OPTIMIZED CABLE SYSTEMS DESIGN WHICH LIMITS SOIL DRYING OUT

by

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SUMMARY

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Underrating of underground cables could result in the drying out of the soil around the cable. This results in inferior cable performance and has potential negative environmental impacts. IEC 60287 is used for cable rating ampacity calculations. One of the parameters used in IEC 60287 is the thermal resistance per unit length between the cable surface and the surrounding medium (T_4), or T_4 can be defined as the thermal resistance to the outside installation environment of the cable.

The soil parameters may be unknown at the initial design phase for final cable rating calculations. Due to the unknown installation conditions; the calculated uncertainty for cable system designs may lead to either under-utilization of the cable system, or underrating of the cable system.

With increasing demand for underground cable systems in South Africa; this increases the probability of soil drying out due to unknown installation conditions, hence the need for improved cable rating design and calculations which will eliminate soil drying out. Cable rating solution that prevents soil drying out for South African (native) soil has been investigated. It was found that the following parameters should be taken into consideration when performing current rating that prevents soil drying out: the soil thermal resistivity at zero percent moisture content, sampling rate for measuring the soil

thermal resistivity should be less than 60 m and that the soil ambient temperature at cable laying depth should be measured.

LIST OF ABBREVIATIONS

AC	Alternating Current
CTM	Conductor Temperature Monitoring
DC	Direct Current
DCR	Dynamic Current Ratting
DTS	Distributed Temperature Sensing
EHV	Extra High Voltage
ERA	Electrical Research Association
GPS	Global Positioning System
HV	High Voltage
LV	Low Voltage
MV	Medium Voltage
PILC	Paper Insulated Lead Covered
SCADA	Supervisory Control and Data Acquisition
TPA	Thermal Property Analyser
XLPE	Cross Linked Polyethylene

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CHAPTER 1 INTRODUCTION

In this Chapter, the introduction to the research is provided. The problem statement, which is the causal effect for this research, is discussed in Section 1.2. The world best practises for cable rating are discussed in Section 1.3. The motivation and original contributions of the study are presented in Sections 1.3.1 to 1.5. The overview layout of this study is presented in Section 1.6. The research outputs are stated in Section 1.7.

1.1 PROBLEM STATEMENT

The Eskom transmission and distribution networks predominately consist of overhead line infrastructures. However, due to the large scale urban developments in South Africa over the past 50 years; the need to use underground cable systems has increased. This is due to servitude availability constraints and the growing demand from customers to reduce the visibility of Eskom power networks in urban areas. Therefore, Eskom and utilities must be equipped to design, install, operate and maintain these underground cable systems. Furthermore, the cable rating and design calculation methods [1] used for installing these cable systems need to be considered. IEC 60287 is a standard that sets out methods for calculating the current rating of cables under a range of different installation conditions [2]. Thus the objective of this research was to establish optimized underground power cable systems designs for the consideration of soil drying out and dryer installation condition environments.

Soil drying out is a result of moisture migration process which begins when a temperature gradient is imposed across the soil [3, 4]. This temperature gradient will cause water vapour pressure gradient to develop; resulting in moisture migrating away from the heat source. In this scenario, the heat source would be the buried cable. The moisture migration will eventually cause local drying of the soil near the cable [3, 4]. Thus the original cable rating calculations [1] which would have been performed before the installation of the cable would not be valid anymore since the resistivity of the soil would have changed. Accurate calculation of real time ampacity is needed in the case of buried cables to optimize the utilization of current carrying capacity of the buried cable [5].

Based on the assumptions made to perform the cable rating calculations; the calculated results for cable system designs may lead to the underutilization of the installed expensive cable system infrastructures during operation by the power utilities. IEC 60287 specifies the following constants and variables to be used in cable rating calculations: the thermal resistance per unit length between one conductor and the metallic sheath (T_1), the thermal resistance per unit length of the bedding between sheath and armour (T_2), the thermal resistance per unit length of the external jacket of the cable (T_3), the thermal resistance to the outside installation environment of the cable (T_4), the number of cable conductors used in the same trench, and other factors not mentioned.

The cable specific constants and variables (T_1, T_2 and T_3) for the IEC 60287 proposed calculation model are dependent on the construction, materials and method used for the manufacturing of the cable. However; the onsite dependent constants and variables (T_4) for the cable installation conditions may be unknown at the initial design phase for final cable rating calculations.

The aim of this research and investigation into the IEC 60287 calculation method was to master the calculation assumptions, variables and formulas. This served to be used for best design practices to find optimized current ratings for considering soil drying out or drier installation conditions, where thermal monitoring techniques are not feasible, and the use of imported backfill soil is not feasible due to cost.

1.2 OVERVIEW OF CURRENT LITERATURE

The literature on soil drying out due to installed power cables is available [4]. The development of a new method to solve the problem of coupled heat and moisture transfers around power cables is discussed in [4].

1.2.1 IEC 60287

Two methods of calculating current rating are discussed: the analytical technique by using IEC 60287, and the numerical technique which can be based on either a finite difference or a finite element method. The analytical technique is usually preferred for installations where approximations of thermal circuit parameters and configurations are known and acceptable. The permissible current rating of an AC cable can be derived from the expression for the temperature rise above ambient temperature [1] as detailed in (1.1) and (1.2).

$$\Delta\theta = (I^2R + W_d/2)T_1 + \left[I^2R(1+\lambda_1) + W_d\right] nT_2 + \left[I^2R(1+\lambda_1+\lambda_2) + W_d\right] n(T_3+T_4) \qquad (1.1)$$

Re-arranging (1.1), yields.

$$I = \left[\frac{\Delta\theta - W_d\left[0.5T_1 + n(T_2+T_3+T_4)\right]}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)}\right]^{0.5} \qquad (1.2)$$

where:

I: is the current flowing in one conductor (A).

$\Delta\theta$: is the conductor temperature rise above the ambient temperature (°K).

R: is the alternating current resistance per unit length of the conductor at maximum operating temperature (Ω/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 (°K.m/W).

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

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

T_4: is the thermal resistance per unit length between the cable surface and the surrounding medium (°K.m/W).

N: is the number of load-carrying conductors in the cable (conductors of equal size and carrying the same load).

λ_1: is the ratio of losses in the metal sheath to total losses in all conductors in that cable.

λ_2: is the ratio of losses in the armouring to total losses in all conductors in that cable.

The focus was directed onto the assumptions made for the calculations of T_4 above. Where T_4 is the thermal resistance per unit length between the cable surface and the surrounding medium [1]; the units thereof are Km/W.

When cable sizes are chosen; the value for the thermal resistivity of the surrounding soil must be determined to calculate how much current any underground cable can carry before it will overheat. Overheating of the cable could result in moisture migration in the soil. This, in turn, will cause the soil surrounding the cable to dry out and solidify. Cable rating calculations will be necessary to avoid drying out of the soil; as the soil to which the cable is installed require to have the ability to maintain constant moisture level. This is known as thermal stability [6].

1.2.2 The law of times

Many sources suggest that if the time it takes for the soil to dry around a heat source of known diameter is measured; it can be used to determine the time it will take the soil to dry around the heat source of any other diameter [6]. The law of times is represented by equation 1.3 below.

$$\frac{t_1}{t_2} = \left(\frac{d_1}{d_2}\right)^2 \tag{1.3}$$

where

t_1: is the time it takes the soil to dry in any particular heat rate.

d_1: is the diameter of the heat source (e.g. test probes).

t_2: is the time it will take the soil to dry at the same heat rate (for t_1), when the heat source is a cable with a diameter (d_2).

d_2: is the diameter of the cable to be installed.

Equation (1.3) above can be used to calculate the time it will take for the soil to dry out at a particular heat rate. The challenge is that the type of soil may change along the cable route. Thus the thermal resistivity of the soil may change along the cable route.

1.2.3 Engineered backfill material for buried power cables

Another solution that can be considered for reduced soil thermal resistivity for the installation of underground power cables is the use of engineered backfill material, placed in the immediate vicinity of the cable [7, 8]. These engineered backfill material are supposed to be having acceptable thermal resistivity in their dried state. Some utilities use specially engineered thermal backfills where geotechnical studies cannot be performed before the cables are to be installed. The following are the different types of backfill materials which can be used: granular thermal backfill, fluidized thermal backfill, thermal grout and different soil combinations [8]. Eskom and other utilities use these special backfills for high voltage (HV) and extra-high voltage (EHV) cable installations; however, no budget is readily available for these technologies to be implemented in medium voltage (MV) and low voltage (LV) cable installations; hence the need for cable rating calculations taking into consideration that the native soil will have to be used to backfill the cable trench.

The different voltage ranges used in Eskom can be defined as follows: low voltage (LV) is any voltage less than 1000 V, medium voltage (MV) is any voltage greater than 1 kV up to and including 33 kV, high voltage (HV) is any voltage greater than 33 kV up to and including 132 kV and extra-high voltage (EHV) is any voltage greater than 132 kV up to and including 765 kV.

1.2.4 Forced cooling systems

Forced cooling systems may be used to prevent soil drying out due to installed power cables. The following are typical forced cooling systems: irrigation systems, separate pipe cooling, concrete racks cooling, and forced air cooling [9]. The problem with the forced cooling method is the requirement to use water to achieve the cooling. South Africa is currently going through a desertification process; thus, the use of water for this purpose would not be feasible due to the scarcity of water in South Africa.

1.2.5 Superconducting cables

Some designs of cables use superconductors. These kinds of conductors use niobium or niobium-tin which at temperatures within a few degrees of absolute zero lose virtually all electrical resistivity. Cooling with liquid helium is necessary to achieve these low temperatures [10]. These technologies are costly and are mostly considered for very long EHV cables, and thus these technologies cannot be considered for MV and LV applications.

1.2.6 Smart Grid Technologies

Smart grid technologies use fibre optic cable solutions to measure and record the ambient soil temperature or the cable conductor temperature for use in cable rating calculations. This is dependent on where in the layers of the power cable, the fibre optic cable is installed [8]. These technologies include the following: distributed temperature sensing (DTS), conductor temperature monitoring technologies, and dynamic current rating (DCR) technologies [11]. These technologies will indicate the real-time loading of the cable system. Other technologies that will promote smart maintenance have been developed for estimating the degree of degradation of power cables based on the polarization/depolarization current measurements [12]. These technologies will ensure smart cable maintenance. However, due to the cost of these technologies, it is not feasible to install these technologies in all MV and LV cable installations.

1.3 RESEARCH MOTIVATION, OBJECTIVE AND QUESTIONS

1.3.1 Motivation

Most of the technologies listed above are seldom used for MV and LV applications. Thus for these applications (MV and LV), it may be prudent to consider an arid environment in ampacity calculation [8] as per IEC 60287. The main focus of the ampacity calculation was the calculation of the variable T_4, which is dependent on the cable installation conditions. These installation conditions include the soil thermal resistivity, moisture content, actual installation depth, soil temperature, and the number of cable circuits in a trench. These installation conditions were investigated to calculate the optimum value for T_4 to avoid soil drying out due to installed power cables in a dry environment for the expected life of the installation (40 years).

1.3.2 Objectives

The main goal of this research was to investigate the optimum value of T_4 (from IEC 60287) for buried MV and LV cables in South African native soil taking into consideration the estimated life of the installed cable (40 years minimum). The focus was on developing a tool that would calculate the soil drying time of typical soil where a cable with a certain continuous current was installed. The soil drying time was to be more than 40 years.

1.3.3 Questions

The following research questions will have to be answered in order for the research to be achieved.

- What assumptions regarding the soil thermal resistivity should be made for a buried cable installation to avoid soil drying out due to the heat dissipated by the installed cable?
- What is the reasonable soil thermal resistivity sampling rate for long routes of cables?
- What is the optimum operating temperature that the cable should be designed for; for installations where no online monitoring systems will be installed?
- How will an online monitoring system assist in achieving the required life or even extended life (more than 40 years) for buried power cables without soil drying out?

1.4 PROPOSED RESEARCH

A software tool to calculate the rate of change in temperature of a known cable was to be developed, and the parameters of T_1, T_2, T_3 and T_4 (see equation 1 above) would be taken into consideration. The rate of change of heat due to continuous current from the cable conductor to the outer cable sheath had to be calculated. The rate of change of heat calculated results was then used to determine the time it would take for the soil to dry around the heat source (where the heat source will be the cable whose T_1, T_2, T_3, and T_4 have already been calculated).

1.4.1 Computer calculating tool

The research developed the calculating tool by using Microsoft Excel. The calculated results were verified by using cable manufacturing data sheets. It was assumed that the cable manufacturers should have used approved commercial software program for cable rating; hence the cable rating information in those data sheets was used to verify the cable rating tool developed.

1.4.2 Soil thermal resistivity tests and measurements

Soil samples were taken to the soil laboratory; soil thermal resistivity measurements were then performed for different moisture levels.

1.5 CONTRIBUTION

The need for the installation of underground power cables has increased due to the population growth in urban areas in South Africa. However, the installation of underground power cables may increase the probability of soil drying out. South Africa is currently going through desertification period;

meaning that South African soil is getting dryer every year and hence the need for underground cable installations that would not exacerbate the situation.

A minimum life span of 40 years is expected from a correctly rated power cable. Thus the calculation tool took into consideration the life of the installation. The calculation method of IEC 60287 currently takes into consideration the construction of the cable to calculate T_1, T_2 and T_3, and the installation environment where the cable will be installed to calculate T_4. However, the life of the installation is not taken into consideration. This research focused on the time it would take for the soil to dry out due to the heat dissipated by the installed power cable. A successful development of the calculation tool will assist Eskom and utilities in rating their cables and avoid soil drying out at least for 40 years (minimum).

The use of thermal monitoring systems (or smart grid system) in buried power cable installations was investigated to determine how the thermal monitoring systems could assist in limiting soil drying out due to installed cables.

1.6 OVERVIEW OF STUDY

Chapter 2 defines a literature study on current rating for buried cables. Focus is paid on to the design principles that can be implemented to prevent soil drying out of the soil around buried power cables. The current rating calculations method discussed in IEC 60287 are studied. Then other solutions/technologies that can be considered for the ratings and designs of power cables are presented. The different solutions/technologies are then evaluated to assist in choosing the best solution for this study.

Chapter 3 provides the solution towards cable rating design that limits soil drying is developed. A cable rating calculation tool is developed to perform the cable design calculations. Soil thermal resistivity tests are performed to evaluate the impact soil thermal resistivity has on the rating of the cable. Three cable data sheets from three different cable manufacturing companies are used to calculate the current rating of a cable with the following design parameters: 3 cores, 185 mm^2, copper conductor, cross linked polyethylene (XLPE) insulated, steel wire armoured, the cable has water blocking tape and has polyethylene outer sheath. Different installation conditions are considered and calculated against the ideal installation conditions.

Chapter 4 details cable rating calculation for different cable installation conditions. The accuracy level of the calculation tool is compared with the cable rating values stated in the cable data sheets from the three different cable manufacturing companies. The relationship between the T_4 changes in cable installation condition and current rating is evaluated.

Chapter 5 discusses the results of the different installation conditions considered in this study . The results where the worst-case scenario (where all the conditions are considered in one installation) are analysed and the implication of each installation condition is discussed.

In Chapter 6, the study is concluded in this chapter. A summary of the contributions made by this study is given as well as suggestions for future work.

1.7 PUBLICATIONS

The following peer-reviewed journal constitutes the output of the Master work.

Journals

1. Ntombifuthi Q. Khumalo, Raj M. Naidoo, Nsilulu T. Mbungu, “Optimized cable systems design which limits soil drying out on native soil,” *To be submitted in Electric Power Systems Research*.

CHAPTER 2 LITERATURE STUDY

2.1 INTRODUCTION

A literature study on current rating for buried cables is presented in this chapter. Focus is paid on to the design principles that can be implemented to prevent soil drying out of the soil around buried power cables. The current rating calculations method, following IEC 60287, is studied. Then other solutions/technologies that can be considered for the ratings and designs of power cables are presented. The different solutions/technologies are then evaluated to assist in choosing the best solution for this study.

2.2 CHAPTER OBJECTIVES

Soil drying out is a result of moisture migration process which begins when a temperature gradient is imposed across the soil [1,3,4]. This temperature gradient will cause water vapour pressure gradient to develop; resulting in moisture migrating away from the heat source. In this scenario, the heat source would be a buried power cable. The moisture migration will eventually cause local drying of the soil near the cable [3,4]. With the increase of the need to install underground cable systems in South Africa; this increases the probability of soil drying out due to these cables; hence the need for cable rating designs and calculations which will eliminate soil drying out.

