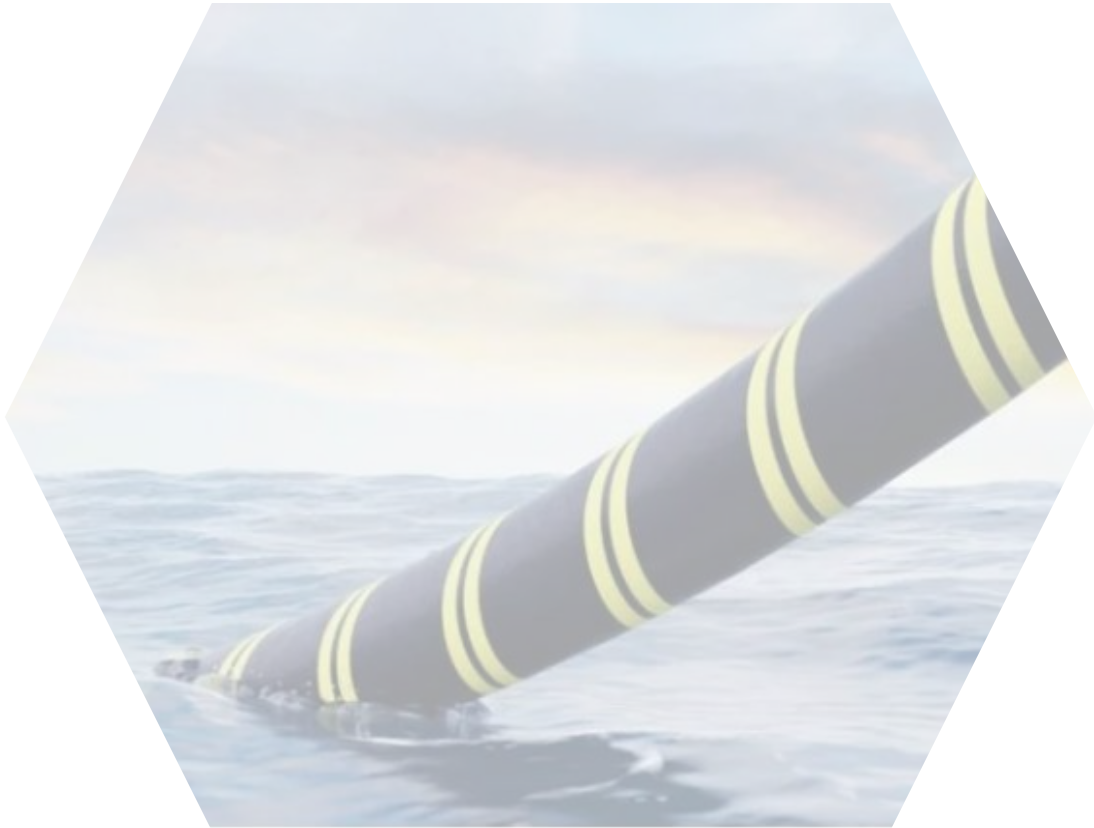




D3.2



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EXECUTIVE SUMMARY

The deliverable *D3.2 – Cable modelling specifications* gathers specifications for predictive models and algorithms essential for understanding and improving the performance, ageing, and reliability of HVDC cable systems that are developed on WP5.

It includes an introduction to the predictive models to be developed during the project. These models are divided into two main sub-parts: models and algorithms. The former focus on more physical methods while the latter are characterised by the use of advanced software and AI techniques.

It addresses the following key areas:

1. **Space Charge Modelling:** Focuses on the accumulation and effects of electric charges within cable insulation, critical for predicting partial discharges and ageing.
2. **Thermal Modelling:** Establishes methods for analyzing the heat generation, distribution, and dissipation within HVDC systems, accounting for real-world conditions.
3. **Algorithms:** Specifies approaches to assess cable ageing, real-time thermal performance, and fault location.

The goal is to define robust frameworks and input/output parameters for these models to ensure precise predictions of cable performance under varying operational scenarios.

Key Features

- **Model Development Framework:**
 - **Physical Models:** Based on finite element methods (FEM) and analytical approaches, addressing space charge and thermal behaviors.
 - **AI-Driven Algorithms:** Incorporates advanced machine learning techniques for predicting ageing and fault conditions.
- **Use Cases and Load Scenarios:**
 - Static, dynamic, and transient cases are analyzed to capture the diverse operational stresses on HVDC cables.
 - Models are tailored for real-life conditions, such as temperature variations, polarity reversals, and voltage spikes.
- **Validation Protocols:**
 - Experimental data, coupled with numerical simulations, will validate the models.
 - Integration of analytical methods and FEM ensures robust and scalable solutions.

Expected Outcomes

Deliverable D3.2 sets the stage for:

1. The creation of **at least four predictive models**, targeting critical aspects such as conductivity, space charge behavior, thermal performance, and fault prediction.



2. Development of tools for **partial discharge prediction** using advanced simulation software like Ansys Lumerical Charge and Ansys Charge Plus.
3. A validated methodology to align the models with operational benchmarks for HVDC systems beyond 525 kV.

