}{1 + \left( \frac{R_S}{X} \right)^2} \]  

(A.14)

where

\( R_S \) is the resistance of sheath or screen per unit length of cable at its maximum operating temperature [\( \Omega/m \)];

\( X \) is the reactance per unit length of sheath or screen per unit length of cable

\[ = 2\omega \cdot 10^{-7} \ln \frac{2A}{d} \, [\Omega/m] \];

\( \omega \) is [1/s];

\( s \) is the distance between conductor axes in the electrical section being considered [mm];

\( d \) is the mean diameter of the sheath [mm].
\( \lambda_1'' = 0 \). The eddy-current loss is ignored according to IEC 60287-1-1 section 2.3.1 [1].

The eddy-current loss \( \lambda_1'' \) is ignored according to IEC 60287-1-1 section 2.3.1 [1].

### A.2 Thermal resistance

#### A.2.1 Thermal resistance of constituent parts of a cable

**Thermal resistance between one conductor and sheath \( T_1 \)**

For screened cables with circular conductors the thermal resistance \( T_1 \) is:

\[
T_1 = \frac{\rho_T}{2\pi} G
\]  

(A.15)

where

- \( G \) is the geometric factor according to IEC60287 [2];
- \( \rho_T \) is the thermal resistivity of insulation \([Km/W]\);

**Thermal resistance between sheath and armour \( T_2 \)**

AXKJ-F 3x95/25 does not contain armour nor metallic sheath. Hence \( T_2 \) is not considered.

**Thermal resistance of outer covering (serving) \( T_3 \)**

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

(A.16)

where

- \( t_3 \) is the thickness of serving \([mm]\);
- \( D_a \) is the external diameter of the armour \([mm]\);

#### A.2.2 External thermal resistance \( T_4 \)

The external thermal resistance of a cable in a duct consists of three parts:

- \( T_4' \) is the thermal resistance of the air space between the cable surface and duct’s internal surface;
- \( T_4'' \) is the thermal resistance of the duct itself;
- \( T_4''' \) is the external thermal resistance of the duct.

\[
T_4 = T_4' + T_4'' + T_4'''
\]  

(A.17)
A.2. THERMAL RESISTANCE

Thermal resistance between cable and duct $T'_4$

$$T'_4 = \frac{U}{1 + 0.1(V + Y\theta_m)D_e}$$  \hspace{1cm} \text{(A.18)}

where

- $D_e$ is the external diameter of the cable [mm];
- $\theta_m$ is the mean temperature of the medium filling the space between cable and duct. An assumed value has to be used initially and the calculation repeated with a modified value if necessary [$^\circ$C];

Thermal resistance of the duct $T''_4$

$$T''_4 = \frac{\rho_T}{2\pi} \cdot \ln \left(1 + \frac{D_0}{D_d}\right)$$  \hspace{1cm} \text{(A.19)}

where

- $D_0$ is the outside diameter of the duct [mm];
- $D_d$ is the inside diameter of the duct [mm];
- $\rho_T$ is the thermal resistivity of duct material [Km/W]

External thermal resistance of the duct $T'''_4$

$$T'''_4 = \frac{1}{2\pi} \rho_T \cdot \ln (2u)$$  \hspace{1cm} \text{(A.20)}

where

- $\rho_T$ is the thermal resistivity of the soil [Km/W];
- $u = \frac{2L}{D_0}$, $L$ is the placement depth [mm];
Appendix B

Detailed Description of Calculations According to IEC-60287

This chapter shows calculations regarding ampacity performed accordingly to IEC-60287 in chapter 4. First of all, standard parts\(^1\) of the ampacity is handled. Secondly, the ampacity is calculated for three specific scenarios.

The ambient soil temperature is estimated to 20 °C and hence the difference in temperature in Kelvin, \(\Delta \theta\), between soil and aluminium conductor is \((90-20) \, ^\circ C + 273.15 = 343.15\) K.

\( B.1 \) Ampacity

Calculations have been performed according to two different prerequisites based on IEC-60287. They are:

1. Buried cables where drying-out of the soil does not occur
2. Buried cables where partial drying-out of the soil occurs

\( B.2 \) Calculation of losses

See chapter 4 or appendix A for details.