Figure 2.1 show a cable buried at 0.8 m underground where the temperature is in degree Celsius. It is shown that an increase in the conductor temperature will increase the temperature of the outer cable sheath; consequently the soil closest to the cable will solidify depending on the surface temperature of the cable outer sheath.

As detailled in Section 1.2, the cable specific constants and variables are dependent on the construction materials and methods used for the manufacturing of the cable. However, at the initial design phase for

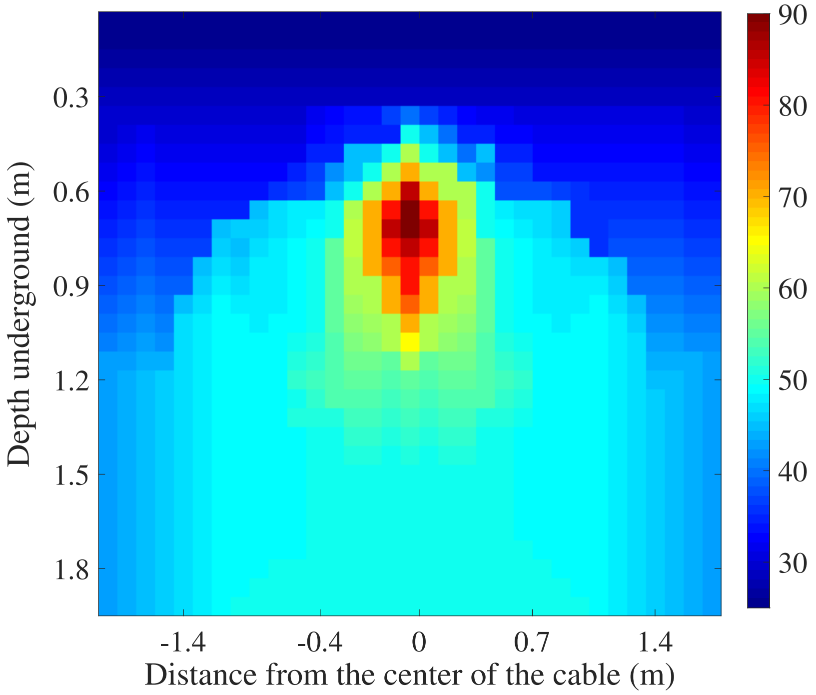


Figure 2.1. Temperature distribution within and around three core 11 kV cable directly buried underground Reproduced from [13].

final cable rating calculations the onsite dependent constants and variables for the cable installations conditions can be unknown. Due to the unknown installation conditions; the calculated uncertainty for cable system designs may lead to either under utilization of the cable system or underrating of the cable system.

Under utilisation of the cable system could result to the installation of expensive infrastructures; while underrating of the cable system design could result to the system being overloaded; thus generating more heat; this, in turn, will accelerate the soil drying out process. This study has investigated the following:

1. The different methods used for the design and installation methods of cables systems that prevent soil drying out due to the heat dissipated by the installed cables. The best solution for South African soil (native) has been investigated and recommended taking into consideration that the type of soil will vary over distances and depths.
2. The minimum cable temperature that could result in soil drying out for buried MV and LV cables

in South African native has been investigated taking into consideration the estimated life of 40 years of the installed cable.

3. The available smart grid technologies that can be used for buried MV and LV cables.
4. A cable rating calculation tool that can be used by the Utilities has been developed.

2.3 CURRENTLY ACCEPTED IEC 60287 CALCULATION METHOD

Literature is available on soil drying out due to installed power cables. The development of a new method to solve the problem of coupled heat and moisture transfers around power cables is discussed in [4]. Two methods of calculating current rating are discussed; which are: the analytical technique by using IEC 60287 and the numerical technique which can be based on either finite difference or finite element method.

The analytical methods have the advantage of producing current rating equations in a closed formulation, whereas the numerical method requires iterative approaches to find cable ampacity [8]. For this research, the numerical method was not investigated further.

The analytical technique is mostly preferred for installations where approximations of thermal circuit parameters and configurations are known and acceptable. IEC 60287 states the following equations:

$$\Delta\theta = \left(I^2R + (1/2)W_d\right)T_1 + \left[I^2R\left(1+{}_1\right) + W_d\right]nT_2 + \left[I^2R\left(1+{}_1+{}_2\right) + W_d\right]n\left(T_3+T_4\right) \tag{2.1}$$

Re-arranging equation (2.1) yields.

$$I = \left[\frac{\Delta\theta - W_d\left[0.5T_1 + n\left(T_2+T_3+T_4\right)\right]}{RT_1 + nR\left(1+{}_1\right)T_2 + nR\left(1+{}_1+{}_2\right)\left(T_3+T_4\right)}\right]^{0.5} \tag{2.2}$$

The focus was paid to the calculation of T_4 for the purpose and conclusion of this research. For the purpose of this research, the outside environment of the cable was the South African native soil. The cable rating calculation performed in this research was based on the assumption that the South African native soil was going to be used to backfill the cable tranches due to unavailability of funds to purchase imported backfill material (backfill material with better soil thermal resistivity). Soil with good thermal resistivity dissipates heat very well; while soil with bad thermal resistivity traps heat; this, in turn, can result in soil drying out of the soil around the cable.

The current carrying capacity of a buried cable is dependent on the efficiency of the outside environment to dissipate the heat generated from the conductor of the cable. Thus it is essential to analyse the process of heat transfer from the cable through the different layers of the cable and then to the soil.

For underground cable installations heat is transferred by conduction from the conductor of the cable through the different layers of the cable, then to the outside environment, which is the native soil. The rate equation known as Fourier's Law can be used to calculate the amount of heat transferred per unit time. For a wall having temperature distribution (x); the rate equation can be expressed by (2.3) below [14], and can be illustrated in Figure 2.2.

$$q = -\frac{1}{\rho}\frac{d\theta}{dx} \tag{2.3}$$

where:

Q: is the heat flux (W/m^2).

P: is the thermal resistivity (K.m/W).

$d\theta/dx$: is the temperature gradient.

The heat flux q (W/m^2) is the heat transfer rate in the x-direction per unit area perpendicular to the direction of transfer. It is proportional to the temperature gradient $d\theta/dx$ in this direction. The proportionality constant p is a transport property or thermal resistivity (K.m/W). This is the thermal resistivity of the soil to which the cable is buried. The minus sign is a consequence of the fact that temperature is in the direction of decreasing temperature [14]. The rate equation (Fourier's Law) is illustrated in Figures 2.2 and 2.3.

Heat transfer in buried cables is through conduction; where the heat is transferred from the conductor, then to the insulation material, then to the outer sheath of the cable and then to the surrounding soil.

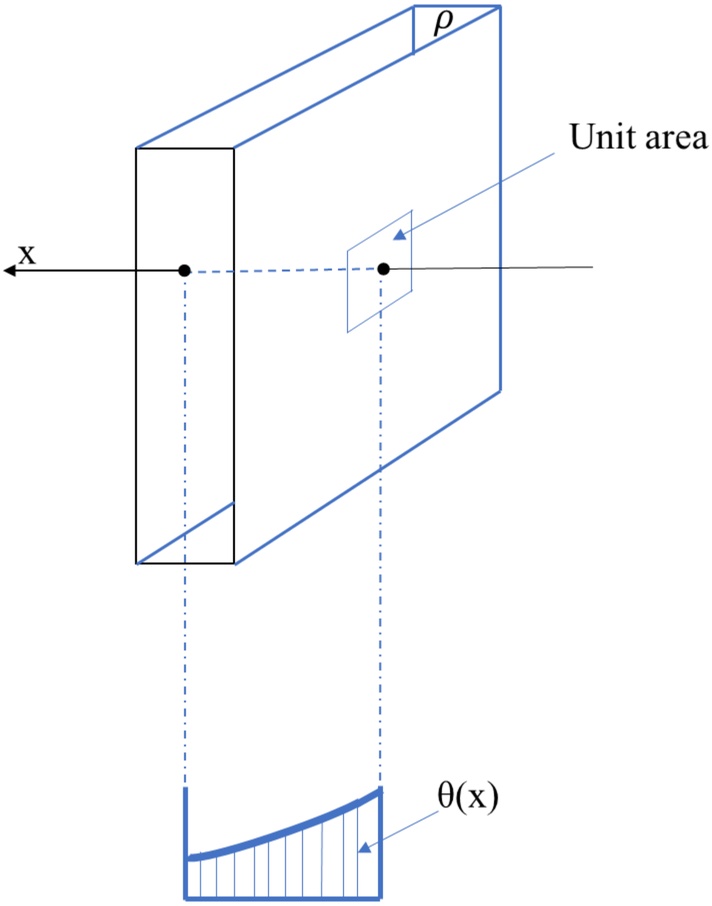


Figure 2.2. Illustration of Fourier's Law Reproduced from [14].

It is required that the value of the thermal resistivity of the surrounding soil must be determined first to calculate how much current an underground cable can carry before it will overheat [6]; this, in turn, can assist the design engineer in choosing the correct size of cable. Overheating of the cable could result in moisture migration in the soil.

Moist soil is assumed to have a uniform thermal resistivity. Suppose the heat dissipation from a cable and its surface temperature are raised above certain critical limits, in that case, the soil will dry out, resulting in a dry zone which is assumed to have a uniform thermal resistivity higher than the original one. The critical conditions are dependent on the type of soil, the original moisture content of the soil and the temperature. Given the known conditions; it is assumed that when the surface of a cable exceeds the critical temperature rise above ambient temperature; a dry zone will then form around the cable [14]. This, in turn, will cause the soil surrounding the cable to dry out and solidify Figures 2.1 and 2.2.

Cable rating calculations are necessary to avoid drying out of the soil as the soil to which the cable is installed is required to have the ability to maintain constant moisture level. This is known as thermal stability [15].

2.4 THE DETERMINATION OF AMBIENT TEMPERATURE AT CABLE DEPTH BEFORE INSTALLATION OF THE CABLE

Ref. [8] discusses the determination of the ambient temperature at cable depth. It is further demonstrated that the main parameter that limits the bulk of electrical power using a buried cable is the conductor temperature of the cable itself. For a power cable there is a maximum operating temperature which if exceeded would result to accelerated ageing of the insulation material of the power cable; this, in turn, reduces the thermal resistance of the insulation material thus the temperature dissipated through the insulation material of the cable to the outside environment increases, this, in turn, will speed up the soil drying out process.

It has been standard engineering practice to calculate the cable rating using worst-case parameter values; ensuring that the maximum operating temperature would not be exceeded even in the most adverse conditions. In some cases, it has been found that the standard rating parameters are too conservative that there is significant underutilization of the cable assets. Underutilization of installed cable assets equates to wasteful expenditure; where the funds could have been used for other projects. The underutilisation of the installed cable assets validated the need to perform a study on the effect of environmental parameters to mitigate the underutilisation of the installed cable assets. The study was performed on a section of the three-phase surface trough, which was constructed with the thermal losses of the cable circuit being represented by heater tape wound around aluminium formers. The trough was fully instrumented, and an adjacent weather station provided meteorological data at regular intervals. The data was obtained over 18 months. The data for 18 months was then used to verify a physical model which was developed and used to determine the ambient temperature at cable depth. The ambient temperature determined by the model was then used with the load history of the circuit to calculate the cable temperature. It was found that this method is, however, feasible for cables buried to a depth between 0.3 m and 0.6 m [8]. This method will not be suitable for cables installed in Eskom's electrical networks because cables installed in Eskom's electrical networks are buried at a minimum depth of 0.85 m.

Thermal probes are another solution that can be used to perform soil thermal resistivity test [3, 16].

Below is the procedure to be followed when thermal probes are used to perform soil thermal resistivity test. The thermal probe technology consists of a thermal heat source which simulates heat from buried cables, and a thermistor temperature sensor which measures the temperature dissipated to the soil, the thermal probe is then connected to a Thermal Property Analyser (TPA) [16]. The thermal probe consists of a distributed heater and a point temperature sensor located approximately mid-point of the probe. The heat output and temperature measurements are controlled and recorded by the TPA equipment. The length of the probe can be selected so that only radial heat flow is occurring such that the end effects do not impact the temperature measurement. The diameter of the probe is selected based on the expected diameter of soil components to be tested such that contact resistance with the probe is kept to a minimum. The test is principally done to measure only thermal resistance where no significant drying of the sample occurs during the test; the same test can be run longer to determine soil drying out time for given heat output. The heat output from the probe can be scaled up to the expected cable diameter according to (2.4) [8].

Equation (2.4) can be defined as “The Law of Times”; which suggest that if the time it takes for the soil to dry around a heat source of known diameter is measured; it can be used to determine the time it will take the soil to dry around the heat source of any other diameter [15]. Figure 2.3 describes the layout of thermal probe.

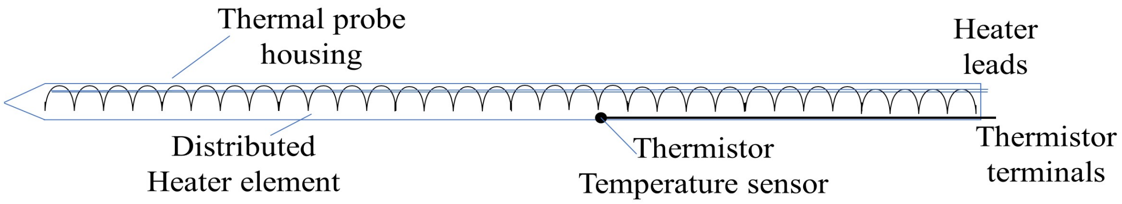


Figure 2.3. Conceptual layout of a thermal probe Reproduced from [16].

$$\frac{t_1}{t_2} = \left(\frac{d_1}{d_2}\right)^2 \tag{2.4}$$

Equation (2.4) above can be used to calculate the time it will take for the soil to dry out at a particular heat rate, as detailled in Section 1.2.2. The challenge is that the type of soil may change along the cable route; thus, the thermal resistivity of the soil may change along the cable route.

Another test method that can be considered is soil boring [8]; where soil samples (for the planned cable route) are taken to a test laboratory [3,8]. The recommended sampling frequency is between 200 m and 600 m depending on the total cable route length [8].

2.5 ENGINEERED BACKFILL MATERIAL

Another solution that can be considered for reduced soil thermal resistivity for the installation of underground power cables is the use of engineered backfill material. Other Utilities use specially engineered thermal backfills that can be considered for installations where geotechnical studies cannot be performed before the cables can be installed. Following are the different types of backfill materials which can be used: granular thermal backfill, fluidized thermal backfill, thermal grout and different soil combinations [8].

An experiment was performed on nine different samples of soil; where the aim was to determine the soil thermal properties of the nine different soil samples. This, in turn, would assist in obtaining the most suitable backfill soil for the maximum current carrying capacity of underground power cables. The test performed on the nine samples proved that the worst hydrological condition during the dry season might be expressed as the worst condition in which the soil has high thermal resistivity [13].

The test was performed by using an 11 kV, 185 mm^2, three core, aluminium conductor, XLPE cable, which was directly buried 0.8 m underground, carrying a continuous current of 352 A, and the conductor maximum operating temperature was fixed at 90°C. It was found that the soil drying out phenomenon forms faster in some soils compared to other soils. The best soil type which yielded the best results was a combination of sand and lime (75% sand + 25% lime); the soil thermal resistivity thereof was 0.522 Km/W. It was further found in the test that the soil started drying out when the outer layer of the cable reached a temperature of 62°C.

Another experiment was performed and directed towards establishing the relationship between the temperature rise of the cable surface, the nature of the load, the soil structure and the seasonal climatic influence. Seventeen test sites were selected to cover a broad range of clearly defined soils encountered in South-Eastern and Southern England [17]. The experiments were conducted on thermally independent test lengths of low-voltage (LV) cables. The cables were laid in 0.9 m deep trenches covered in local soil or imported sand. The cable surface temperature was kept at 60 °C. At the end of the test series after 10 years, excavations were carried out to establish the effects and extent of moisture migration near the cables. It was concluded that the effects and extent of moisture migration were more evident near cables which were buried in soils which were previously used for agriculture. Another conclusion was that in clay soils; there is an advantage in using sand as bedding material rather than using the local soil even if the sand was not of good quality [9].

Walker and Roux performed simulations where soil properties of two different types of backfill material were used to backfill a buried cable circuit. The soil thermal resistivity of the two sampled backfill material was 0.8 Km/W and 1 Km/W. The cable circuit consisted of three single-core cables laid in trefoil formation, buried 1 m underground, and the width of the trench was 1.2 m [18]. Six different simulations were performed where the layers of the backfill material are presented in Table 2.1, and the rest of the soil was the native soil above the imported backfill soil. Table 2.2 summarizes the best results achieved.