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ABBREVIATIONS AND ACRONYMS

Abbreviations / Acronyms	Description
AC	Alternate Current
AI	Artificial Intelligence
ANN	Artificial Neural Network
BN	Bayesian Network
CNN	Convolutional Neural Network
CTT	Conductor Temperature Time
DAG	Directed Acyclic Graph
DAS	Distributed Acoustic Sensing
DC	Direct Current
DTS	Distributed Temperature Sensing
FEA	Finite Element Analysis
FEM	Finite Element Method
GRU	Gated Recurrent Unit
HVAC	High Voltage Alternate Current
HVDC	High Voltage Direct Current
IF	Isolation Forest
KNN	k-Nearest Neighbours
LOF	Local Outlier Factor
LR	Logistic Regression
LSTM	Long Short-Term Memory
NB	Naïve Bayes
PEA	Piezoelectric Actuator
PEEC	Partial Element Equivalent Circuit
PNP	Poisson-Nernst-Planck
RNN	Recurrent Neural Network
RTTR	Real Time Thermal Rating
SPC	Space Charge
SVM	Support Vector Machine
XLPE	Cross-linked polyethylene

1 INTRODUCTION

1.1 Purpose

The aim of EASYDC-FOS “Cable modelling specifications” is to detail the predictive models and algorithms’ specifications so that they can be developed correctly during the project.

Section 2 explores the different kind of techniques that are proposed for the project, and it breaks them into two major groups: Models (Section 2.1) and Algorithms (Section 2.2). This distinction is mainly done due to each type’s development type, as the models use FEM and analytical techniques, and the algorithms use other software tools.

Section 2.1 is focused on physical modelling. Starting with Space Charge Modelling (Section 2.1.1), this subsection begins with an analysis of the current state-of-the-art, followed by an examination of the different datasets that will be provided to the model as well as the possible load cases for the cable. The next subsection analyses +the Thermal and Ampacity Models (Section 2.1.2), which follows a similar structure to the previous one. Then, both type of models are to be developed in an analytical way and using Finite Element Analysis (FEA) techniques.

In addition to physical modelling, the report also focuses on Algorithms (Section 2.2), particularly those related to system aging and real-time thermal rating (RTTR). The aging algorithms (Section 2.2.1) integrate state-of-the-art methods for predicting equipment degradation over time, offering insights into inputs, outputs, and validation results. RTTR algorithms (Section 2.2.2) are further broken down into cable and connector thermal ratings, each utilizing methodologies that ensure the system operates within safe thermal limits in real time. Lastly, Fault Location Algorithms (Section 2.2.3) are introduced as a critical tool for detecting and pinpointing faults in power systems. This section provides a structured approach to understanding the methodologies, inputs, outputs, and results validation used in fault location prediction.

1.2 Relation to other project documents

This document will include the specifications for the algorithms developed in WP5 and WP6, thus it will be referenced in those work packages.

2 PREDICTIVE MODELS

2.1 Models

2.1.1 Space Charge Modelling

The space charge phenomenon refers to the accumulation of electrical charge inside or on the surface of a dielectric material, which can involve the distortion of the electric field originating from a conductor. In our case study (high-voltage cables), this distortion can be more significant since the physical phenomena that can generate or transport electrical charges within the insulating material are amplified by the higher electrical voltage to which the cable conductor will be exposed.

Depending on the distortion of the electric field (which could also be amplified by voids or protrusions, for example), the insulating material may become partially ionized locally, potentially causing partial discharges. Over time, if the same operating conditions persist, these discharges will lead to the deterioration of the insulating material.

2.1.1.1 State-of-the-art

Considering the effect of charge accumulation and that the goal is the prediction of HVDC cable aging, several factors such as temperature, electric field, external environment, space charge, and partial discharges are usually considered to monitor material aging. Among other causes and effects, we have:

- **Space charge:**

The accumulation of space charges, as mentioned earlier, can cause a local amplification of the electric field, which may exceed the dielectric strength of the material, leading to partial discharges.

- **Numerical models:**

The most recent models use numerical simulations, such as the finite difference or finite element method, to predict how space charges accumulate and migrate within the insulator. These models are coupled with experimental data from electric field measurements and partial discharges.

- **Temperature Effect:**

Temperature affects insulation aging, accelerating processes such as charge conduction and thermal oxidation. Models based on the Arrhenius law are used to predict how temperature increases accelerate the aging of the insulating material.

- **Thermoelectric models:**

These models integrate both resistive heating from the current (Joule effect) and the applied electric field, simulating how temperature gradients affect space charge distribution and aging rates.

- **Electrical Aging Modelling:**

It is based on the relationship between the applied electric field and the insulating material's response. Electric field aging models study degradation as a function of long-term applied voltages.

- **Lifetime models:**

These empirical models are often based on the Weibull equation or power law to extrapolate the material's failure time under different electric field and temperature conditions.

- **Partial Discharges:**

Partial discharges occur when there are defects in the insulation, such as voids or protrusions, which are locations where the electric field intensifies locally. Partial discharges accelerate material aging by creating stress in the polymer structure.

- **Coupled numerical models:**

In modern simulations, partial discharge models are coupled with space charge and electric field models to capture how discharges contribute to aging.

- **Chemical Degradation:**

Prolonged exposure to strong electric fields can induce chemical reactions that degrade the insulating polymers. This includes oxidation processes and the formation of degradation products that weaken the material.

- **Chemo-electric models:**

Some models include the evolution of the insulator's chemical composition and how it relates to the material's electrical properties.