\( B.2.1 \) AC resistance of conductor

\[
R = R' (1 + y_s + y_p) \tag{B.1}
\]

\(^1\)Calculations common for all cables studied in this report.
APPENDIX B. DETAILED DESCRIPTION OF CALCULATIONS ACCORDING TO IEC-60287

DC resistance of conductor

\[ R' = R_0[1 + \alpha_{20}(\theta - 20)] \quad (B.2) \]

where \( R_0 \) is the dc resistance of the conductor at 20 °C.

\[ R_0 = \rho L A = \left[ \rho = \rho_{\text{aluminium}} = 2.8264 \cdot 10^{-8} [\Omega \cdot m], \; L = 1 [m], \; A = 95 \cdot 10^{-6} [m^2] \right] = 2.8264 \cdot 10^{-8} \frac{1}{95 \cdot 10^{-6}} = 0.00029752 [\Omega/m] \]

and \( \alpha_{20} = 4.03 \cdot 10^{-3} [1/K], \; \theta = 90 \degree C \)

\[ \rightarrow R' = R_0[1 + \alpha_{20}(\theta - 20)] = 0.00029752 \cdot [1 + 4.03 \cdot 10^{-3}(90 - 20)]\Omega = 0.00038144 \Omega \]

Skin effect factor \( y_s \)

\[ y_s = \frac{x_s^4}{192 + 0.8 \cdot x_s^4} \quad (B.3) \]

where

\[ x_s = \sqrt{\frac{8\pi f}{R'}} \cdot 10^{-7} \cdot k_s \{ k_s = 1 \} = \sqrt{\frac{8\pi 50}{0.00038144} \cdot 10^{-7}} = 0.57397 \]

\[ \rightarrow y_s = \frac{0.57397^4}{192 + 0.8 \cdot 0.57397^4} = 0.00056501 \]

Proximity effect factor \( y_p \) (for three-core cables)

The proximity effect factor is given by:

\[ y_p = \frac{x_p^4}{192 + 0.8 x_p^4} \left( \frac{d_c}{s} \right)^2 \left[ 0.312 \cdot \left( \frac{d_c}{s} \right)^2 + \frac{1.18}{192 + 0.8 x_p^4} + 0.27 \right] \quad (B.4) \]

where

\[ x_p = \sqrt{\frac{8\pi f}{R'}} \cdot 10^{-7} \cdot k_p \{ k_p = 0.8 \} = \sqrt{\frac{8\pi 50}{0.00038144} 0.8 \cdot 10^{-7}} = 0.26355 \]

d_c=12 mm, the diameter of the conductor;
s=30 mm, the distance between conductor axes.
B.2. CALCULATION OF LOSSES

\[ y_p = \frac{0.26355^4}{192 + 0.8 \cdot 0.26355^4} \left( \frac{12}{30} \right)^2 \left[ 0.312 \cdot \left( \frac{12}{30} \right)^2 + \frac{1.18}{192 + 0.8 \cdot 0.26355^4 + 0.27} \right] = 0.00025545 \]

\[ \rightarrow R = R'(1 + y_s + y_p) = 0.00038144 \cdot (1 + 0.00056501 + 0.00025545) \, \Omega = 0.0038175 \, \Omega \]

B.2.2 Dielectric losses

The dielectric loss per unit length in each phase is given by:

\[ W_d = \omega U_0^2 \tan \delta \]  \hspace{1cm} (B.5)

\[ \omega = 2\pi f = \{ f = 50 \, \text{Hz} \} = 2\pi 50 \, \text{rad/s}; \]
\[ U_0 = \frac{36}{\sqrt{3}} \cdot 10^3 = V, \text{ the voltage to earth}; \]
\[ \tan \delta = 0.004, \text{ loss factor of the insulation (XLPE)}. \]