It was found that for a cable where the maximum conductor temperature was 70 °C; the temperature of the cable surface did not rise much higher than 55 °C. While for a cable where the maximum conductor temperature was 90 °C; the temperature of the cable surface did not rise much higher than 70 °C. It was found that the 90 °C conductor temperature and 70 °C cable surface temperature could result to irreversible drying out of the soil surrounding the cable if incorrect backfill material was used and if the thickness of the backfill material was not sufficient. The best result was obtained in model 4 (Table 2.1); where the thickness of the backfill material above and below the cable were 200 mm and -300 mm respectively, the soil thermal resistance was 0.8 Km/W, and the cable surface temperature was 55 °C. It was therefore recommended that the maximum cable conductor operating temperature should be kept at 70 °C for installations where the backfill material has thermal resistance greater than 0.8 Km/W; this, in turn, will result to a maximum cable surface temperature of 55 °C which will not cause the soil surrounding the cable to dry out [18].

2.6 FORCED COOLING SYSTEMS

Forced cooling systems may be used to prevent soil drying out due to installed power cables. A forced cooling system can be defined as a system that is designed to cool power cables by using external methods. The following are typical forced cooling systems: irrigation system, separate pipe cooling, concrete racks cooling, and forced air cooling [9].

Table 2.1. Backfill thickness and native soil thickness Reproduced from [18].

Model number	Backfill thickness below cable (mm)	Backfill thickness above cable (mm)	Thickness of native soil (mm)
1	-100	100	800
2	-200	100	700
3	-200	200	600
4	-300	200	500
5	-300	300	400
6	-400	400	200

Table 2.2. Test results for the two different backfill material used for the simulations Reproduced from [18].

Backfill material	70°C Conductor temperature	90°C Conductor temperature	Backfill thickness below cable (mm)	Backfill thickness above cable (mm)
0.8 K.m/W	55°C	60°C	-300	200
1.0 K.m/W	58°C	61°C	-300	200

The irrigation cooling systems: is when the water irrigation system is installed above the cable route; water is then sprayed through the irrigation system above the ground where the power cables are installed. The soil above the cable will absorb the water, which in turn will assist in maintaining an acceptable level of moisture in the soil [9]

Different pipe cooling method: this method is employed by running multiple water pipes parallel with the power cable [9]; this particular pipe cooling method acts as a heat sink close to the power cable. This method is practical in a closed-loop system where water can be circulated by pumps and cooled in heat exchanger stations sited along the cable route.

Concrete racks cooling can be achieved by building deep open concrete racks filled with running water; the power cables are then laid in the racks. Another method that can be used is forced air cooling; which is achievable only in cable systems installed in tunnels [9].

2.7 TYPES OF CONDUCTORS USED IN POWER CABLES

South Africa has standardized on copper and aluminium for conductors to be used on power cables [6]. However, the study of the production and behaviour of materials at shallow temperatures [10] have been performed; this study is called the study of cryogenic techniques. The study of power cables systems using cryogenic techniques is divided into two parts: Cryoresistive cables and superconducting cables.

Cryoresistive cables: these kinds of cables are based on metallic conductors, usually copper or aluminium having a high degree of purity and cooled with liquid nitrogen. At this temperature, the resistivity of these metals is about an order lower than at its average operating temperatures [10]. This method of cooling has proven to have no advantage of the economy; thus, the majority of research has been more focused on superconducting cables.

Superconducting cables: These kinds of conductors use niobium or niobium-tin which at temperatures within a few degrees of absolute zero lose all electrical resistivity virtually. To achieve these low temperatures; cooling with liquid helium or nitrogen is necessary [10].

2.8 SMART GRID TECHNOLOGIES

Installation of the fibre optic cable is performed during the manufacturing process of the cable; where each cable manufacturer in agreement with the user (e.g. the Utility) will decide on the location of the optical fibre cable. These types of cables are called optical fibre composite cables. The DTS or DCR will measure the distributed temperature of the power cable along the cable route by analysing reflected optical signal of the optical cable [19].

CTM technique estimates the temperature variation of the conductor by analysing the dynamic heat transfer model. CTM considers temperature thermal time constant based on IEC 60287 standards [1]. The monitored temperature can further be used to calculate the surface temperature of the cable.

Another smart grid technology that can be used for load management is the DCR. This technology evaluates ampacity of the cable in real-time by considering the ambient environment. To evaluate the ampacity of cable in real-time; DCR uses the transient responses of load current. Thus it can yield the optimum level of overload operation in case of temporary load concentration [19]. For this research; this technique will not be considered.

An experiment or test where cables were buried at depths between 0.3 m and 0.6 m was performed [8]. The cables were installed for 18 months; where the ambient temperature around the cable was measured continuously and logged in a data logger system. The results obtained indicated that the model offered a significant improvement on the existing approaches for determining the ambient temperature parameters.

Cable joints are customarily seen as the weakest link in a cable system; this is because a cable joint has more layers than the cable. Site jointing of cable joints generally necessitates the insulation being applied by hands in an uncontrolled environment; the electrical stresses are set to lower values compared to a controlled environment (e.g. the manufacturing factory). As a result of this, the insulation thickness is more significant than for the cable (being jointed); this, in turn, increases the thermal resistance of the joint. Joint cooling techniques have been developed and implemented to reduce the thermal resistivity of the joint [19].

A novel approach to estimate the temperature of the conductor in a cable joint was developed. Where the surface temperature of the cable closest to the joint was measured, and the conductor temperature was then calculated based on the measured temperature. The measured temperatures were then used in a mathematical algorithm to calculate the temperature in the conductor of the joint [11].

The different types of smart grid technologies can be used to diagnose the performance of the power cable, and to analyse the surface temperature of the cable. These technologies can further be used to send alarms to supervisory control and data acquisition (SCADA) if the cable surface temperature reaches a set maximum allowed cable surface temperature, this, in turn, will assist the utilities in preventing the drying out of the soil due to installed power cables.

2.9 DISCUSSION AND EVALUATION OF THE DIFFERENT METHODS

2.9.1 Engineered backfill material

The use of engineered back fill material for buried cable has proven to be the best-preferred technology around the world. Eskom has decided to use engineered back feel material on buried HV, EHV, and on selected MV cable systems, due to the cost implication for implementing this solution; thus this solution cannot be feasible for most of MV or LV cable systems.

2.9.2 Forced cooling systems

The forced cooling system is the most reliable cooling method that can be used provided there is sufficient cooling resource (e.g. water). This method can be further improved where the cooling water is re-used for bathing, this, in turn, will reduce the electricity demand for water heating purposes for human use. The scarcity of water in South Africa makes this solution not viable for South African use.

2.9.3 Cryoresistive cables and superconducting cables

Cryoresistive cables and superconducting cables carry larger loads with smaller sizes of conductors. This technology is mostly implemented in long cable routes for HV and EHV cables. It has been found that these technologies are expensive and need special care when they are being installed [10]. South

Africa does not have the required skills to install such technologies. Implementing such technologies in South Africa will require that the necessary skilled people are brought from the countries with the required skills; this, in turn, will result to an increase in the total cost of the installation of the cable.

2.9.4 Smart grid technologies

Soil drying out due to buried cable can be easily prevented with the use of smart grid technologies. Furthermore, these technologies can assist with diagnostic analysis, thereby assisting utilities in planning their maintenance pro-actively; provided the Utilities have the necessary funds to install such technologies.

2.9.5 Determination of cable temperature and soil thermal resistivity

Determination of cable temperature and soil thermal resistivity at cable depth seems to be the cheapest method that can be used in South Africa for buried MV and LV cables. Measuring the soil thermal resistivity before the power cable can be installed, and determining the cable temperature that could result to soil drying out would assist the Utilities in determining the maximum loading of the cable at the determined maximum cable temperature.

2.10 CHAPTER SUMMARY

A review of techniques for optimized cable systems design which limits soil drying out has been presented. It can be concluded that although several cable design industry specialists have presented different and effective methods to prevent drying out of soil due to installed power cables; many of these methods are either expensive, or the technique can only be implemented on HV or EHV cables, or the technique requires the use of water for cooling purposes.

The different types of smart grid technologies can be used to diagnose the performance of the power cable, and to analyse the surface temperature of the cable. These technologies can further be used to send alarms to SCADA if the cable surface temperature reaches a set maximum allowed cable surface temperature, this, in turn, will assist the utilities in preventing the drying out of the soil due to installed power cables. These technologies cannot be considered for this research due to cost.

The most feasible solution that can be used in South Africa would be: the determination of soil thermal resistivity of the native soil which will be used for backfilling of the cable trench, the determination of the soil ambient temperature before installing the cable; and then determine the minimum cable temperature that could result to soil drying out.

CHAPTER 3 METHODS TO BE CONSIDERED FOR OPTIMISED CABLE SYSTEMS DESIGN WHICH LIMITS SOIL DRYING OUT

3.1 INTRODUCTION

The solution towards cable rating design that limits soil drying was developed. A tool was developed to perform the cable rating calculations. Soil thermal resistivity tests were performed to evaluate the impact soil thermal resistivity has on the rating of the cable. Three cable data sheets from three different cable manufacturing companies were used to calculate the current rating of a cable. The cable used for the calculations has the following design parameters: 3 cores, 185 mm^2 copper conductors, XLPE insulated, steel wire armoured, the cable has water blocking tape and has polyethylene outer sheath. Different installation conditions were considered and calculated against the ideal installation conditions.

3.2 CABLE RATING AMPACITY CALCULATIONS

Figure 3.1 shows all the different thermal resistances on the different layers of the cable. T_1, T_2 and T_3 are dependent on the cable design and raw material used to manufacture the cable, and they can be calculated by using the applicable equations given in IEC 60287. However, T_4 is dependent on the onsite installation conditions; which may be unknown at the initial design phase for final cable rating calculations.

The onsite installation conditions include the cable burial depth, the type of soil used to backfill the cable trench, the moisture content of the soil, the number of cable circuits in the trench and the space between the different cable circuits. For this research, the cable will be directly buried 850 mm underground, the cable trench will be backfilled with native soil, and there will only be one cable circuit in the trench.

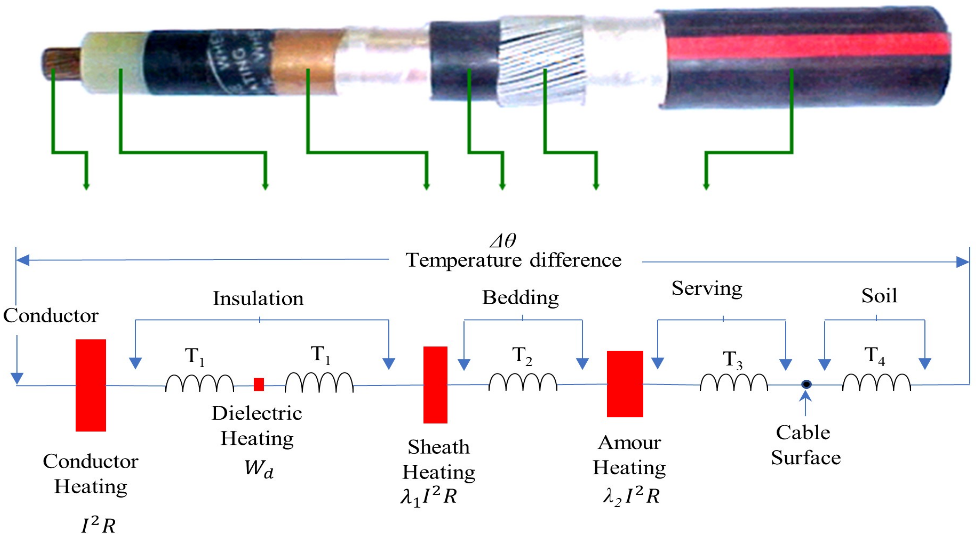


Figure 3.1. Single core cable showing all the different thermal resistivity on the different layers of the cable Reproduced from [4].

Different cable designs and installations have been considered in IEC 60287; the different designs, as stated in IEC 6287 include:

1. The different insulation materials: this could be paper insulated lead covered cable (PILC), XLPE, oil-filled cable, etc.

2. The design of cable: whether single core or three cores.

For this research, only the equations for XLPE, three core cables will be considered. This is due to the fact that Eskom has standardized on XLPE cables for MV application. The equations specified below are based on 60287 [1].

Equations (2.1) and (2.2) can be used to calculate the cable rating of any kind of cable and any kind of design.

The AC resistance per unit length of the conductor at its maximum operating temperature is given by 3.1.

$$R = R^{'}\left(1 + 1.5(y_s + y_p)\right) \tag{3.1}$$

where:

R: is the resistance of the conductor at maximum operating temperature (Ω/m).

$R^{'}$: is the DC resistance of the conductor at maximum operating temperature (Ω/m).

Y_s: is the skin effect factor.

Y_p: is the proximity effect factor.

The DC resistance per unit length of the conductor at its maximum operating temperature is given by 3.2.

$$R^{'} = R_0\left[1 + \alpha_{20}\left(\theta - 20\right)\right] \tag{3.2}$$

where:

R_0: is the DC resistance of the conductor at 20°C (Ω/m). The value for R_0 shall be derived from IEC 60228 [4], or the value for R_0 shall be obtained from the cable manufacturer datasheet.

α_{20}: is the constant mass temperature coefficient at 20°C per kelvin.

θ: Is the maximum operating temperature in degree Celsius. This value shall be determined by the type of insulation used.

The skin effect factor is given by (3.3).

$$y_s = \frac{X_s^4}{192 \, + \, 0.8 \, X_s^4} \tag{3.3}$$

with:

$$X_s^2 = \frac{8\pi f}{R' 10^{-7} \, k_s} \tag{3.4}$$

where:

f: is the supply frequency (i.e. 50Hz).

X_s: argument of Bessel function used to calculate the skin effect.

k_s: factor used to calculate skin effect. This factor can be obtained from IEC 60287.

The proximity effect factor (y_p) for three core cables is given by (3.5).

$$y_p = \frac{X_p^4}{192 + 0.8 \, X_p^4} \left(\frac{d_c}{s}\right)^2 \left[0.312 \left(\frac{d_c}{s}\right)^2 + \frac{1.18}{\frac{X_p^4}{192 \, + \, 0.8 \, X_p^4} \, + \, 0.27}\right] \tag{3.5}$$

with:

$$X_p^2 = \frac{8\pi f}{R' \; 10^{-7} \, k_p} \tag{3.6}$$

where:

d_c: is the diameter of the conductor (mm).

s: is the distance between conductor axes (mm).

x_p: argument of Bessel function used to calculate the proximity effect.

The dielectric loss W_d is given by (3.7).

$$W_d = \omega\, C\, U_0^2\, tan\delta \tag{3.7}$$

with:

ω: 2πf.

C: is the capacitance per unit length (F/m).

U_0: is the voltage to earth (V).

$tan\ \delta$: is the loss factor, and it can be obtained from IEC 60287-1-1 standard.

The capacitance of a circular conductor is given by (3.8) expressed in (F/m).

$$C = \frac{\varepsilon}{18\ln(\frac{D_i}{d_c})}\, 10^{-9} \tag{3.8}$$

with:

ε: is the relative permittivity of the insulation given from IEC 60287-1-1 standard.

D_i: is the external diameter of the insulation (excluding insulation screen) (mm).

d_c: is the diameter of the conductor (including conductor screen) (mm).

Loss factor is given by (3.9).

$$\lambda_1 = \lambda_1^{'} + \lambda_1^{''} \tag{3.9}$$

where:

λ_1: loss factor for sheath and screen.

λ'_1: loss caused by circulating currents.

λ''_1: eddy current loss. Eddy current loss is ignored for cable with round conductors except for large conductors with segmental construction.

Thus: $\lambda_1 = \lambda'_1$.

The resistance of the sheath (R_s) or screen is given by (3.10) expressed in (Ω/m).

$$R_s = R_{so}\left[1 + \alpha_{20}\ (\theta_{sc} - 20)\right] \tag{3.10}$$

where:

θ_{sc}: is the maximum operating temperature of the cable screen or sheath (°C).

R_{so}: is the resistance of the cable sheath or screen at 20°C.

R_s: is the resistance of sheath or screen per unit length of cable at its maximum operating temperature(Ω/m).

The loss caused by circulating current is given by (3.11).

$$\lambda'_1 = \frac{R_s}{R}\frac{1}{1 + \left(\frac{R_s}{X}\right)^2} \tag{3.11}$$

The reactance (X) per unit length of sheath or screen per unit length of cable is given by (3.12 expressed in (Ω/m).

$$X = 2\ \omega\ 10^{-7}\ln\left(\frac{2s}{d}\right) \tag{3.12}$$

where:

X: is the reactance per unit length of sheath or screen per unit length of cable (Ω/m).