- **Effects of Moisture and Contaminants:**

Moisture and other contaminants can enter the insulating material through defects in design or installation. These contaminants affect the electrical behavior of the material, facilitating the formation of partial discharges and accelerating degradation.

- **Multiparametric models:**

These models integrate moisture and other environmental factors to adjust material aging predictions.

- **Residual Life Models:**

These models attempt to estimate the remaining useful life of the cable, based on continuous measurements of parameters such as conductivity, space charge accumulation, and the presence of partial discharges. Techniques like machine learning are used to improve failure time prediction.

2.1.1.2 Datasets and Load Cases

2.1.1.2.1 Static



This load case involves steady-state conditions, where the system operates under constant voltage, temperature, and other parameters. The scenarios under static load cases typically include:

- **Constant DC Voltage:**

A steady DC voltage applied to the conductor, with no change in voltage or external conditions (ideal operational condition).

- **Equilibrium State:**

The system reaches equilibrium with a constant electric field across the cable, allowing the initial space charge distribution to stabilize.

- **No External Perturbations:**

The insulation and conductor are not influenced by any external variations (e.g., temperature, voltage fluctuations), providing a baseline state for comparison with dynamic or transient cases.

2.1.1.2.2 *Dynamic*

In dynamic load cases, the operating conditions change gradually over time, simulating real-world operational environments where conditions vary. These cases include:

- **Slow Voltage Variations:**

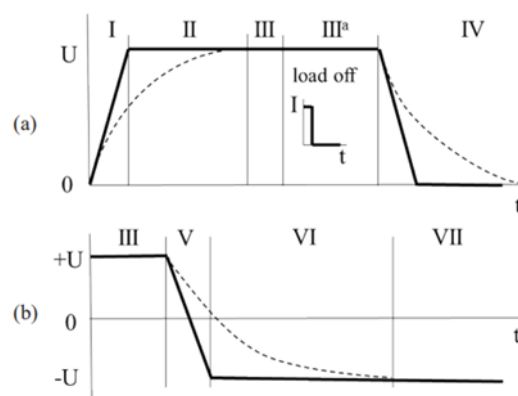
Gradual fluctuations in DC voltage, where small AC ripple components (superimposed on the DC voltage) may induce periodic changes in the electric field and space charge distribution.

- **Temperature Gradients:**

Gradual changes in the temperature, typically due to external environmental conditions (e.g., seasonal temperature changes) or internal heat generation from Joule losses. These temperature variations affect the material properties and can influence space charge distribution within the insulation.

- **Long-Term Load Cycling:**

Periodic operational loading and unloading of the system, where the voltage or current is increased or decreased over time (e.g., in the case of a transmission line with varying power demand).



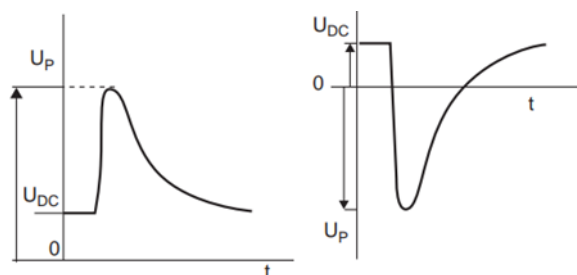


Figure 1 Dynamic and transient cases

2.1.1.2.3 Transient

Transient load cases involve sudden, rapid changes in operational conditions, which can cause immediate changes in electric fields and space charge accumulation. Typical scenarios for transient load cases include:

- **Voltage Spikes:**

A sudden increase in voltage, such as during a switching event or due to faults in the system. This can lead to rapid changes in the space charge distribution and electric field, possibly triggering partial discharge or insulation breakdown.

- **Polarity Reversal:**

Sudden reversal of voltage polarity, which can cause fast changes in space charge distribution, particularly during the **polarization and depolarization** phases.

- **Switching Events:**

Rapid switching on or off the HVDC system, which induces fast transients in voltage, resulting in quick changes to the electric field and localized charge accumulation.

- **Fault Conditions:**

Sudden voltage drops or faults that cause significant shifts in the electric field, affecting space charge dynamics in the cable insulation.

2.1.1.2.4 Partial discharges

These stages can be very important for the onset of partial discharges since they can lead to accumulation of space charges within the insulation.

Although small, partial discharges are one of the main causes of insulation degradation and aging, potentially compromising the reliability and lifespan of HVDC cables, so the idea is to develop an algorithm to predict partial discharges using a model based on space charge accumulation for whatever condition.

The main tools used will be **Ansys Lumerical Charge** for space charge modelling and **Ansys Charge Plus**, which enables the modeling of partial discharges.

So, the primary goal is to identify the range of operating parameters (such as temperature gradients, applied electric field, insulating material properties, and structural defects) that lead to the onset of partial discharges. The project will also analyze the frequency and magnitude of these discharges, providing a quantitative framework for assessing insulation stability under different operating conditions.

General Methodology:

Space charge modeling: Configuring the model in Lumerical Charge to simulate the accumulation and distribution of charges within the insulation.

Partial discharge prediction: Using Ansys Charge Plus to identify the critical conditions under which partial discharges occur.

Parametric analysis: Evaluating the impact of different operating parameters on the occurrence, frequency, and magnitude of partial discharges.

Machine learning algorithms: With the parametric study, it is possible to detect unsimulated scenarios where partial discharge inception may occur, aiding in the preventive maintenance of the insulation and the identification of problematic scenarios.