The capacitance for circular conductors is given by:

\[ C = \frac{\varepsilon}{18 \ln \frac{D_i}{d}} \cdot 10^{-9} = \frac{2.5}{18 \ln \frac{28}{12}} \cdot 10^{-9} \, F/m = 0.16392 \cdot 10^{-9} \, F/m \]  \hspace{1cm} (B.6)

\[ \varepsilon = 2.5, \text{ the relative permittivity of the insulation (XLPE)}; \]
\[ D_i = 28 \, \text{mm}, \text{ the external diameter of the insulation (excluding screen)}. \]

\[ \rightarrow W_d = \omega U_0^2 \tan \delta = 2\pi 50 \cdot 0.16392 \cdot 10^{-9} \left( \frac{36}{\sqrt{3}} \cdot 10^3 \right)^2 \cdot 0.004 \, W/m = 0.088987 \, W/m \]

B.2.3 Loss factor ($\lambda_1$) for screen

\[ \lambda_1 = \lambda_1' + \lambda_1'' \]  \hspace{1cm} (B.7)

\[ \lambda_1' = \frac{R_S}{R} \frac{1}{1 + \left( \frac{R_S}{X} \right)^2} \]  \hspace{1cm} (B.8)

where

\[ X = 2\omega \cdot 10^{-7} \ln \frac{2s}{d} = 2 \cdot 2\pi 50 \cdot 10^{-7} \ln \frac{2 \cdot 30}{55.168} \, \Omega/m \approx 5.275 \cdot 10^{-6} \, \Omega/m \]

\[ R_S = R_{S0} \left[ 1 + \alpha_{20}(\theta_{SC} - 20) \right] \]  \hspace{1cm} (B.9)

\[ R_{S0} = \rho C U \cdot \frac{l_{SC}}{A_{SC}} = 1.7241 \cdot 10^{-8} \frac{1}{25 \cdot 10^{-6}} \, \Omega/m = 0.00068964 \, \Omega/m, \text{ the resistance of the cable screen at 20} \, ^\circ \text{C}; \]
\[ \theta_{SC} = \theta - 20 = 95 - 20 \, ^\circ\text{C} = 75 \, ^\circ\text{C}, \text{ the approximated maximum operating temperature of the screen.} \]

\[ R_S = 0.00068964 \left[ 1 + 4.03 \cdot 10^{-3} (95 - 20) \right] \Omega/m = 0.000856394952 \Omega/m \]

\[ \lambda_1' = \frac{R_S}{R} \frac{1}{1 + \left( \frac{R_S}{X} \right)^2} = \frac{0.000856394952}{0.0038175} \frac{1}{1 + \left( \frac{0.000856394952}{3.275 \cdot 10^{-6}} \right)^2} = 8.798 \cdot 10^{-5} \]

The eddy-current loss \( \lambda_1'' \) is ignored according to IEC 60287-1-1 section 2.3.1 [1].

\[ \lambda_1 = \lambda_1' + \lambda_1'' = 8.798 \cdot 10^{-5} + 0 = 8.798 \cdot 10^{-5} \]

### B.3 Thermal resistance T

See section 4.3 for extended explanation of how the thermal resistance \( T \) is considered.

\[ T = T_1 + T_2 + T_3 + T_4 \]

#### B.3.1 Internal thermal resistances, \( T_1, T_2 \) and \( T_3 \)

Thermal resistance between one conductor and sheath \( T_1 \)

\[ T_1 = \frac{\rho_{T, PEX}}{2\pi} G \]  

\( G \approx 1.63 \), the geometric factor according to IEC60287 [2];
\( \rho_{T, PEX} = 3.5 \, \text{Km/W} \), the thermal resistivity of PEX insulation.

\[ T_1 = \frac{\rho_{T, PEX} G}{2\pi} = \frac{3.5}{2\pi} 1.63 \, \text{Km/W} = 0.90798 \, \text{Km/W} \]  

#### Thermal resistance between sheath and armour \( T_2 \)

AXKJ-F 3x95/25 does not contain armour nor metallic sheath. Hence \( T_2 \) is not considered.

\[ T_2 = 0 \]
B.3. THERMAL RESISTANCE $T$

Thermal resistance of outer covering (serving) $T_3$

$$T_3 = \frac{\rho_{T,PVC}}{2\pi} \cdot \ln \left(1 + \frac{2t_3}{D'_a}\right)$$  \hspace{1cm} (B.13)

$t_3=3$ mm, the thickness of the serving;

$D'_a=55.168$ mm, the external diameter of the armour (or mean diameter of the screen).