ω: 2πf (1/s).

s: is the distance between conductor axes in the electrical section being considered (mm).

It is essential to note that λ_1'' is equal to zero (0) for cables with small conductors.

The maximum operating temperature of the armour is given by 3.13, which is expressed in °C.

$$\theta_{ar} = \theta_c - \left\{ \left(I^2 R + 0.5 W_d \right) T_1 + \left[I^2 R \ (1 + \lambda_1) + W_d \right] \ nT_2 \right\} \tag{3.13}$$

with

$$R_A = R_{Ao} \ [1 + \alpha_{20} \ (\alpha_{ar} - 20)] \tag{3.14}$$

and

$$R_{AO} = \frac{\rho l}{A}$$

$$A = \pi d_{arm} t_{arm}$$

where:

θ_{ar}: is the maximum operating temperature of the armour.

R_{Ao}: is the resistance of the armour at 20°C.

R_A: is the resistance of the armour at operating temperature.

d_{arm}: Is the diameter of the armouring in mm.

t_{arm}: is the thickness of the armouring in mm.

The ratio of losses in the armouring to total losses in all conductors is given by (3.15).

$$\lambda_2 = 1.23\,\frac{R_A}{R}\left(\frac{2c}{d_A}\right)^2 \frac{1}{\left(\frac{2.77\ R_A\ 10^6}{\omega}\right)^2 + 1} \tag{3.15}$$

where:

d_A: is the mean diameter of the armour (mm).

c: is the distance between the axes of a conductor and the cable centre (mm).

The thermal resistance per core between conductor and sheath is given by (3.16).

$$T_1 = \frac{\rho T}{2\pi} ln\left[1 + \frac{2t_1}{d_c}\right] \tag{3.16}$$

where:

ρT: is the thermal resistivity of the insulation (K.m/W)

d_c: is the diameter of the conductor (mm).

t_1: is the thickness of the insulation between conductor and sheath (mm).

Thermal resistance between sheath and armour is given by (3.17).

$$T_2 = \frac{1}{2\pi}\rho T ln\left[1 + \frac{2t_2}{D_a}\right] \tag{3.17}$$

with: t_2: Is the thickness of the bedding.

D_a: is the external diameter of the armour (mm).

Thermal resistance for the cable outer covering (T_3) is given by (3.18).

$$T_3 = \frac{1}{2\pi}\rho T \ln\left(1+\frac{2t_3}{D_s'}\right) \tag{3.18}$$

where:

t_3: is the thickness of the serving or jacket (mm).

D'_s: is the external diameter of the serving (mm).

External thermal resistance T_4 is given by (3.19).

$$T_4 = \frac{1.5}{\pi}\rho_T\left[\ln(2u) - 0.630\right] \tag{3.19}$$

where:

$$u = \frac{2L}{D_e} \tag{3.20}$$

with:

ρ_t: is the thermal resistivity of the soil (K.m/W).

L: is the distance from the surface of the ground to the cable axes (mm).

De: is the external diameter of the cable (mm).

3.2.1 Determination of thermal resistivity of soil

The thermal resistivity of the soil is a measure of the resistance of the soil to the flow of heat, and its value is inversely related to the moisture content of the soil [14]. When electric cables are continuously operated at outer cable sheath (surface) temperatures of 55 °C or above [14, 15], the moisture in the soil surrounding the cable may migrate away from the cable, leading to an increase in the thermal resistivity of the soil locally and a consequent increase in the cable conductor temperature, this, in turn, will lead to soil drying out of the soil surrounding the cable [15].

Soil thermal resistivity can be measured in a laboratory; samples will have to be taken to the laboratory where the measurements will be performed. Another standard method would be to perform onsite measurements to determine soil thermal resistivity [20].

The onsite measuring method is called the Electrical Research Association (ERA) transient needle probe. This method consists of the following apparatus: a stainless steel tube of length 450 mm with an outside diameter of 5 mm and containing a heater and thermocouples, and a reference probe of length 150 mm and containing only thermocouples [14] see Figure 3.2. The needle probe is inserted into the soil, and then the reference probe is inserted into the soil a short distance from the probe. The thermal resistance is then calculated by (3.21).

$$g = \frac{4\pi\left(\theta_2 - \theta_1\right)}{qlog_e\left(\frac{t_2}{t_1}\right)} \tag{3.21}$$

where:

g: is the thermal resistivity of soil (Km/W).

q: is the power output of the heater (W/m).

θ_1 and θ_2: are the needle probe temperatures at times t_1 and $t_{2,}$ respectively.

The soil thermal resistivity changes with the change in the moisture content of the soil tested. It is, therefore, necessary to determine the soil moisture content [4].

The soil moisture content is determined by taking samples of the soil tested for soil thermal resistivity (above). Samples are transported in a sealed glass container. The soil moisture content can be calculated by using (3.22)

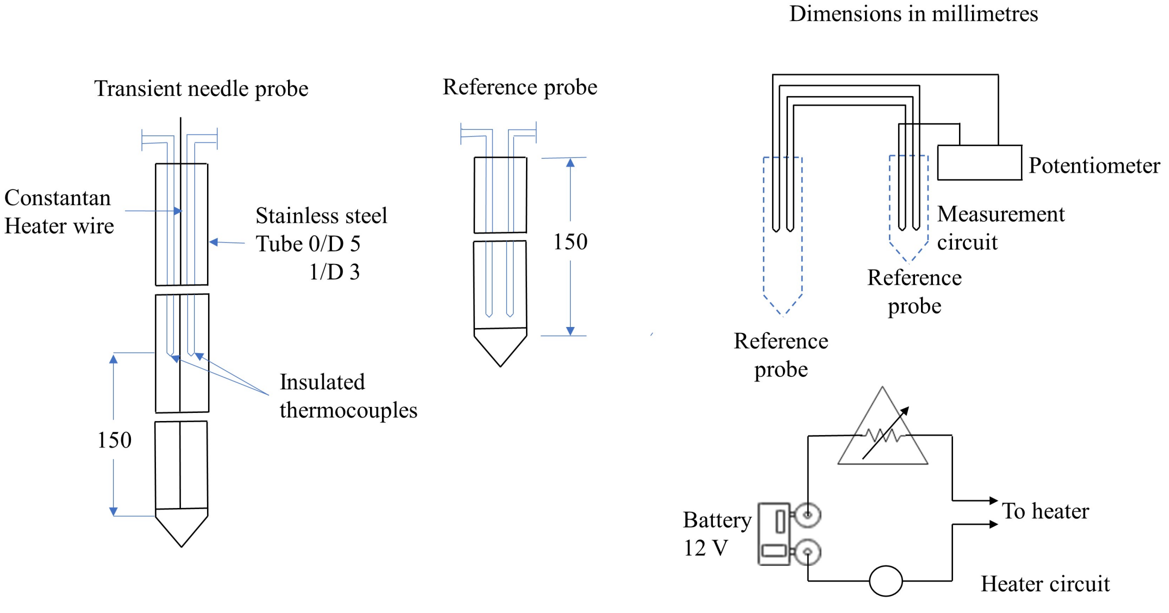


Figure 3.2. ERA Probe and control circuit Reproduced from [20].

$$\textit{soil moisture content} = \frac{m_w - m_d}{m_d} \times 100\ \% \tag{3.22}$$

where:

m_w: is the mass of un-dried test sample.

m_d: is the mass of the dried-out sample.

The worst-case soil thermal resistivity has to be used for cable rating calculations to prevent soil drying out due to power cables. This worst-case thermal resistivity can be archived by performing the soil thermal resistivity measurement during the driest season [20]. The soil thermal resistivity during the dry season is given by (3.23).

$$g_{max} = g \times f \tag{3.23}$$

And the minimum moisture content during the dry season is given by (3.24).

$$g_{min} = \frac{g_m}{f_{mm}} \times f \tag{3.24}$$

where:

g_{max}: is the maximum thermal resistivity during the dry season.

f: is appropriate of the factors (see Table 3.1).

f_{mm}: is the known minimum moisture content.

This test method will require multiple samples to be taken along the cable route. The worst measured soil thermal resistivity along the cable route will have to be used for the cable rating calculations.

Table 3.1. Soil moisture factor for different soil types Reproduced from [20].

Moisture content %	Clay	Sand	Sand/Gravel	San/clay	Loamy	Chalk
1.5	-	1.00	-	-	-	-
2	-	1.25	1.00	-	-	1.0
3	-	1.65	1.31	-	-	1.40
4	-	2.00	1.54	-	-	1.75
5	1.00	2.25	1.73	-	1.00	2.06
6	1.09	2.42	1.89	1.00	1.05	2.32
7	1.18	2.54	2.00	1.13	1.08	2.54
8	1.26	2.64	2.10	1.26	1.12	2.71
9	1.33	2.73	2.18	1.39	1.14	2.83
10	1.39	2.80	2.25	1.52	1.17	2.95
11	1.45	2.86	2.29	1.65	1.19	3.06
12	1.50	2.90	2.32	1.78	1.21	3.16
13	1.54	2.94	2.34	1.90	1.23	3.26
14	1.58	2.98	2.34	2.00	1.24	3.36
15	1.62	3.01	2.34	2.11	1.26	3.45

Continued on next page.

Table 3.1 – continued from previous page.

Moisture content %	Clay	Sand	Sand/Gravel	San/clay	Loamy	Chalk
16	1.65	3.04	2.34	2.20	1.27	3.55
17	1.67	3.06	2.34	2.29	1.29	3.63
18	1.70	3.09	2.34	2.36	1.30	3.70
19	1.72	3.11	-	2.43	-	3.78
20	1.75	3.13	-	2.48	-	3.85
21	1.77	-	-	2.52	-	-
22	1.80	-	-	2.56	-	-
23	1.82	-	-	2.58	-	-
24	1.84	-	-	2.61	-	-
25	1.86	-	-	2.62	-	-
26	1.88	-	-	2.63	-	-
27	1.90	-	-	2.64	-	-
28	-	-	-	2.66	-	-
29	-	-	-	2.66	-	-
30	-	-	-	2.66	-	-

3.2.2 Weather climate in South Africa

South Africa has a wide variety of climate than most other countries. The variety of climate includes Mediterranean, desert (arid), semi-desert (semi-arid), subtropical, and temperate (Koppen) climate.

Mediterranean climate: is characterized by rainy winters and dry summers. The Western Cape Province is the only province in South Africa which has a Mediterranean climate.

Desert climate: is a climate in which precipitation is too low to sustain any vegetation. The Northern Cape Province is the only province in South Africa which has a desert climate.

The semi-desert climate is the climate of a region that receives precipitation below potential evapotranspiration but not as low as the desert climate. Mpumalanga Province and Gauteng province have semi-desert climates.

Subtropical climate: is characterized by warm to hot summers and cool to mild winters with infrequent frost. The KwaZulu Natal Province is the only province in South Africa which has a subtropical climate.

Temperate or Koppean climate: can be classified as a combination of climate types. This kind of climate has a combination of tropical climate and desert climate. The Limpopo Province has a temperate climate.

The provinces in the in-land of South Africa have combinations of the different types of climate listed above; with the majority of the country having semi-desert climate. Thus this then makes South Africa a semi-desert country.

The different climate conditions in South Africa result in different soil ambient temperatures, which in turn dramatically affects the current rating of buried cables. Different soil ambient temperatures will be taken into consideration to evaluate the impact of change in soil ambient temperature for the current rating of cables. The soil ambient temperatures to be considered will be 24 °C, 25 °C, 26 °C, 27 °C, and 28 °C. The considered temperature range is chosen to consider the effect of global warming on soil ambient temperature and cable current rating. This is compared with the cable current rating based on soil ambient temperature of 25 °C.

3.2.3 Cable current rating at different cable depths

Eskom has standardized on 850 mm depth for MV cable tranches. However, due to challenges on-site, it does happen that the cable trench requires to be more or less than the standard depth of 850 mm. The challenges on-site could include rocky surface few millimetres below the topsoil or other services in the same cable route.

For rocky surface few millimetres below the topsoil: the use of power tools (e.g. directional drilling machine) might be required to ensure that the required cable trench depth is achieved. If the use of power tools is impossible due to either access of availability of funds; then the cable trench depth might not be achieved. This will result in a shallow cable trench.

The shallow cable trench could pose an environmental hazard or a safety risk. The environmental hazard could be due to soil erosion which could, in turn, expose the cable to the public. Safety of human beings and animals could be compromised once the cable is exposed to the public. Hence the need for environmental assessment before power cables can be installed.

For installations where there are other services on the same cable route: Eskom has specified clearances between different services which are running parallel with electrical cables [4].

With all these scenarios; the standard depth for cable trench may not be met; this, in turn, will affect the cable ratting of cables which will be installed in those trenches. The following cable trench depth will be considered for the purpose of this research: 750 mm, 850 mm, 950 mm, 1000 mm and 1150 mm. Where 750 mm is a reasonable shallow cable trench for MV cable system.

3.2.4 Parameters of the cable to be used

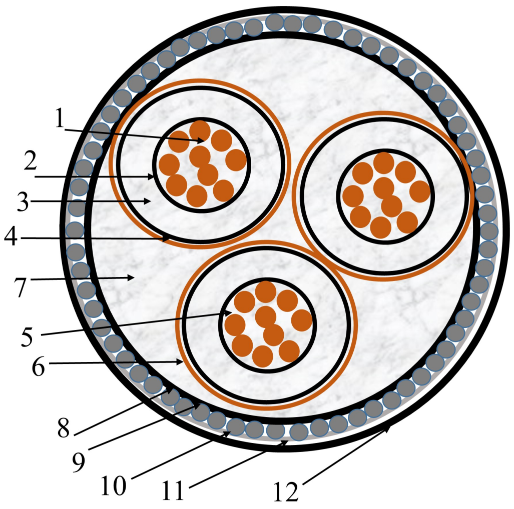
Three cable datasheets from three different cable manufacturing companies were used for the cable rating calculations. For this research the names of the cable manufacturing companies are not shared; thus they (the cable manufacturing companies) are referred to: cable A, cable B and cable C. Figure 3.3 show a typical cross-sectional drawing of a 3 core XLPE cable manufactured by the three different cable manufacturers, such as cable A, cable B and cable C.

3.2.5 Cable rating calculating tool

Microsoft Excel software was used to calculate the cable rating. Table 3.3 below shows the cable rating calculated results; where the calculations were performed by using (2.1) to (3.21). The manufacturers' data sheets shown in Figure 3.3 was used to perform the calculated results, as shown in Table 3.3. This strategy uses a soil thermal resistivity of 1.2 K.m/W; this is considered to be a good value for soil thermal resistivity.

3.2.6 Soil thermal resistivity test

Soil samples from a park called George Lea Park (Sandton Sports club) in South Africa were taken for verification of the soil thermal resistivity and moisture content of the soil. The Sandton area was chosen due to the fact that Eskom has a lot of cable projects in this area. Some of these projects are due to new customer application where new cable networks have to be built, while some are refurbishment projects or cable replacement projects. The coordinates of the area where the soil samples were taken are -26.099573 and 28.034719.



1	Annealed stranded copper conductor
2	Semi-conductive conductor screen
3	XLEP Insulation
4	Semi-conductive core screen
5	Semi-conductive water blocking tape
6	Copper screened tape
7	Filler
8	Binding tape
9	FR PVC bedding
10	Galvanized steel wire armouring
11	Binding tape
12	UV stabilized PVC sheath

Figure 3.3. Typical cross-sectional drawing for MV XLPE.

Table 3.2 summarizes the parameters of the three cable data sheets as detailed in Figure 3.3.

Eskom had a cable replacement project in this area; where a cable was stolen and had to be replaced. The length of the cable route was about 200 m. Three samples were taken at about 60 m intervals, and about 1 m depth. The 60 m intervals were chosen due to the physical change of the soil in terms of the texture of the soil and the color of the soil. The samples were then taken to a laboratory called SOIL LAB were the soil thermal resistivity tests were to be performed. For the research, only one sample of the three samples was tested due to the costs of the test per sample. Table 3.4 summarizes the soil test results.

Table 3.2. Cable cross-sectional dimension for the three different cables updated from [8, 14, 15].