So, considering the load conditions above, we can include these stages to simulate:

Table 1 Typical operational stages

TYPICAL OPERATIONAL STAGES	
I. U from 0 -> +U ₀ (capacitive field)	- The initial field distribution is determined by the variation of the permittivity inside the insulation - Duration: some seconds
II. E = E(t) and U stable	Distribution is changing capacitive -> resistive field Needed bc and initial conditions: - E for t=0 - Voltage across the insulation - T(r,t) as the conductivity varies with temperature Scenes: - I off -> E = E(t) - I on -> E = E(t) - I on -> E stable - Duration: ¿?
III. E is stable -> distribution resistive	- There is charge accumulation due to injection and conductivity distribution (ΔT) - With greater ΔT, charge density commutes more to metallic screen - Duration?
IV. +U ₀ -> 0 and E = E(t)	Voltage reduction to zero:

	There is electric field due to space charge a polarization, so that we can have 3 scenes: • The cable load is zero before switching off the voltage • The cable load is zero neither before nor after switching off the voltage • The cable load is not zero before, but it is switched off together with the voltage (Worst scene)
V. Polarity reversal	• Duration?
VI. Charge Redistribution at the New Voltage	• Duration?
VII. New stable field	• Duration?
ATYPICAL OPERATIONAL STAGES	
Impulses superimposed onto a dc voltage.	
Harmonic Waves in AC/DC Conversion: Converters generate residual harmonics that can induce local variations in the electric field, even within the high-frequency range.	

Where we have different parameters (a priori) to study the inception of the partial discharges:

Table 2 Parameters for the analysis of the PD inception

inputs	
Parameters	Description / Relevance to PD
Void size	Larger voids can sustain higher electric field intensities and have a greater probability of partial discharge initiation. The size of the void also determines the energy released during a discharge, influencing the rate of insulation degradation.
Void position	The position of voids relative to the applied electric field and the material layers significantly influences the local field enhancement.
Applied Electric Field (E)	High electric field levels can lead to the ionization of voids or defects within the insulation, initiating partial discharges.

Critical Threshold (E_c)	The minimum electric field strength required to initiate partial discharges within the insulation.
Applied tension	Higher applied voltages increase the electric field strength within the insulation, potentially exceeding the material's critical threshold and triggering partial discharges, especially in the presence of defects or voids.
Cable temperature	Higher cable temperatures can reduce the insulation material's dielectric strength, increase charge mobility, and exacerbate space charge accumulation.
Thermal gradient	This temperature difference induces internal stresses and affects the redistribution of charges within the insulation
Disturbance Frequency	Refers to the frequency of residual harmonics or oscillations superimposed on the electrical signals within the system.
Disturbance magnitude	The amplitude of the residual harmonic waves or oscillations generated within the system.
Trap Density	Concentration of localized energy states within the insulation material that can capture and retain charge carriers.
Charge mobility	Ability of charge carriers to move through the insulation material under the influence of an electric field.
Dielectric Resistivity	Low resistivity can lead to faster charge redistribution and localized electric field enhancements, increasing the risk of partial discharge occurrence.

Which are inputs for the machine learning algorithms.

From the simulation steps, we can obtain the following outputs:

Table 3 PD results for aging algorithm

output	
PD frequency	A higher PD frequency indicates a higher occurrence of partial discharges, which can accelerate insulation degradation and increase the risk of insulation failure
Discharged Charge	This output quantifies the severity of partial discharges and can be used to assess the

	insulation's condition over time. A higher discharged charge indicates more significant degradation and a higher risk of insulation failure.
Released Energy	Higher released energy corresponds to more severe discharges, which can accelerate insulation degradation and lead to failure over time.
Dynamic Void Size	It can affect the electric field distribution and the likelihood of partial discharge initiation.

These outputs can be used in the machine learning algorithms for getting new scenes where partial discharges can occur.

The following flowchart shows the steps from data gathering until a model capable of predicting partial discharges:

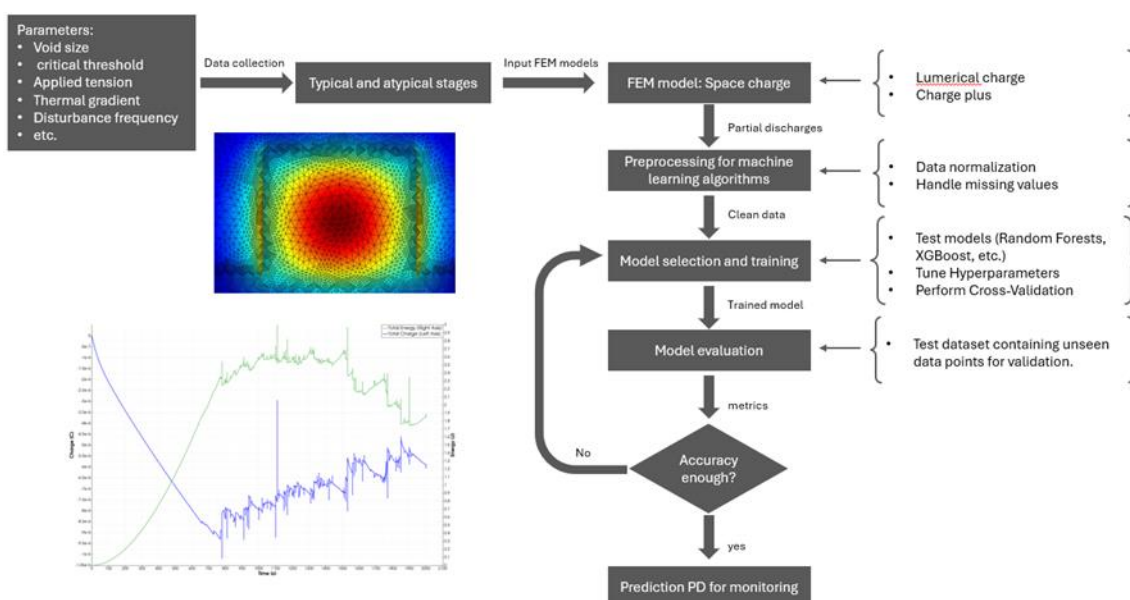


Figure 2 Flowchart - Partial discharges prediction

2.1.1.3 Number of Models (minimum 4)

As explained, there are various factors that can influence space charge within HVDC cable insulators. There are different models that consider each of these sources:

- **Conductivity model**

This model considers the influence of the electric field and temperature on the conductivity.

These assumptions come from the conductivity behavior where often increases with the applied electric field due to the enhanced mobility of the charge carries.

Conductivity also depends on temperature, often following an Arrhenius-type relationship:

$$\sigma(T, E) = \sigma_0 \cdot \exp(\alpha \cdot T) \cdot \exp(\beta \cdot E)$$

σ_0 conductivity at a reference field (or zero field)

E electric field.

T temperature.

α temperature factor of conductivity

β Field factor of conductivity

Getting the factors can be very problematic since the data obtained from various probes show a large dispersion of their values.

So, to consider the influence of the temperature and electric field on conductivity a model was developed based on the hopping theory of conduction in dielectric:

$$\sigma(T, E) = A \exp(-(\phi q e)/(k_B T)) \cdot (\sinh |B|E|)/|E|$$

Where you can see a greater weight in the temperature over the conductivity compared to the electric field by means of the exponential term as is expected in dielectric materials.

It typically assumes a quasi-static or averaged behavior of charge transport without explicitly resolving the dynamics of individual charge carriers which can lead to inaccuracies in predicting local fields variations or transient behaviors.

Other models consider different physics for the dynamics of the individual charges as we will see:

- **Poisson-Nernst-Planck model (PNP)**

This model combines Poisson's equation for the electric field with the Nernst-Planck equation, which describes the diffusion and movement of charge carriers. It is useful for describing the charge distribution in a dielectric material under an electric field.

- **Poisson's equation:**

Where:

$$\nabla \cdot (\epsilon \nabla \phi) = -\rho. \nabla \cdot (\epsilon \nabla \phi) = -\rho \nabla \cdot (\epsilon \nabla \phi) = -\rho$$

ϵ permittivity of the material.

ϕ electric potential.

ρ charge density.

- **Nernst-Planck equation:**

Where:

$$J_i = -D_i \nabla c_i - z_i u_i c_i \nabla \phi$$

J_i current density of carrier i.

D_i diffusion coefficient of carrier i.

c_i concentration of charge carriers.

z_i valence of the carrier.

u_i mobility of the charge carrier.

Limitations:

It does not easily account for complex nonlinear effects or charge recombination processes.

- **Electric Displacement Model**

This model focuses on the relationship between the electric field and the polarization of the dielectric material, considering both free charges and bound charges (fixed within the material). This approach is useful for describing how charge accumulation affects the electrical behavior of insulators.

- **Electric Displacement:**

Where:

$$D = \epsilon_0 E + P$$

D electric displacement.

ϵ permittivity of free space.

E electric field.

P polarization.

Relationship with Charge Density:

Where:

$$\nabla \cdot D = \rho_{free}$$

ρ_{free} free charge density.

Application:

Where the accumulation of space charge is primarily related to the polarization of the dielectric material, rather than the injection or transport of charges. It is useful in long-term studies of HVDC cables, where space charges accumulate due to polarization induced by strong electric fields.

Limitations:

The model is simplistic and does not explicitly include the movement of mobile charges (such as electrons or ions). It focuses more on how charges are organized and affect the material, making it less ideal for studies where active charge transport is critical.

- **Bipolar Charge Transport Model**

This model describes the transport of two types of charge carriers (positive and negative), considering processes such as injection, transport, and recombination. It is particularly useful for studying dielectrics where both electrons and holes, or even ions, are expected to be present.

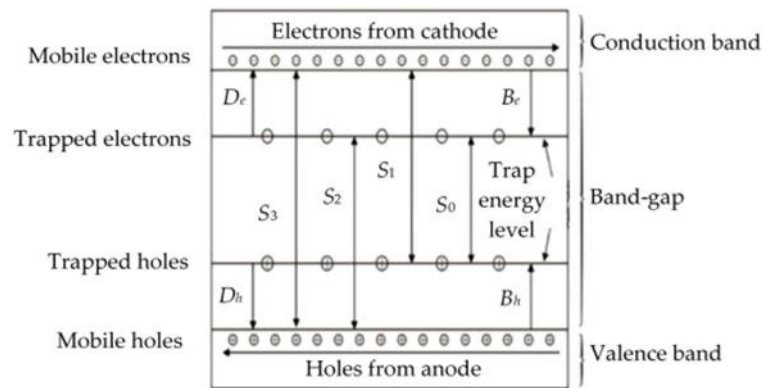


Figure 3 Band structure for modelling insulation material

The model considers trap states where carriers can be trapped, and recombination can occur changing charge distribution.