$\rho_{T,PVC}=6.0$ Km/W, the thermal resistivity of the PVC serving.

$$T_3 = \frac{6.0}{2\pi} \cdot \ln \left(1 + \frac{2 \cdot 3}{55.168}\right) = 0.098588 \text{ Km/W}$$ \hspace{1cm} (B.14)

B.3.2 External thermal resistance $T_4$

$$T_4 = T'_4 + T''_4 + T'''_4$$  \hspace{1cm} (B.15)

Thermal resistance between cable and duct $T'_4$

$$T'_4 = \frac{U}{1 + 0.1(V + Y\theta_m)D_e}$$  \hspace{1cm} (B.16)

$U=1.87$, $V=0.312$ and $Y=0.0037$, material constants;

$D_e=64$ mm, the external diameter of the cable;

$\theta_m=40 \, ^\circ\text{C}$, the mean temperature of the medium filling the space between cable and duct.

$$T'_4 = \frac{1.87}{1 + 0.1(0.312 + 0.0037 \cdot 40)64} = 0.4129 \text{ Km/W}$$ \hspace{1cm} (B.17)

Thermal resistance of the duct $T''_4$

$$T''_4 = \frac{\rho_{T,PVC}}{2\pi} \cdot \ln \left(\frac{D_0}{D_d}\right)$$  \hspace{1cm} (B.18)

$D_0=110$ mm, the outside diameter of the duct;

$D_d=95$ mm, the inside diameter of the duct;

$$T''_4 = \frac{3.5}{2\pi} \cdot \ln \left(\frac{110}{95}\right) \text{ Km/W} = 0.0817 \text{ Km/W}$$ \hspace{1cm} (B.19)

External thermal resistance of the duct $T'''_4$

$$T'''_4 = \frac{1}{2\pi\rho_{soil}} \cdot \ln (2u)$$  \hspace{1cm} (B.20)
\( \rho_{soil} = 1.0 \text{ Km/W}, \) the thermal resistivity of earth around bank;

\( L = 700 \text{ mm}, \) the depth of the laying to centre of duct bank;

\( D_0 = 110 \text{ mm}, \) the external diameter of the duct;

\( u = \frac{2 \pi L}{D_0} = \frac{2 \pi 700}{110} = 12.73; \)

\[
T''''_4 = \frac{1}{2 \pi} \rho_{soil} \cdot \ln (2u) = \frac{1}{2 \pi} \cdot 1.0 \cdot \ln (2 \cdot 12.73) \text{ K/m/W} = 0.6137 \text{ K/m/W} \quad \text{(B.21)}
\]

\[
T'_4 = T'''_4 + T''''_4 = 0.4129 + 0.0817 + 0.6137 \text{ K/m/W} = 1.1083 \text{ K/m/W} \quad \text{(B.22)}
\]

### B.4 Summary

Table B.1. Ampacity common physical quantities.

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>No dry-out; Partial dry-out; Avoid dry-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta \theta )</td>
<td>343.315 K</td>
</tr>
<tr>
<td>( R )</td>
<td>0.0038175 ( \Omega )/m</td>
</tr>
<tr>
<td>( W_d )</td>
<td>0.088987 W/m</td>
</tr>
<tr>
<td>( T_1 )</td>
<td>0.90798 Km/W</td>
</tr>
<tr>
<td>( T_2 )</td>
<td>0 Km/W</td>
</tr>
<tr>
<td>( T_3 )</td>
<td>0.098588 Km/W</td>
</tr>
<tr>
<td>( T_4 )</td>
<td>1.1083 Km/W</td>
</tr>
<tr>
<td>( n )</td>
<td>3</td>
</tr>
<tr>
<td>( \lambda_1 )</td>
<td>8.798 \times 10^{-5}</td>
</tr>
<tr>
<td>( \lambda_2 )</td>
<td>0</td>
</tr>
</tbody>
</table>