11 kV, 3 core, copper, XLPE insulated cable with longitudinal water blocked material						
Cable Manufacturer	Cable A		Cable B		Cable C	
Cable parameters	Thickness	Diameter	Thickness	Diameter	Thickness	Diameter
Copper conductor (water blocked) (mm)	-	15.9	-	16.2		16.5
Semi-conducting conductor screen (mm)	0.6	17.1	0.7	18.2	0.8	18
XLPE insulation (mm)	3.4	25.05	3.4	25.3	3.4	25
Semi-conducting core screen (mm)	0.6	-	0.6	26.9	0.8	26.5
Semi-conducting water blocking tape (mm)	-	-	0.3	27.8	0.3	27.5
Copper tape (mm)	0.1	25.95	0.1	28.1	0.1	28
Semi-conducing water blocking tape (mm)	-	-	0.3	29.0	-	-
Water blocking center tissue tape filler (mm)	-	-	-	-	-	-
Water blocking tape and PPL tape binder (mm)	0.3	57.66	0.3	63.5	0.1	66
FR PVC bedding (mm)	1.7	67.44	1.7	67.4	1.7	70
None-conductive water blocking tape (mm)	-	-	0.3	68.0		
Steel wire armour (mm)	3.15	74.5	3.15	74.3	3.15	73.5
None-conductive water blocking tape (mm)	-	-	0.3	74.9		
PE outer sheath (mm)	3.2	75.28	3.2	81.9	3.2	80

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Table 3.2 – continued from previous page.

11 kV, 3 core, copper, XLPE insulated cable with longitudinal water blocked material

Cable Manufacturer	Cable A		Cable B		Cable C	
Cable parameters	Thickness	Diameter	Thickness	Diameter	Thickness	Diameter
Water blocking tissue tape filler	-	-	-	-	-	-
DC resistance at 20°C (Ω/km)	0.0991		0.0991		0.099	
Reactance (Ω/km)	0.326		0.098		0.090	
Capacitance (μF/km)	0.0415		0.423		0.494	
Current rating at 90°C (A)	419		389		394	
Maximum AC resistance at 90°C (Ω/km)	0.1281		0.128		0.128	
Impedance (Ω/km)	0.16		0.161		01.56	
Current rating at 70°C (A)	358		333		331	
Maximum AC resistance at 70°C (Ω/km)	0.1204		0.120		0.120	
Standard laying Conditions:	Soil thermal resistance		Cable burial depth		Number of cable	
Soil temperature = 25°C	= 1.2Km/W		=800 mm		circuit =1	

The 14.5% moisture content was measured on the soil as it was taken from the Sandton area. Three more tests were performed at different soil moisture content to simulate different seasons. Where 0% to 2% moisture content represents a dry to arid season; this could be in the middle of winter season or in a dry summer season where there has been no rain. The 5% moisture content represents a semi-dry season; this could be in autumn. The 14.5% represents a wet season; this can only be achieved in a rainy season. It should, however, be noted that the sample was taken a few days after heavy rain and the trench was already excavated when it was raining. It is shown in Table 3.4 above that the dryer the soil, the higher the thermal resistivity of the soil.

3.3 SMART GRID TECHNOLOGY

The use of smart grid technologies can be used to perform online monitoring of the cable network. There are a lot of developed technologies that have been tested and have proven to perform as per requirements.

The best technology to implement for this dissertation would be to install online thermal motoring technology that will continuously monitor the surface temperature of the cable outer-sheath.

This can be done by installing a fibre optic cable in a fibre optic duct running parallel with power cable. Care should be taken to ensure that the fibre optic duct makes physical contact with the cable outer-sheath.

The fibre optic cable will have to be connected to a Distributed Temperature Sensing (DTS) which will measure the surface temperature of the cable outer-sheath [9]. The measured surface temperature of the cable outer-sheath shall then be compared with the allowed maximum surface temperature of the cable outer-sheath.

Table 3.3. Calculated cable rating results for the three different cables [1, 8, 15, 16].

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
System voltage (V)	Cable data sheath	(V)	11000	11000	11000
Conductor material	Cable data sheath	Copper	Copper	Copper	Copper
Insulation: Cross-linked polyethylene	Cable data sheath	XLPE	XLPE	XLPE	XLPE
Type of conductor	Cable data sheath	Stranded	Stranded	Stranded	Stranded
Armouring: Steel wire armoured	Cable data sheath	SWA	SWA	SWA	SWA
Outer-sheath: Polyethylene	Cable data sheath	PE	PE	PE	PE
Dimensional Characteristics					
Conductor diameter	Cable data sheath	d_c (mm)	15.9	16.2	16.3
Conductor cross-section	Cable data sheath	(mm^2)	185	185	185
Thickness of the inner semiconductor	Cable data sheath	(mm)	0.6	0.6	0.8
Average insulation thickness	Cable data sheath	(mm)	3.4	3.4	3.4
Diameter of the conductor semi-conductive screen	Cable data sheath	(mm)	17.1	17.1	18
Outer diameter of the insulation	Cable data sheath	(mm)	23.85	25.3	25

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Thickness of the insulation semi-conductive screen	Cable data sheath	(mm)	0.6	0.6	0.8
Diameter of the water blocking tape above the insulation semi-conductive screen	Cable data sheath	(mm)	25.05	25.05	18.6
Thickness of the water blocking tape above the insulation semi-conductive screen	Cable data sheath	(mm)	0.3	0.3	0.3
Diameter of the fillers above the water blocking tape	Cable data sheath	(mm)	25.65	25.65	28.2
Thickness of the filters above the water blocking tape	Cable data sheath	(mm)	15	15	9.6
Thickness of metallic sheath/ copper tape screen	Cable data sheath	t_s (mm)	0.1	0.1	0.1
Diameter of metallic sheath (inner)/ copper tape screen	Cable data sheath	(mm)	25.95	25.95	28
Binding tape thickness	Cable data sheath	(mm)	1.7	1.7	0.1

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Thickness of armouring	Cable data sheath	t_s (mm)	3.15	3.15	3.15
Diameter of the metallic sheath (Outer)	Cable data sheath	(mm)	2.615E+01	26.15	28.2
Thickness of the metallic sheath	Cable data sheath	t_s (mm)	1.00E-01	1.00E-1	1.00E-01
Diameter of the armouring	Cable data sheath	(mm)	74.5	74.3	73.5
Cross-sectional area of the armouring	Equation 3.16	A (mm^2)	7.37253256E-04	7.3527405E-04	7.27357239E-4
Thickness of the outer sheath	Cable data sheath	t_s (mm)	3.2	3.2	3.2
Diameter of binding tape	Cable data sheath	(mm)	67.44	67.44	66
Diameter of the outer sheath	Cable data sheath	(mm)	81.66	81.99	80
Approximate weight	Cable data sheath	(kg/m)	10	10	10
Distance between conductor axes	Cable data sheath	s (mm)	25.25	26.7	26.5
Maximum cable conductor temperature (°C)	Cable data sheath	θ (°C)	70	70	70
Number of load-carrying conductors in the cable (n)	Cable data sheath	n	3	3	3

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
DC resistance of the conductor at 20°C (Ω/m)	Cable data sheath	R_o (Ω/m)	9.91E-05	9.91E-05	9.91E-05
System frequency (Hz)	Cable data sheath	F (Hz)	50	50	50
Pi (π)		π	3.141592654	3.141592654	3.141592654
Number of circuits	Standard design	1	1	1	1
Installation configuration	Cable data sheath	3 core	3 Core	3 Core	3 Core
Laying depth (m)	Standard design	L (m)	0.85	0.85	0.85
Ambient ground temperature (°C)	Assumption	θ_a (°C)	25	25	25
In-situ soil thermal resistivity (K.m/W)	IEC 60287-1-1	P (K.m/W)	1.2	1.2	1.2
Earthing of the metallic screens/armouring	Single-end bonded		Yes	Yes	Yes
Skin effect factor	IEC 60287-1-1, Table 2	k_s	1	1	1
Proximity effect factor	IEC 60287-1-1, Table 2	k_p	1	1	1

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Thermal resistivity of insulation material (XLPE)	IEC 60287-2-1, Table 1	ρ_i (K.m/W)	3.5	3.5	3.5
Thermal resistivity of the armouring	IEC 60287-2-1, Table 1	P_{armor} (K.m/W)	1.38E-07	1.38E-07	1.38E-07
Temperature coefficient of electrical resistivity for steel armour at 20°C per Kelvin	IEC 60287-1-1, Table 1	α_{20} (/K)	4.5E-03	4.5E-3	4.5E-3
Relative permittivity of insulation	IEC 60287-1-1, Table 3	ε	2.5	2.5	2.5
Insulation loss factor	IEC 60287-1-1, Table 3	$\tan\delta$	0.004	0.004	0.004
Thermal resistivity of cable outer sheath material (PE)	IEC 60287-2-1, Table 1	ρ_s (K.m/W)	3.5	3.5	3.5
Thermal resistivity of semi-conductive layer	IEC 60287-2-1, Table 1	ρ_{sc} (K.m/W)	2.5	2.5	2.5
Thermal resistivity of water blocking tape	IEC 60287-2-1, Table 1	$\rho_{water\ b/t}$ (K.m/W)	2.5	2.5	2.5

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Thermal resistivity of fillers	IEC 60287-2-1, Table 1	$\rho_{fillers}$ (K.m/W)	6	6	6
Temperature coefficient of electrical resistivity for copper conductor at 20°C per Kelvin	IEC 60287-1-1, Table 1	α_{20} (/K)	3.93E-3	3.93E-3	3.93E-3
Thermal resistivity of copper tape at 20°C	IEC 60287-1-1, Table 1	$P_{cu\ tape}$ (K.m/W)	2.14E-7	2.14E-7	2.14E-7
Temperature coefficient of electrical resistivity for metallic tape (copper tape) at 20°C per Kelvin	IEC 60287-1-1, Table 1	α_{20} (/K)	4.0E-03	4.0E-3	4.0E-03
Argument of a Bessel function used to calculate skin effect	IEC 60287-1-1, Clause 2.1.2	x_s	1.0294654	1.0294654	1.0294654
Skin effect factor	IEC 60287-1-1, Clause 2.1.2	y_s	5.8226150E-3	5.822615E-3	5.8226150E-3
Argument of a Bessel function used to calculate proximity effect	IEC 60287-1-1, Clause 2.1.3	x_p	1.0294654	1.0294654	1.0294654

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Proximity effect factor	IEC 60287-1-1, Clause 2.1.3	y_p	1.0163016E-2	9.41637675E-3	9.6844388E-3
DC resistance of conductor at maximum operating temp. (Ω/m)	IEC 60287-1-1, Clause 2.1.1	R'(Ω/m)	1.1857315E-4	1.1857315E-4	1.1857315E-4
Alternating current resistance of conductor at operating temp. (Ω/m)	IEC 60287-1-1, Clause 2.1	R (Ω/m)	1.2141635E-4	1.2128355288E-4	1.2133123E-4
Capacitance (F/m)	IEC 60287-1-1, Clause 2.2	C (F/m)	4.1745262E-10	3.54556279E-10	4.2279199E-10
AC resistance of cable sheath at 20oC (Ω/m)	IEC 60287-1-1, Clause 2.3	R_{so} (Ω/m)	1.59104079E-4	1.595323534E-4	1.61268759E-4
AC resistance of cable sheath at their maximum operating Temperature (Ω/m)	IEC 60287-1-1, Clause 2.3	R_s (Ω/m)	2.5882335E-2	2.5882335E-2	2.39873782E-2
Reactance of sheath or screen per unit cable length (Ω/m)	IEC 60287-1-1, Clause 2.3.1	X (Ω/m)	4.1833556E-05	4.534192419E-5	4.0092214E-5

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Operating temperature metallic sheath, armour or screen (°C)	Assume 10 °C less than conductor temperature	θ_{sc} (°C)	60	60	60
Equivalent resistance of sheath and armour at operating temperature (Ω/m)	Equation 16 above	R_e (Ω/m)	2.60414391E-2	2.604186732E-2	2.41486471E-2
Power loss in sheath or screen	IEC 60287-1-1, Clause 2.3.1	λ_1	8.35331905E-4	9.82391181E-4	8.28427943E-4
Circulating losses	IEC 60287-1-1, Clause 2.3.10	λ_1‘	8.35331905E-4	9.8239118071E-4	8.28427942E-4
Eddy current losses	IEC 60287-1-1, Clause 2.3.1	λ_1“	0.00	0.00	0.00
AC resistance of armour tape at 20°C (Ω/m)	R= l/A	R_{ao} (Ω/m)	1.59104079E-4	1.5953235E-4	1.6126876E-4
AC resistance of armour at their max. op. Temp. (Ω/m)	R= ρl/A	R_a (Ω/m)	1.931825E-4	1.9370251E-4	1.95810836E-4

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Operating temperature armour (°C)	IEC 60287-1-1, Clause 2.3	θ_{ar} (°C)	60	60	60
Ratio of power loss in armour	IEC 60287-1-1, Clause 2.4.2.3	λ_2	7.5744654E-2	7.57446548E-2	7.5744654E-2
Thermal resistance between conductor and sheath (K.m/W)	IEC 60287-2-1, Clause 2.1.1.1	T_1 (K.m/W)	2.3497992E-1	2.333686125E-1	2.40455923E-1
Thermal resistance between sheath and armour (K.m/W)	IEC 60287-2-1, Clause 2.1.2.1	T_2 (K.m/W)	1.78294E-9	1.78754911E-9	1.80622678E-9
Thermal resistance of outer covering (K.m/W)	IEC 60287-2-1, Clause 2.1.3	T_3 (K.m/W)	1.810106E-9	1.814782072E-9	1.83373258E-9
Thermal resistance of surrounding medium (K.m/W)	IEC 60287-2-1, Clause 2.2.2	T_4 (K.m/W)	7.12069862E-1	7.112987212E-1	7.15996705E-1
Losses in conductor per unit length (W/m)	I^2R	W_c (W/m)	1.7752036E+1	1.777875914E+1	1.76258356E+1
Dielectric losses per unit length per phase(W/m)	IEC 60287-1-1, Clause 2.2	W_d (W/m)	2.1158319E-2	1.797045861E-2	2.14289421E-2

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Table 3.3 – continued from previous page.

Description	Source of input value	Input & units	Cable A	Cable B	Cable C
Losses dissipated in sheath or screen per unit length(W/m)	$\lambda_1.W_c$	W_s (W/m)	1.4828842E-2	1.74656962E-2	1.46017347E-2
Permissible temperature rise of the conductor above soil ambient temperature	IEC 60287-1-1, Clause 1.4.1.1	$\Delta\theta$ (°C)	45	45	45
Current rating (A)	IEC 60287-1-1, Clause 1.4.1.1	I (A)	382.371	382.869	381.143

Table 3.4. Soil moisture content and soil thermal resistivity test.

Soil moisture content	Thermal Conductivity (W/Km)	Thermal Resistivity (Km/W)
14.5% (as obtained from the sample)	1.678	0.596
0%	0.269	3.720
2%	0.428	2.341
5%	0.607	1.646

CHAPTER 4 RESULTS

4.1 INTRODUCTION

This section details the calculation results of the different installation conditions considered. The different installation conditions include the thermal resistivity of the soil, the ambient temperature of the soil and burial depth of the cable. The accuracy level of the calculation tool is compared with the cable rating calculations stated in the datasheets of the three different cable manufacturing companies. Furthermore: this section has a summarized procedure to be followed by the utilities for preliminary cable rating calculations.

4.2 CURRENT RATING BASED ON SOIL THERMAL RESISTIVITY

The soil thermal resistivity test results, as stated in Table 3.4 were used to re-calculate the current rating of the three different cables. Table 4.1 shows the different moisture content of the soil tested and the corresponding soil thermal resistivity. It is shown in Table 4.1 that the higher the soil moisture content; the lower the thermal resistivity of the soil.

Table 4.1 shows the calculated current rating of the different cables, as shown in Table 3.3.

The developed Excel calculating tool was used to calculate the cable rating. The information captured in Table 3.3 was used; only the soil thermal resistivity was changed, and the calculated current rating was recorded in Table 4.1.

The best current rating results were obtained when the soil thermal resistivity was 0.596 K.m/W, and moisture content was 14.5%. The probability of soil moisture content greater than 14.5% exists. The greater soil moisture content will then result to favorable cable current rating. The inclusion of water blocking material, as shown in item 5 of Fig. 3.3, and the polyethylene cable outersheath makes the cable suitable for installation in wet environment.

4.3 CURRENT RATING BASED ON DIFFERENT SOIL AMBIENT TEMPERATURE

Section 3.1.2 describes the climate in South Africa. The rain pattern in South Africa has changed over the years due to global warming. The majority of South Africa is going through a desertification period. This could mean that the soil ambient temperature could increase by a few degrees Celsius from the standard 25 °C. The impact of the change in soil ambient temperature was investigated; Table 4.2 represents the current rating based on the change in soil ambient temperature.