There are deep and shallow traps that affect the mobility of the carriers in two ways:

- **Shallow traps:**

They are near the conduction or valence band so that they have relatively low energy levels that the carriers must overcome to escape.

As a result, they temporarily delay the movement of the carriers but do not significantly hinder long-term transport.

- **Deep traps:**

These traps are farther from the conduction or valence band, with higher energy barriers so that the carriers need more energy to escape from these traps.

As a result, they immobilize the carriers for longer periods of time and as consequence the conduction decreases leading to more accumulation of charge.

Finally, we can infer that the probability of recombination increases by changing the net charge in the insulation.

These effects are considered in the following equations:

- **Continuity Equations for Electrons and Holes:**

$$\frac{\partial n}{\partial t} + \nabla \cdot J_n = G - R$$

$$\frac{\partial p}{\partial t} + \nabla \cdot J_p = G - R$$

Where:

n electron concentration.

p hole concentration.

G generation rate of carrier pairs.

R recombination rate.

J_n and J_p are the current densities of electrons and holes.

○ **Current Transport Equations:**

Where:

$$\begin{aligned} J_n &= -\mu_n n \nabla \phi + D_n \nabla n \\ J_p &= -\mu_p p \nabla \phi + D_p \nabla p \end{aligned}$$

μ_n and μ_p are the mobilities of electrons and holes.

D_n and D_p are the diffusion coefficients of electrons and holes.

Application:

This model is essential when dealing with semiconductor or dielectric materials that have significant transport of two types of mobile charges (electrons and holes). In our case, it can be useful for studying the injection of charges from conductors into insulators and their transport within the dielectric.

Limitations:

It is more complicated from a computational standpoint, as it must simultaneously solve the continuity equations for both species of carriers and the electric field equations.

2.1.1.4 Analytical

2.1.1.4.1 Hypothesis

Analytical models assume that fundamental equations, such as Poisson's equation and continuity equation, are sufficient to describe the space charge distribution in HVDC cables. Simplifications include homogeneous insulation, thermal independence, or limited dynamics.

2.1.1.4.2 Methods and Physical Events

- **Poisson's Equation (Static Model)**

$$\nabla^2 V = -\frac{\rho}{\epsilon}$$

Solution:

$$V(r) = \frac{\rho}{2\epsilon} r^2 + C_1 \ln(r) + C_2$$

They work well in:

Static and homogeneous charge distribution.

Limitations:

Does not capture transient events.

- **Continuity Model (Modified Ohm's Law)**

$$j = \sigma E + \mu \rho E, \quad \nabla \cdot j = \frac{\partial \rho}{\partial t}$$

Solution:

$$\rho(t) = \rho_0 e^{-\frac{t}{\tau}} + \frac{\sigma E}{\mu} (1 - e^{-\frac{t}{\tau}})$$

They work well in:

Dynamic calculations with constant polarization.

Limitations:

Ignores deep traps and recombination.

- **Trap Model (Shallow and Deep Traps)**

$$\frac{\partial \rho}{\partial t} = -\nabla \cdot (\mu \rho E) - \frac{\rho}{\tau_s} - \frac{\rho}{\tau_d}$$

Solution:

$$\rho(t) = A e^{-\frac{t}{\tau_s}} + B e^{-\frac{t}{\tau_d}}$$

They work well in:

Transient events with multiple characteristic times.

Limitations:

Accuracy depends on the exact parameterization.

- **Temperature-Dependent Thermoelectric Model**

$$\sigma(T) = \sigma_0 e^{-\frac{W}{kT}}, \quad E(r) = \frac{\sigma_0}{r} \int_{\tau_a}^r e^{-\frac{W}{kT(r')}} dr'$$

They work well in:

Significant thermal gradients.

Limitations:

Requires a detailed thermal profile.

2.1.1.4.3 *Number of Models*

- **Static Poisson (1D Radial):**
Simplifies the charge distribution in equilibrium.
- **Dynamic Transport with Continuity:**
Models the temporal evolution of charges.
- **Double Trap:**
Analyses charges trapped and released in traps.
- **Thermoelectric:**
Considers thermal effects on conductivity and the electric field.

2.1.1.4.4 *Outputs*

- Space charge distribution (ρ) in time and space.
- Radial electric field (E) and potential (V).
- Characteristic times for traps.
- Thermal gradients and their influence on conductivity.

2.1.1.4.5 *Model Validation*

- Comparison with experimental data: Using PEA or current measurements.
- Numerical simulations: Comparison with software such as Lumerical Charge.
- Simplified analytical solutions: For controlled cases.

2.1.1.5 **Finite Element Method (FEM)**

2.1.1.5.1 *Hypothesis*

Given the presence of nonlinear phenomena, such as the behaviour of dielectric materials under electric fields, temperature distribution, the influence of energy traps due to impurities or defects, increasingly complex cable geometry designs, or the type of operation to which they are subjected, predicting charge accumulation becomes difficult to calculate, as it may not be possible to make simplifications that approximate reality.

Therefore, in the case of the equations described above without making significant simplifications, nonlinear effects can be considered locally by solving the equations in small elements that make up our geometric model.