### B.4.1 Buried cables where drying-out of the soil does not occur

As declared in chapter 4 the ampacity can be calculated according to:

\[
I = \left[ \frac{\Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)]}{R[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + T_4)]} \right]^{0.5} \quad \text{(B.23)}
\]

### B.4.2 Buried cables where partial drying-out of the soil occurs

The permissible current rating is obtained from 4.1 according to [1] as follows:
B.5. AMPACITY IN TWO CASES

\[ I = \left[ \frac{\Delta \theta - W_d[0.5T_1 + n(T_2 + T_3 + vT_4)] + (v - 1)\Delta \theta_x}{R[T_1 + n(1 + \lambda_1)T_2 + n(1 + \lambda_1 + \lambda_2)(T_3 + vT_4)]} \right]^{0.5} \]  \hspace{1cm} (B.24)

Table B.2. Physical quantities for partial dry-out.

<table>
<thead>
<tr>
<th>Physical quantity</th>
<th>Partial dry-out</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_d )</td>
<td>3 Km/W</td>
</tr>
<tr>
<td>( \rho_w )</td>
<td>1 Km/W</td>
</tr>
<tr>
<td>( v )</td>
<td>3</td>
</tr>
<tr>
<td>( \theta_x )</td>
<td>50 °C</td>
</tr>
<tr>
<td>( \theta_a )</td>
<td>20 °C</td>
</tr>
<tr>
<td>( \Delta \theta_x )</td>
<td>303.15 K</td>
</tr>
</tbody>
</table>

\( \rho_d \) is the thermal resistivity of the dry soil;
\( \rho_w \) is the thermal resistivity of the moist soil;
\( v = \rho_d/\rho_w \), the ratio of the thermal resistivities of the dry and moist soil zones;
\( \theta_x \) is the critical temperature rise of the soil and temperature of the boundary between dry and moist zones;
\( \theta_a \) is the ambient temperature;
\( \Delta \theta_x = \theta_x - \theta_a \), the critical temperature rise of the soil. This is the temperature rise of the boundary between the dry and moist zones above the ambient temperature of the soil.

### B.5 Ampacity in two cases

Table B.3. Electric power cable ampacity in two cases.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Ampacity [A]</th>
</tr>
</thead>
<tbody>
<tr>
<td>No dry-out</td>
<td>205</td>
</tr>
<tr>
<td>Partial dry-out</td>
<td>180</td>
</tr>
</tbody>
</table>
Appendix C

Power cable placement

Figure C.1. Model describing current placement of cables and suggested placement of plastic duct (bird’s-eye view of the road).
Appendix D

Temperature data

All data gathered from the data loggers (see figure 5.1 on page 30) was controlled for errors (such as abnormal temperatures compared to mean values) and is presented in diagrams according to figures D.1, D.2, and D.3. The x-axis shows time in days and the y-axis shows temperature in °C.

D.0.1 Sand

Figure D.1 shows temperature changes inside the duct (according to figure 5.3 on page 32, marker number 4), on the duct (marker number 5) and 2 dm above the duct (marker number 6).

D.0.2 Gravel/stones

Figure D.2 shows temperature changes inside the duct (according to figure 5.3 on page 32, marker number 1), on the duct (marker number 2) and 2 dm above the duct (marker number 3).

D.0.3 All values

Figure D.3 shows data from all used probes. This diagram can be used to see differences in between system constituents.

Figures D.4, D.5 and D.6 show the effect on temperature when the heat cable was turned off.
APPENDIX D. TEMPERATURE DATA

**Figure D.1.** Data from probes placed inside the duct, immediately outside the duct and 2 dm above, surrounded by sand.

**Figure D.2.** Data from probes placed inside the duct, immediately outside the duct and 2 dm above, surrounded by gravel and stones (material contents according to 5.3 on page 30).
Figure D.3. Data from all probes.
Figure D.4. Moment of heat cable being shut off. Probe on plastic duct surrounded by sand.

Figure D.5. Moment of heat cable being shut off. Probe on plastic duct and road surface.
Figure D.6. Moment of heat cable being shut off. Probe inside duct and 2 dm above surrounded by gravel and stones.
Appendix E

Acknowledgements

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