The developed Excel calculating tool was used to calculate the cable rating. The information captured in Table 3.3 was used, only the soil ambient temperature was changed, and the calculated current rating was recorded on Table 4.2. The best current rating results were obtained when the soil ambient temperature was 24 °C.

4.4 CABLE CURRENT RATING AT DIFFERENT CABLE LAYING DEPTHS

The onsite installation conditions differ per project site. There could be site conditions that would require that the cable trench be dug deeper or shallower; thus the standard cable trench depth of 850 mm might not be achieved due to those challenges on-site; hence cable rating due to different cable trench/laying depth is investigated. Table 4.3 represents the current rating based on the change in cable trench/laying depth.

The developed Excel calculating tool was used to calculate the cable rating. The information captured in Table 3.3 was used, only the cable laying depth was changed, and the calculated current rating was recorded in Table 4.3. $\Delta\theta$ was kept fixed at 45 °C, as shown in Table 3.3. The best current rating results were obtained when the cable laying depth was 750 mm.

4.5 CURRENT RATING BASED ON WORST CASE INSTALLATION CONDITIONS

The worst installation condition was considered; where all worst-case scenarios as listed from Table 4.1 to Table 4.3 were considered and the current rating results thereof are shown in Table 4.4.

Table 4.1. Cable rating results for different soil moisture content.

Cable manufacturer	I (at 14.5% & 0.596 Km/W)	I (Imported soil & 1.2 Km/W)	I (at 5% & 1.646 Km/W)	I (at 2% & 2.341 Km/W)	I (at 0% & 3.72 Km/W)
Cable A	518.746 A	382.371 A	330.663 A	280.169 A	224.330 A
Cable B	519.540 A	382.869 A	331.070 A	280.495 A	224.582 A
Cable C	516.723 A	381.143 A	329.667 A	279.372 A	223.730 A
Average	518.34 A	382.13 A	330.47 A	280.01 A	224.21 A

Table 4.2. Current rating based on the change in soil ambient temperature.

Cable manufacturer	24 °C	25 °C	26 °C	27 °C	28 °C
Cable A	386.597 A	382.371 A	378.099 A	373.777 A	369.405 A
Cable B	387.100 A	382.869 A	378.590 A	374.263 A	369.886 A
Cable C	385.355 A	381.143 A	376.884 A	372.577 A	368.219 A

Table 4.3. Cable rating based on the change in different cable trench depth.

Cable manufacturer	750 mm	850 mm	950 mm	1000 mm	1150 mm
Cable A	388.321 A	382.371 A	377.308 A	375.040A	369.062 A
Cable B	388. 833 A	382.869 A	377.793 A	375.520 A	369.527 A
Cable C	387.0.31 A	381.143 A	376.132 A	373.888 A	367.967 A

The developed Excel calculating tool was used to calculate the cable rating. The information captured in Table 3.3 was used, and the following values were changed: the soil thermal resistivity, the cable laying depth and the soil ambient temperature. $\Delta\theta$ changed with the change in soil ambient temperature. The current rating reduced to an average of 45.4% of the calculated current rating with ideal conditions.

4.6 FACTORS AFFECTING T_4

T_4 is the onsite dependent constant; which is dependent on the environment where the cable is installed. The behaviour of T_4 was analysed for different installation conditions; this includes the change in soil thermal resistivity, the change in soil ambient temperature and the change in cable laying depth. Only cable A was analysed for this section of the report.

4.6.1 T_4 Based on the change in soil thermal resistivity

The developed Excel calculating tool was used to calculate the cable rating. The information captured in Table 3.3 was used, only the soil thermal resistivity was changed; while the soil ambient temperature was kept at 25 ºC and the cable laying depth was kept at 850 mm.

Table 4.4. Worst installation condition versus ideal installation condition.

	Installation condition	Value	Cable A	Cable B	Cable C
Worst installation condition (I_{worst})	Soil thermal resitivity	3.72 Km/W	208.70 A	208.93 A	208.19 A
	Cable laying depth	1150 mm			
	Soil temperature	28 ºC			
Ideal installation Condition (I_{ideal})	Soil thermal resistivity	1.2 Km/W	382.37 A	382.87 A	381.14 A
	Cable laying depth	850 mm			
	Soil temperature	25 ºC			
	$I_{rating} = \frac{I_{worst}}{I_{ideal}}$	Average: 45.40%	45.42%	45.43%	45.38%

The following results were observed when the soil thermal resistivity was changed: $\Delta\theta$ remained the same, the current rating of the cable and the T_4 reduced when the soil thermal resistivity was increased as shown in Table 4.5.

Figure 4.1 is a graphical representation of the results stated in Table 4.5 above. It is shown on Figure 4.1 that the current rating of the cable is inversely proportional to T_4 and inversely proportional to the increase in soil ambient temperature; however, there is no mathematical relationship between the changes in soil thermal resistivity and the temperature rise of the cable [1].

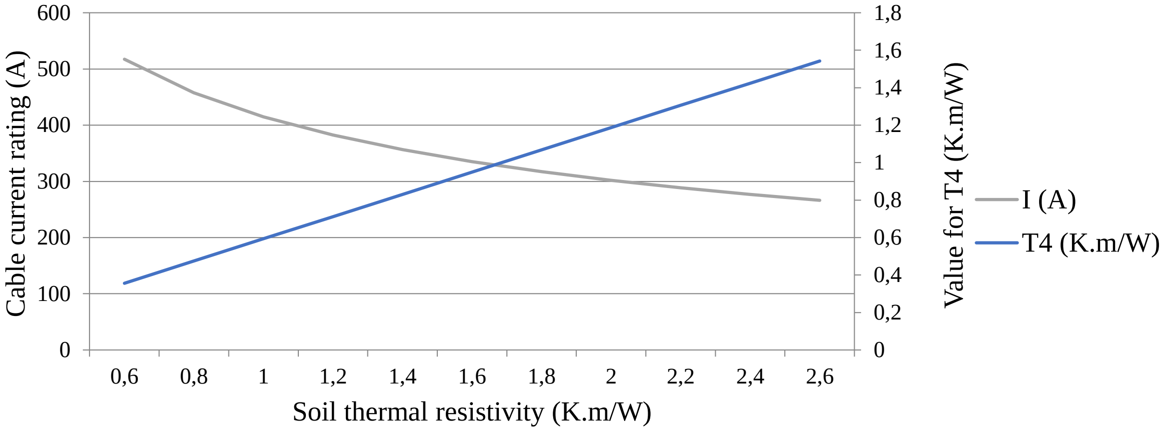

Figure 4.1. The relationship between T_4 and the current cable rating when the soil thermal resistivity is changed.

Table 4.5. The relationship between T_4 and the current cable rating when the soil thermal resistivity is changed.

Cable A			
Soil thermal resistivity (K.m/W)	ΔΩ (ºC)	I (A)	T_4 (K.m/W)
0.6	45	517.3085	0.356034930
0.8	45	457.8175	0.474713241
1.0	45	415.0372	0.593391550
1.2	45	382.3714	0.712069870
1.4	45	356.3748	0.830748172
1.6	45	335.0487	0.949426482
1.8	45	317.1435	1.068104790
2.0	45	301.8327	1.186783102
2.2	45	288.5448	1.305461413
2.4	45	276.8702	1.068104790
2.6	45	266.5070	1.186783102

4.6.2 T_4 Based on the change in soil ambient temperature

The developed Excel calculating tool was used to calculate the cable rating. The information captured in Table 3.3 was used; only the ambient temperature was changed. $\Delta\theta$ and the current rating reduced for an increase in soil ambient temperature while the T_4 remained the same.

Figure 4.2 is a graphical representation of the results stated in Table 4.6 above. It is shown on Figure 4.2 that the current rating of the cable and temperature rise are inversely proportional to the increase in soil ambient temperature; however, there is no mathematical relationship between the value of T_4 and the increase in soil ambient temperature [1].

4.6.3 T_4 Based on the change in cable laying debth

The developed Excel calculating tool was used to calculate the cable rating. The information captured in Table 3.3 was used; only the cable laying depth was changed. The current rating of the cable reduced for an increase in cable laying depth; the value of T_4 increased while the soil ambient temperature remains unchanged when the cable laying depth was increased. It should be noted that a significant

Table 4.6. The relationship between T_4, temperature rise and current rating when the soil ambient temperature is increased.

Cable A			
Ambient temperature (°C)	$\Delta\theta$ (°C)	I (A)	T_4 (K.m/W)
23.0 °C	47.0	390.777	0.71207
23.5 °C	46.5	388.692	0.71207
24.0 °C	46.0	386.597	0.71207
24.5 °C	45.5	384.490	0.71207
25.0 °C	45.0	382.371	0.71207
25.5 °C	44.5	380.241	0.71207
26.0 °C	44.0	378.099	0.71207
26.5 °C	43.5	375.944	0.71207
27.0 °C	43.0	373.777	0.71207
27.5 °C	42.5	371.597	0.71207
28.0 °C	42.0	369.405	0.71207

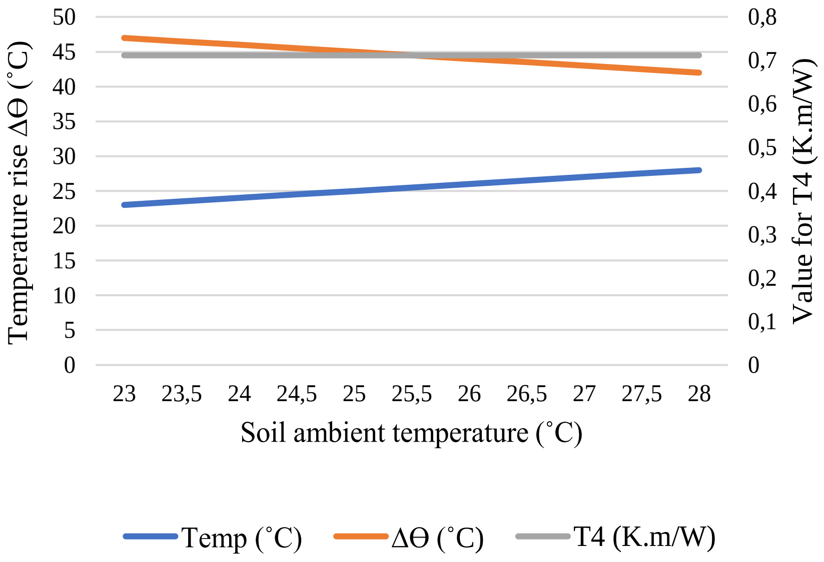

Figure 4.2. The relationship between T_4, temperature rise and current rating when the soil ambient temperature is increased.

Table 4.7. Relationship between the change in cable laying depth, T_4, temperature rise and current rating.

Cable A			
Cable laying depth (m)	$\Delta\theta$	I (A)	T4 (K.m/W)
0.650	45	395.47736	0.660756803
0.70	45	391.72211	0.674936407
0.75	45	388.32101	0.688134063
0.80	45	385.21871	0.700477184
0.85	45	382.37148	0.712069861
0.90	45	379.74422	0.722998235
0.95	45	377.308343	0.733334400
1.00	45	375.04030	0.74313930
1.05	45	372.92052	0.75246495
1.10	45	370.93251	0.76135604
1.15	45	369.06230	0.76985130

change in cable laying depth could result in a change in soil ambient temperature; this, in turn, could result in a change in the current rating of the cable. This, however, does not prove that there is a mathematical relationship between the cable laying depth and temperature rise. This proves that the thermal resistivity of the soil increases the more profound is the trench. This is due to the hardness of the soil, the deeper the trench thus making it difficult to dissipate heat.

Figure 4.3 is a graphical representation of the results stated in Table 4.7. It is shown in Figure 4.3 that the current rating of the cable and T_4 are inversely proportional to the increase in cable laying depth. At the same time, T_4 is directly proportional to the increase in cable laying depth.

4.7 THERMAL MONITORING OF THE CABLE SYSTEM USING SMART GRID TECHNOLOGY

If a cable is expected to carry the same load (382.13 A) under non-ideal conditions as stated in Section 4.2 to Section 4.4 (Tables 4.2 to 4.4); the surface temperature of the cable outer-sheath will increase; thus this could result in the drying out of the soil. An increase in the surface temperature of the cable outer-sheath will result in an increase in $\Delta\theta$ to more than 45 °C (Table 3.3). If a cable has to be installed

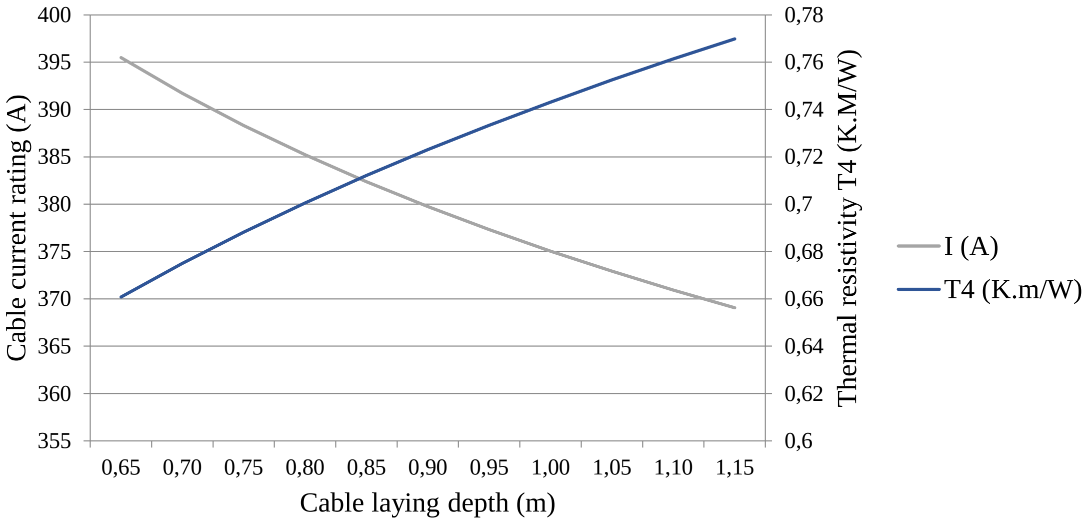

Figure 4.3. Relationship between the change in cable laying depth, T_4, temperature rise and current rating.

in a non-ideal condition, as stated in Section 4.2 to Section 4.4, then the use of smart technologies like thermal monitoring of the cable outer-sheath should be considered.

The smart grid technology used (e.g. DTS) shall be used to measure the surface temperature of the cable outer-sheath and compare the measured value with the allowed maximum surface temperature of the cable outer-sheath. If the measured surface temperature of the cable outer-sheath is greater than the maximum allowed surface temperature of the cable outer-sheath; then the necessary switching shall be performed to reduce the load; thus the surface temperature of the cable outer-sheath will be reduced.

4.8 SENSITIVITY

The calculated results in Table 3.3 were used and compared with data sheets from the cable manufacturers. Table 4.8 show the calculated current rating for the three different cables and the current rating, as stated in the manufacturer’s data sheets.

The three cable manufacturer’s data sheets considered the following installation condition: 1.2 K.m/W soil thermal resistivity, 850 mm cable laying depth, 25 °C soil ambient temperature, 70 °C continuous conductor temperature and that there was only one cable in the trench.

Table 4.8. Accuracy level compared with the manufacturer's data sheet.

Cable Manufacturer	Cable A	Cable B	Cable C
Manufacturer's data sheet	358 A	333 A	331 A
Calculated @ 0.8 m depth	385 A	386 A	384 A
Accuracy Level	92.99%	86.27%	86.20%
Average accuracy level	88.48 %		

The accuracy level for the different cables varied between 86.2% and 92.99%, with an average of 88.48%. This low accuracy level is due to assumptions made on the material used to manufacture the cables. The information of the material and their properties is seen as intellectual property; thus, the cable manufacturers cannot share such information with the public.

CHAPTER 5 DISCUSSION

5.1 INTRODUCTION

In this Chapter, the results of the different installation conditions considered in this dissertation are discussed. The results where the worst case scenario (where all the conditions are considered in one installation) are analysed, the implication of each installation condition is discussed, and the effect of T_4 on the different installation conditions.

5.2 CURRENT RATING BASED ON SOIL THERMAL RESISTIVIY AND SOIL MOISTURE CONTENT

Section 3.1.2 describes the climate in South Africa [14]. The rain pattern has changed over the years due to global warming. The majority of South Africa is going through a desertification phase. The desertification phase will result to the migration of the moisture content in the soil; this in turn will result to higher soil thermal resistivity. The higher the soil thermal resistivity the more difficult it will be for the soil to dissipate heat around the cable.

An increase in the conductor temperature will increase the surface temperature of the cable; consequently the soil closest to the cable will solidify depending on the surface temperature of the cable.