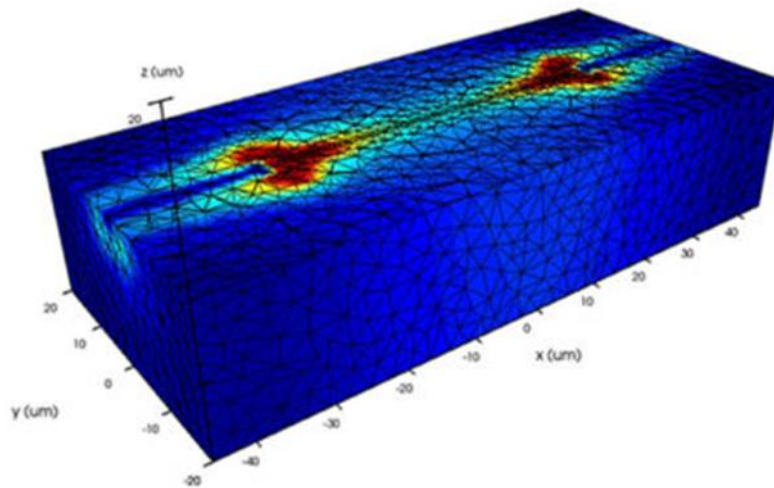


Figure 4 Discretization domain for FEM model

2.1.1.5.2 Methods and Physical Events

The finite element method applied to HVDC cables in predicting charge accumulation can consider all the previously discussed effects; however, it is necessary to couple the different physical phenomena according to the scenario:

Physical Phenomena to Consider:

- Space Charge Dynamics
 - Charge transport equations (continuity and drift-diffusion) coupled with Poisson's equation for the electric field.
 - Include charge injection at the electrode interfaces (Schottky or Hopping mechanisms).
 - Incorporate the dynamics of shallow and deep traps to model trapping and release rates.
- Electric Field Distribution
 - Solve Poisson's equation to determine the electric potential and field distribution.
 - Use boundary conditions to simulate the applied voltage and grounded layers.
- Thermal Effects and Heat Transfer
 - Solve the heat conduction equation to model the temperature distribution.
 - Include thermal boundary conditions, such as convection or radiation at the cable surface.
 - Couple thermal and electrical simulations to account for temperature-dependent properties.

- **Trap-Assisted Charge Transport**
 - Include trapping and release rates as functions of the local electric field and temperature.
 - Implement energy level models for shallow and deep traps, with parameters such as trap density and depth.
- **Partial Discharges (PD)**
 - Identify high-field regions prone to PD through field analysis.
 - Optionally, simulate PD initiation and energy release in critical regions.

Numerical methods:

- **Coupled Multiphysics Solvers**

In this case, for coupling the necessary physics for charge transport (electric field, thermal gradients, charge diffusion and transport, as well as injection and recombination phenomena, etc.), Ansys Lumerical Charge will be used, while for partial discharge calculations, Ansys Charge Plus will be utilized.

The equations will be solved according to the flowchart shown below:

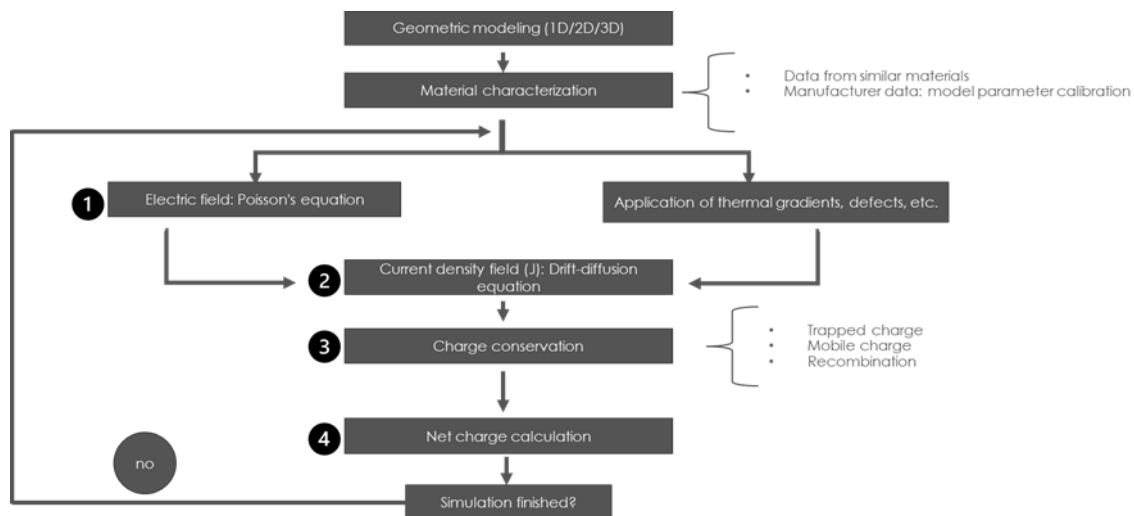


Figure 5 Flowchart - development of space charge models

Where the outcome of the process is the charge distribution, and consequently, the distribution of the electric field inside the insulator, which will allow identifying regions where partial discharges may occur, and therefore, the aging of the material.

- **Time Advancement Techniques**
 - Use implicit methods for stability in transient simulations of space charge dynamics.
 - Use adaptive time steps to balance accuracy and computational cost.
 - Time stepping scheme:

- BDF2 - Backward Differentiation Formula (2nd order) method.
- TR-BDF2 - Trapezoidal Rule/Backward Differentiation Formula (2nd order) method.