Figure 2.1 shows a cable buried at 0.8 m underground. It describes that the soil closest to the cable is exposed to higher temperature than the soil further away from the cable.

5.3 CURRENT RATING BASED ON DIFFERENT SOIL AMBIENT TEMPERATURE

The average ambient temperature in South Africa has been increasing by an average of 0.9°C [15] per year for the past few years due to climate change (global warming); this equates to an average increase

Table 5.1. Difference of current ratting with varied selected soil ambient temperature range

Cable Sample	24°C - 25°C	25 °C	26°C - 25°C	27°C - 25°C	28°C - 25°C
Cable A	4.226 A	382.371 A	-4.272 A	-8.594 A	-12.966 A
Cable B	4.231 A	382.869 A	-4.279 A	-8.606 A	-12.983 A
Cable C	4.212 A	381.143 A	-4.259 A	-8.566 A	-12.924 A
Average	4.223 A	382.128 A	-4.270 A	-8.589 A	-12.958 A
Average	1.110%	-3.390%	-1.120%	-2.250%	-3.390%

of 9°C every ten years. This could result to a fraction of an increase of soil ambient temperature. This in turn will have a negative impact on the ampacity of buried cables.

The South African Weather Services further indicated that the average annual rainfall has been reducing by about 6 % since 1904 to 2016 [15]. This clearly indicates the rate in which the desertification process of South Africa is happening.

If it is assumed that the average ambient temperature increases by 9°C every ten years; this could result to an increase of 1°C in soil ambient temperature. Table 5.1 shows the difference of current rating calculations when the ambient ground temperature was increased by 1°C for every ten years.

Table 5.1 shows the current rating calculations when the ambient ground temperature was increased by 1°C for every ten years. It can be seen that the current rating will increase by an average of 4.223 A (1.11%) for a 1°C reduction in soil ambient temperature, and will reduce by an average of 4.27A (1.12%) for a 1°C increase in soil ambient temperature.

5.4 CURRENT RATING BASED ON DIFFERENT BURIAL DEPTH

Soil composes of four major distinct layers which are called; the top soil, the subsoil, the parent rock and the bedrock. These layers of the soil differ in texture, color, depth and chemical composition. The top soil is usually between 130 mm deep and 250 mm deep from the surface of the earth, while the sub soil ranges between 200 mm to1000 mm.

The top soil is dark in color, generally soft, porous and can retain more water [21]. The second layer of the soil (the subsoil) is generally harder and more compact than the top layer.

Electrical cables are generally buried between the topsoil and the subsoil. The thermal resistivity of the soil increases the deeper is the trench. This is due to the hardness of the layer thus making it difficult to dissipate heat.

5.5 CURRENT RATING BASED ON WORST CASE INSTALLATION CONDITIONS

The worst case scenario as tabled in Table 4.4 cannot be ignored. This scenario could result from various factors; and those factors could include:

1. Soil thermal resistivity: the soil thermal resistivity could increase due to moisture migration.

2. Cable laying depth: some installation conditions could require that the cable trench be dug deeper than the standard cable laying depth. These installations could include: road crossing installations, or multiple services on a trench; where the electrical cable could be at the bottom of the trench, then other services could be installed in the same trench above the cable. This installation condition is very common in densely populated arrears like Sandton in South Africa.

3. Soil ambient temperature could increase due to global warming and other factors.

Table 4.4 shows that the cable rating worsens by an average of 45.4% when all the worst case scenarios are considered.

5.6 FACTORS AFFECTING T_4

The behavior of T_4 was analyzed for different installation conditions; this includes the change in soil thermal resistivity, the change in soil ambient temperature and the change in cable laying depth. It was found that:

1. The current rating of the cable is inversely proportional to T_4,
2. The current rating of the cable is inversely proportional to the increase in soil ambient temperature,
3. The soil thermal resistivity is directly proportional to T_4, which in turn inversely proportional to the cable current rating,

4. There is no mathematical relationship between the change in soil ambient temperature and T_4,
5. However it was found that there is no mathematical relationship between the cable laying depth and the temperature rise of the cable. This proves that the thermal resistivity of the soil increases the deeper is the trench. This is due to the hardness of the soil at about 1000 mm below ground surface thus making it difficult to dissipate heat.

5.7 PROCEDURE TO BE FOLLOWED FOR CABLE CURRENT RATING

Figure 5.1 summarizes a step by step procedure that can be used by utilities to perform current cable rating calculations. The aim of the procedure is to assist the utilities and Eskom to perform cable current rating calculations.

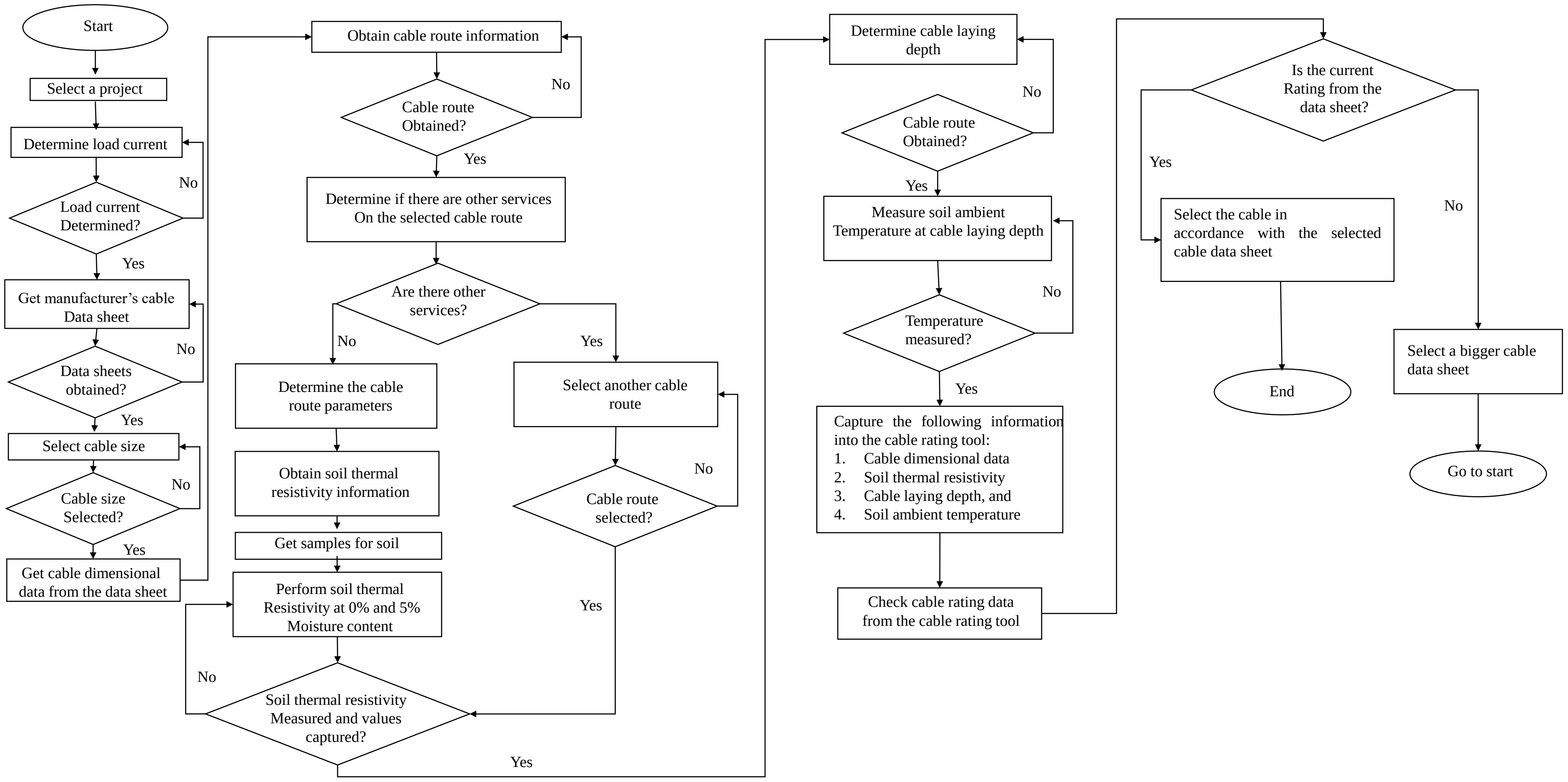

Figure 5.1. Procedure to be followed for cable rating calculations when using the cable rating tool summary.

5.8 SUMMARY

In this Chapter, it was shown that three major installation conditions/parameters are to be considered when performing current ratting calculations for a single circuit of buried cables; these parameters are: the soil thermal resistivity including the soil moisture content, the cable laying depth and the soil ambient temperature. These three parameters are unfortunately not fixed as they can change depending on the environment.

It was shown in this chapter that the best current rating for buried cables is achieve when the soil is moist; the moist the soil the less is the soil thermal resistivity, and the more current can be transmitted through a cable, thus the current rating is directly proportional to the percentage of moisture content of the soil where the cable will be installed. South Africa has been going through a desertification phase due to global warming. This means that the design engineers will have to be more conservative when designing and selecting cable sizes for projects.

The average ambient temperature has been increasing over the years; this is directly proportional to the soil ambient temperature to which power cables are installed. The relationship between the soil ambient temperature and the current rating of the cable is discussed in Section 4.2 and Section 5.2.

Eskom and other Utilities have standard designs for cable trenches for different types of cable installations. However, it is not always possible to comply with the required installation depth due to onsite conditions. There are installations which would require that the cable be installed at a deeper cable trench compared to the standard design of cable trench. De-rating of the cable will then have to be considered for this kind of installation. It is shown in Section 4.3 that the deeper is the cable laying depth the less the current rating. The best results were achieved when the cable was layed in a shallow cable trench. This however cannot be permitted as these cables would be alive, carrying current in the range of hundreds of amps and in the range of thousands of volts; this is a safety hazard to the public and the environment.

The cable ratting results get worse when all the three parameters are taken into consideration (3.72 K.m/W soil thermal resistivity, 1150 mm cable laying depth and 28 °C soil ambient temperature), this results to a drop by 54.6% to 45.4% (382.37 A to 208.70 A) of the current ratting with ideal installation condition (1.2 K.m/W soil thermal resistivity, 850 mm cable laying depth and 25 °C soil ambient temperature).

It was found that the current rating of the cable is inversely proportional to T4, inversely proportional to the increase in soil ambient temperature; however it was found that there is no mathematical relationship between the changes in cable laying depth and the temperature rise of the cable. The temperature rise of the cable due to increased cable depth can only be verified by measuring the ambient temperature at the cable laying depth. However the probability of increase of temperature rise is high when the cable laying depth is increased. This proves that the thermal resistivity of the soil increases the deeper is the trench. This is due to the hardness of the soil the deeper the trench thus making it difficult to dissipate heat.

The flow diagram of the procedure as shown in Figure 5.1 is aimed at assisting the utilities and Eskom to perform the cable rating calculations. The tool can further be used to verify the work done by consultants (where applicable).

The use of DTS to monitor the surface temperature of the cable outer-sheath against the allowed maximum surface temperature of the cable outer-sheath would reduce the probability of soil drying out due to high surface temperature of the cable outer-sheath. This is due to the fact that the DTS will allow the utilities to pro-actively perform the necessary switching to reduce the load on the affected cable networks.

CHAPTER 6 CONCLUSION

The main objective of this dissertation was to investigate cable rating design that eliminates soil drying out due to installed power cables. Different on-site parameters (soil moisture content, including soil thermal resistivity, soil ambient temperature and cable laying depth) were considered for the investigation.

It was found that the effect of soil moisture migration to calculate current ratings has a significant impact when performing cable rating calculations. The measured soil thermal resistivity of the same soil ranged between 0.596 K.m/W (when the soil had a moisture content of 14.5%) and 3.72 K.m/W (when the soil had a moisture content of 0.00%). These gave two current ratting values; which are 518.34 A (average) when the soil moisture content was 14.5%, and 224.21 A (average) when the soil moisture content was 0.00%. Thus it has been proven that the drier the soil the worst will be the current rating. The average values were calculated based on cable construction data sheets from three different cable manufacturing companies.

It was found that the best soil sampling rate to perform soil thermal resistivity tests is 60 m due to the observed physical change in the texture and the colour of the soil within a distance of 60 m (see section 3.16). Only one sample of the three samples was tested due to the cost of performing the soil thermal resistivity test per sample. Thus soil thermal resistivity of the other two soil samples was not obtained. This could have assisted in determining the variance of soil thermal resistivity within the 60 m distance between the samples taken.

The literature study in Chapter 2 revealed that there had been several studies done to prevent soil drying out due to installed power cables; however, no studies have been performed to prove the same studies on South African native soil. It should, however, be noted that these studies were done on cooler and more moist conditions; thus, the impact could be more severe in South African native soil.

The effect of soil ambient temperature and cable laying depth were further investigated. It was found that both scenarios: an increase in soil ambient temperature and an increase in cable laying depth worsens the current rating of the cable when compared with the ideal cable installation conditions. The cable rating reduces by an average of 54.6% when these two conditions and the worst measured soil thermal resistivity of 3.72 K.m/W are taken into consideration. This then means that the cable installation designs need to be more conservative; this, in turn, will result in an acceptable life expectancy which is more than 40 years.

It was found that the current rating of the cable is inversely proportional to T_4, inversely proportional to the increase in soil ambient temperature; however, it was found that there is no mathematical relationship between the cable laying depth and the temperature rise of the cable. The temperature rise of the cable due to increased cable depth can only be verified by measuring the ambient temperature at the increased cable laying depth. However, the probability of an increase in thermal resistivity due to increase in cable laying depth is very high due to the hardness of the soil 1000 mm below ground surface; thus making it difficult to dissipate heat.

The use of smart grid technologies was investigated. It was found that these technologies can significantly assist in cable current rating and in turn increase the life expectancy of the cable because a cable would never be operated beyond its maximum surface temperature or its maximum conductor temperature as per the design.

An Excel cable rating calculation tool was developed. The cable rating calculations performed using this tool were compared with the cable rating information found on three different cable manufacturer data sheets from three different cable manufacturers. It was found that the accuracy level of the developed calculation tool is 88.48% (average). The low accuracy level could be due to assumptions made on the grade of material used to manufacture the cables and assumptions on other dimensions not shown on the data sheets. The information of the grade of material used and their properties is seen as intellectual property; thus, the cable manufacturers cannot share such information with the public. The advanced Excel cable rating calculation tool allows for the following three parameters to be varied for evaluating different scenarios: soil ambient temperature, cable laying depth and soil thermal resistivity.

6.1 ANSWERED RESEARCH QUESTIONS

The following research questions have been answered for the dissertation to be achieved.

1. The best assumption is to assume dry moisture content (0.0%); which represents a dry season. The sampled soil had thermal resistivity of 3.72 K.m/W when the moisture content was 0.0%; which was much higher than the ideal soil thermal resistivity of 1.2 K.m/W considered for HV and EHV cable installations (where imported soil is usually purchased for these installations).
2. The acceptable soil sampling rate for the measurement of soil thermal resistivity can be performed in intervals of 60 m. The use of the worst measured soil thermal resistivity at 0% moisture content will assist Eskom and Utilities to rate and operate cables to acceptable conductor continuous temperatures; thereby preventing accelerated ageing of the cable and drying out of the soil around the cable, this, in turn, will assist in ensuring that the estimated life of 40 years of the cable systems can be achieved.
3. The ideal soil ambient temperature that the cable should be designed for is 25 °C; however, it is recommended that the soil ambient temperature should be measured at the intervals of 60 m. It should be noted that the average ambient temperatures have increased over the years; consequently the soil ambient temperature at 800 mm below the ground surface has increased; thus it is recommended that the soil ambient temperature should be measured to verify if it is not more than the ideal set value of 25 °C.
4. The current rating of the cable is inversely proportional to T_4 and inversely proportional to the increase in soil ambient temperature; however, it was found that there is no mathematical relationship between the cable laying depth and the temperature rise of the cable. The temperature rise of the cable due to increased cable depth can only be verified by measuring the ambient temperature at the increased cable laying depth.
5. The online monitoring system will assist by sending an alarm to SCADA if the measured surface temperature of the cable outer sheath exceeds the allowed maximum surface temperature of the cable outer sheath. This will, in turn, ensure that SCADA performs the necessary remote switching to reduce the load supplied by the affected cable.
6. Cable rating tool has been developed using Excel. The average accuracy level of the developed calculating tool is 88.48%.

7. A procedure in a format of flow diagram has been compiled; this procedure is aimed at assisting the utilities and Eskom in performing cable rating calculations.

6.2 FUTURE WORK

The duration, it takes the cable to dry out: This dissertation did not investigate the time it will take for the soil to dry out due to the heat dissipated by the installed power cable. However, it was shown in [18] that soil drying out could be eliminated as long as the surface temperature of the cable outer-sheath does not exceed 55 °C. This then means that the life expectancy of 40 years of the cable system can be achieved as long as the surface temperature of the cable outer-sheath does not exceed 55 °C

A design for an experiment still needs to be performed to assist in investigating the duration it will take for the soil to dry up. This will have to be addressed in the Thesis for PhD.

The impact of other services installed on the same cable trench: The impact of other services installed parallel with power cable still needs to be investigated.

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ADDENDUM A MATERIAL CONSTANTS AND OTHER PARAMETERS

A.1 MATERIAL CONSTANTS

Table A.1. Lists of material constants used to perform the calculations.

Symbol	Description	Units	Constant value
$\alpha_{20\ Arm}$	Temperature coefficient of electrical resistivity for steel armour at 20°C per Kelvin	/K	0.0045
α_{20Cu}	Temperature coefficient of electrical resistivity for copper conductor at 20°C per Kelvin	/K	0.00393
$\alpha_{20Cutap}$	Temperature coefficient of electrical resistivity for metallic tape (copper tape) at 20°C per Kelvin	/K	0.004
ε	Relative permittivity of insulation	-	2.5
f	System frequency	Hz	50
k_p	Proximity effect factor	-	1
k_s	Skin effect factor	-	1
ρ_{armou}	Thermal resistivity of the armouring (Steel)	K.m/W	0.000000138
$\rho_{cu\ tape}$	Thermal resistivity of copper tape at 20°C	K.m/W	0.000000214
ρ_i	Thermal resistivity of insulation material (XLPE)	K.m/W	3.5
$\rho_{fillers}$	Thermal resistivity of fillers	K.m/W	6

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Table A.1 – continued from previous page.

Symbol	Description	Units	Constant value
ρ_{sheath}	Thermal resistivity of cable outer sheath material (PE)	K.m/W	3.5
ρ_{sc}	Thermal resistivity of semi-conductive layer	K.m/W	2.5
$\rho_{water\ b/t}$	Thermal resistivity of water blocking tape	K.m/W	2.5
π	Pi	-	3.1415926536
$\tan\delta$	Insulation loss factor	-	0.004
$\lambda 1''$	Eddy current losses (this value is zero for 3 core cables)	-	0.00

A.2 SOFTWARE TOOL

Table A.2 shows the input form where the parameters of a cable can be input as stated in a relevant cable data sheet. The three cells bolded in Table A.2 (Page 84) (Laying depth (m), Ambient ground temperature (°C) and In-situ soil thermal resistivity (K.m/W)) are the only three values which were varied to calculate the different scenarios as stated in Chapter 4.

Table A.3 shows the code for the calculation tool sheet; where each calculation step of the tool is shown, and how the final calculation results are obtained.

Table A.2. Input sheet of the calculation tool.

Description	Source of input value	Input symbol and units	Input value
System voltage (V)	Cable data sheath	(V)	11000
Conductor material	Cable data sheath	Copper	
Insulation: Cross linked polyethylene	Cable data sheath	XLPE	
Type of conductor	Cable data sheath	Stranded	
Armouring: Steel wire armoured	Cable data sheath	SWA	
Outer-sheath: Polyethylene	Cable data sheath	PE	
Dimensional Characteristics	-	-	-
Conductor diameter	Cable data sheath	d_c (mm)	16.3
Conductor cross section	Cable data sheath	(mm^2)	185
Thickness of the inner semiconductor	Cable data sheath	(mm)	0.8
Average insulation thickness	Cable data sheath	(mm)	3.4

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Table A.2 – continued from previous page.

Description	Source of input value	Input symbol and units	Input value
Diameter of the conductor semi-conductive screen	Cable data sheath	(mm)	18
Outer diameter of the insulation	Cable data sheath	(mm)	25
Thickness of the insulation semi-conductive screen	Cable data sheath	(mm)	0.8
Diameter of the water blocking tape above the insulation semi-conductive screen	Cable data sheath	(mm)	18.6
Thickness of the water blocking tape above the insulation semi-conductive screen	Cable data sheath	(mm)	0.3
Diameter of the fillers above the water blocking tape	Cable data sheath	(mm)	28.2
Thickness of the fillers above the water blocking tape	Cable data sheath	(mm)	9.6

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Table A.2 – continued from previous page.

Description	Source of input value	Input symbol and units	Input value
Thickness of metallic sheath/ copper tape screen	Cable data sheath	t_s (mm)	0.1
Diameter of metallic sheath (inner)/ copper tape screen	Cable data sheath	(mm)	28
Binding tape thickness	Cable data sheath	(mm)	0.1
Thickness of armouring	Cable data sheath	t_s (mm)	3.15
Diameter of the metallic sheath (Outer)	Cable data sheath	(mm)	2.82E+01
Thickness of the metallic sheath	Cable data sheath	t_s (mm)	1.00E-01
Diameter of the armouring	Cable data sheath	(mm)	7.35E+01
Cross sectional area of the armouring		A (mm^2)	7.2736E-04
Thickness of the outer sheath	Cable data sheath	t_s (mm)	3.2
Diameter of binding tape	Cable data sheath	(mm)	66
Diameter of the outer sheath	Cable data sheath	(mm)	80
Approximate weight	Cable data sheath	(kg/m)	10

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Table A.2 – continued from previous page.

Description	Source of input value	Input symbol and units	Input value
Distance between conductor axes	Cable data sheath	s (mm)	26.5
Maximum cable conductor temperature (°C)	Cable data sheath	(°C)	70
Number of load-carrying conductors in the cable (n)	Cable data sheath	n	3
DC resistance of the conductor at 20°C (Ω/m)	Cable data sheath	R_o	9.91E-05
System frequency (Hz)	Cable data sheath	f	50
Pi ()		π	3.1415927
Number of circuits	Standard design	1	1
Installation configuration	Cable data sheath	1* 3 core (trefoil)	3 Core
Laying depth (m)	Standard design	L	**0.8**
Ambient ground temperature (°C)	Assumption	θ_a	**25**
In-situ soil thermal resistivity (K.m/W)	IEC 60287-1-1	ρ	**1.2**

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Table A.2 – continued from previous page.

Description	Source of input value	Input symbol and units	Input value
Earthing of the metallic screens/armouring			Single end bonded
Skin effect factor	IEC 60287-1-1, Table 2	k_s	1
Proximity effect factor	IEC 60287-1-1, Table 2	k_p	1
Thermal resistivity of insulation material (XLPE)	IEC 60287-2-1, Table 1	ρ_i (K.m/W)	3.5
Thermal resistivity of the armouring	IEC 60287-2-1, Table 1	ρarmou (K.m/W)	1.38E-07
Temperature coefficient of electrical resistivity for steel armour at 20°C per Kelvin	IEC 60287-1-1, Table 1	α_{20} (/K)	4.5E-03
Relative permittivity of insulation	IEC 60287-1-1, Table 3	ε	2.5
Insulation loss factor	IEC 60287-1-1, Table 3	$\tan\delta$	0.004
Thermal resistivity of cable outer sheath material (PE)	IEC 60287-2-1, Table 1	ρ_s (K.m/W)	3.5

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Table A.2 – continued from previous page.

Description	Source of input value	Input symbol and units	Input value
Thermal resistivity of semi-conductive layer	IEC 60287-2-1, Table 1	ρ_{sC} (K.m/W)	2.5
Thermal resistivity of water blocking tape	IEC 60287-2-1, Table 1	ρwater b/t (K.m/W)	2.5
Thermal resistivity of fillers	IEC 60287-2-1, Table 1	ρfillers (K.m/W)	6
Temperature coefficient of electrical resistivity for copper conductor at 20°C per Kelvin	IEC 60287-1-1, Table 1	α_{20} (/K)	3.93E-03
Thermal resistivity of copper tape at 20°C	IEC 60287-1-1, Table 1	Pcopper tape (K.m/W)	2.14E-07
Temperature coefficient of electrical resistivity for metallic tape (copper tape) at 20°C per Kelvin	IEC 60287-1-1, Table 1	α_{20} (/K)	4E-03

Table A.3. Code for the calculation tool.

Parameter	Reference	Equation	Calculated Results
R‘	IEC 60287-1-1, Clause 2.1.1	='11kV Input and results'!E37*(1+'11kV Input and results'!E57*('11kV Input and results'!E35-20))	1.1857315E-04
x_s	IEC 60287-1-1, Clause 2.1.2	=SQRT((8*'11kV Input and results'!E39*'11kV Input and results'!E38*0.0000001*'11kV Input and results'!E46)/'11kV 3C 185mmsq Cu Calculation'!C2)	1.0294654
y_s	IEC 60287-1-1, Clause 2.1.2	=((C3∧4)/(192+0.8*(C3∧4)))	5.822614995E-03

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
x_p	IEC 60287-1-1, Clause 2.1.4.1	=SQRT((8*’11kV Input and results’!E39*’11kV Input and results’!E38*0.0000001)*’11kV Input and results’!E47/’11kV 3C 185mmsq Cu Calculation’!C2)	1.029465397
y_p	IEC 60287-1-1, Clause 2.1.4.1	=(C5∧4/(192+0.8*C5∧4))*(’11 kV Input and results!́E11/’11kV Input and results’!E34)∧2*(0.312*(’11kV Input and results’!E11/’11kV Input and results’!E34)∧2+(1.18/((’11kV 3C 185mmsq Cu Calculation’!C5∧4/(192+0.8*’11kV 3C 185mmsq Cu Calculation’!C5∧4))+0.27)))	9.6844E-03

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
R	IEC 60287-1-1, Clause 2.1	=C2*(1+1.5*(C4+C6))	1.2133123E-4
Area of the armour	A= d t	='11kV Input and results'!E28*'11kV Input and results'!E25*'11kV Input and results'!E39*0.000001	7.27357239E-04
Rarmou @ 20 deg	R= l/A	='11kV Input and results'!E49*'11kV Input and results'!E42/'11kV 3C 185mmsq Cu Calculation'!C8	1.5178236E-4
sc	IEC 60287-1-1, Clause 2.3	='11kV Input and results'!E35-10	60
Rarmou	IEC 60287-1-1, Clause 2.4	=C9*(1+'11kV Input and results'!E50*(67.5976681051-20))	1.84292551E-4

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
Area *copper tape*	A= d t	='11kV Input and results'!E23*'11kV Input and results'!E27*'11kV Input and results'!E39*0.000001	8.79645943E-6
Rcopper tape @ 20dg	IEC 60287-1-1, Clause 2.3	='11kV Input and results'!E58*'11kV Input and results'!E42/'11kV 3C 185mmsq Cu Calculation'!C12	1.9462375E-2
Rcopper tape	IEC 60287-1-1, Clause 2.3	=C13*(1+'11kV Input and results'!E59*('11kV 3C 185mmsq Cu Calculation'!C10-20))	2.2576356E-2
		=2*'11kV Input and results'!E39*'11kV Input and results'!E38	314.15926

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
X	IEC 60287-1-1, Clause 2.3.1	=C15*2*0.0000001*LN((2*’11 kV Input and results’!E34/’11kV Input and results’!E23))	4.0092213E-5
$_1$‘	IEC 60287-1-1, Clause 2.3.1	=(C14/C7)*(1.5/(1+(C14/C16)∧2))	8.80204372E-4
$_1$"	IEC 60287-1-1, Clause 2.3.1	0.00	0.00
$_1$	IEC 60287-1-1, Clause 2.3	=’11kV 3C 185mmsq Cu Calculation’!C19	8.80204372E-4
$_2$	IEC 60287-1-1, Clause 2.4.2.3	=’11kV 3C 185mmsq Cu Calculation’!C20	7.5744655E-2
C	IEC 60287-1-1, Clause 2.2	=’11kV Input and results’!E51*0.000000001/(18*LN(’11kV Input and results’!E16/’11kV Input and results’!E15))	4.22792E-10

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
W_d	IEC 60287-1-1, Clause 2.2	=C15*C21*('11kV Input and results'!E4/SQRT(3))∧2*'11kV Input and results'!E52	2.142894E-2
$T_{1\ (Inner\ SC)}$	IEC 60287-2-1, Clause 2.1.1.1	='11kV Input and results'!E54/(2*'11kV Input and results'!E39)*LN(1+(2*'11kV Input and results'!E13/'11kV Input and results'!E11))	3.725642348E-2
$T_{1\ (insulation)}$	IEC 60287-2-1, Clause 2.1.1.1	='11kV Input and results'!E48/(2*'11kV Input and results'!E39)*LN(1+(2*'11kV Input and results'!E14/'11kV Input and results'!E15))	1.78516402E-1

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
$T_{1\ (Outer\ SC)}$	IEC 60287-2-1, Clause 2.1.1.1	=’11kV Input and results’!E54/(2*’11kV Input and results’!E39)*LN(1+(2*’11kV Input and results’!E17/’11kV Input and results’!E16))	2.46830978E-2
T_1	IEC 60287-2-1, Clause 2.1.1.1	=C23+C24+C25	2.4045592E-1
$T_{2\ (water\ bloking\ T)}$	IEC 60287-2-1, Clause 2.1.2.1	=’11kV Input and results’!E55/(2*’11kV Input and results’!E39)*LN(1+(2*’11kV Input and results’!E19/’11kV Input and results’!E18))	1.26324057E-2
$T_{2\ (copper\ tape)}$	IEC 60287-2-1, Clause 2.1.2.1	=’11kV Input and results’!E58/(2*’11kV Input and results’!E39)*LN(1+(2*’11kV Input and results’!E27/’11kV Input and results’!E26))	2.407017638E-10

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
$T_{2\ (Fillers)}$	IEC 60287-2-1, Clause 2.1.2.1	='11kV Input and results'!E56/(2*'11kV Input and results'!E39)*LN(1+(2*'11kV Input and results'!E21/'11kV Input and results'!E20))	0.4958952111
T_2 $(binding\ tape)$	IEC 60287-2-1, Clause 2.1.2.1	='11kV Input and results'!E56/(2*'11kV Input and results'!E39)*LN(1+(2*'11kV Input and results'!E21/'11kV Input and results'!E20))	1.685454541E-3
$T_{2(Armouring)}$	IEC 60287-2-1, Clause 2.1.2.1	='11kV Input and results'!E49/(2*'11kV Input and results'!E39)*LN(1+(2*'11kV Input and results'!E25/'11kV Input and results'!E28))	1.8062268E-9
T_2	IEC 60287-2-1, Clause 2.1.2.1	=C27+C28+C29+C30+C31	0.5102130734126

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
T_3	IEC 60287-2-1, Clause 2.1.3	=’11kV Input and results’!E49/(2*’11kV Input and results’!E39)*LN(1+(2*’11kV Input and results’!E30/’11kV Input and results’!E28))	1.8337325E-9
u	IEC 60287-2-1, Clause 2.2.2	=2*’11kV Input and results’!E42*1000/’11kV Input and results’!E32	20
T_4	IEC 60287-2-1, Clause 2.2.4.3.1	=(’11kV Input and results’!E44/(2*’11kV Input and results’!E39))*(LN(C34+SQRT(C34∧2-1)))	0.70440460124
Δ (°C)	IEC 60287-1-1, Clause 1.4.1.1	=’11kV Input and results’!E35-’11kV Input and results’!E43	45

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
I (A)	IEC 60287-1-1, Clause 1.4.1.1	=SQRT((C36-C22*(0.5*C26+’11kV 3C 185mmsq Cu Calculation’!E38*(’11kV 3C 185mmsq Cu Calculation’!C31+’11kV 3C 185mmsq Cu Calculation’!C33+’11kV 3C 185mmsq Cu Calculation’!C35)))/(’11kV 3C 185mmsq Cu Calculation’!C7*’11kV 3C 185mmsq Cu Calculation’!C26+’11kV Input and results’!E36*’11kV 3C 185mmsq Cu Calculation’!C7*(1+’11kV 3C 185mmsq Cu Calculation’!C17)*’11kV 3C 185mmsq	**383.961**

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Table A.3 – continued from previous page.

Parameter	Reference	Equation	Calculated Results
		Cu Calculation’!C31+’11kV Input and results’!E36*’11kV 3C 185mmsq Cu Calculation’!C7*(1+’11kV 3C 185mmsq Cu Calculation’!C17+’11kV 3C 185mmsq Cu Calculation’!C20)*(’11kV 3C 185mmsq Cu Calculation’!C33+’11kV 3C 185mmsq Cu Calculation’!C35)))	