- **Nonlinear Solvers**

In Lumerical Charge, there are mainly two types of solvers:

- Gummel Method:

Iteratively solves the decoupled equations, first the electrostatic potential, and then the charge distribution. It is efficient for devices with small currents and moderate charge variations.

- Newton Method:

Solves the equations simultaneously. It is suitable for devices with large variations in charge density but requires a good initial estimate to converge.

It also allows solving different combinations of equations:

- Self-consistent (default):

Solves Poisson, drift-diffusion, and heat transport equations.

- Electrostatic:

Solves only Poisson, using charge density as a fixed input.

- Charge:

Solves only drift-diffusion, using the electrostatic potential as a fixed input.

2.1.1.5.3 *Number of Models*

It is necessary to consider different models that address various objectives and help provide both general and specific insights. For example, we need to validate our FEM models with experimental data, as well as account for preprocessing and calculation time, which will depend on the complexity we wish to add.

Therefore, the following models will be considered:

- **Baseline Model**

This is the starting point for the FEM analysis.

- Objective:

Provide an initial understanding of the electrical and thermal behaviour of the system under simplified assumptions.

- Features:
 - Homogeneous insulation: It is assumed that the insulation is uniform, with constant properties (permittivity, conductivity, etc.).
 - Uniform thermal conditions: No significant temperature gradients are considered.
 - Simplified space charge: No traps are included, or a homogeneous charge distribution is assumed.
- Purpose:
 - Identify general behaviours, such as the initial electric field distribution or the effect of applied charge.
 - Serve as a reference to assess the importance of added complexities in subsequent models.

- **Advanced Models**

These models extend the baseline model by introducing additional complexities to capture more realistic and specific phenomena.

Considered Variations:

- **Temperature-Dependent Properties:**
 - The permittivity and conductivity of the material vary with temperature.
 - Dielectric losses and Joule heating effects are included.
- **Non-Uniform Trap Distribution:**
 - Different densities and depths of traps (shallow and deep traps) depending on the electric field and temperature.
 - Impact on space charge accumulation and electric field distortion.
- **Heterogeneous Insulation Layers:**
 - Simulation of cables with multiple insulation layers, each with specific properties.
 - Consideration of interfaces between layers, where injection or charge accumulation effects may occur.
- **Local Defects:**
 - Inclusion of voids, protrusions, or imperfections in the insulation.
 - Evaluation of the risk of partial discharges (PD) in these critical regions.
- **Electro-Thermal Coupling:**

- Interaction between the electric field and temperature distributions to evaluate long-term effects, such as material aging.
- Assess behaviour under realistic operating conditions.
- Study specific scenarios, such as insulation aging or the effect of thermal gradients.

- **Validation Model**

This model is a simplification specifically designed to compare numerical results with experimental data or analytical solutions.

- Objective: Validate the accuracy of advanced models through controlled testing.
- Features:
 - Simplified geometry and material parameters like those used in experiments.
 - Reduced computational load to allow for quick simulations.
 - Boundary conditions and loads adjusted to replicate specific experiments or theoretical scenarios.
- Purpose:
 - Ensure that the predictions from the advanced model align with experimental data.
 - Adjust input parameters, such as trap density or temperature-dependent properties, to better match reality.

2.1.1.5.4 CAD model

The models discussed in the previous section are also defined by the geometry of the cable being simulated. These can range from a base model where the geometry is as simple as possible for studying general concepts of potential results, to highly complex models that account for the exact shapes of the different cable layers, as well as joints and terminals.

In general, the different elements of the cable must be modeled as follows:

- **Conductors:**
 - Geometry of the conductor core, which is usually cylindrical.
- **Insulation:**
 - Representation of the main dielectric material surrounding the conductor.
 - It may be homogeneous or divided into several layers with different electrical and thermal properties.
- **Semiconductor Layer and Screens:**
 - Internal semiconductor layer between the conductor and insulation.

- External semiconductor screen between the insulation and the protective sheath.
- **External Sheath:**
 - Mechanical protection and additional insulation.
 - It may include a metallic layer or polymers with specific properties.
- **Additional Elements:**
 - Voids or imperfections to analyze charge accumulation and potential initiation of partial discharges.
 - Interfaces between layers to study charge injection or field accumulation at boundaries.

As previously mentioned, the models' objectives for each FEM scenario can benefit from:

- **Detailed Geometry:**
 - Faithfully represents all layers and elements of the cable, including details such as microscopic voids or roughness at interfaces.
 - It could be used in advanced models to predict the space charge distribution accurately, as well as determine the path of partial discharges.
- **Simplified Model:**
 - Simplifies the geometry to a basic representation (e.g., concentric cylinders) to reduce computational load.
 - Ideal for preliminary studies or analytical/experimental validation, where complex details are not essential.
- **2D or Axisymmetric Model:**
 - Instead of a full 3D model, a 2D or axisymmetric model is used to take advantage of the cable's geometric symmetry.
 - It drastically reduces simulation time without sacrificing accuracy in applications where the radial distribution is sufficient.

Finally, since modifications in the cable geometry are considered due to simplifications and redesigns, **Ansys SpaceClaim** has been chosen as the geometric modelling software. SpaceClaim is integrated within the ANSYS environment, allowing direct connection with Lumerical Charge and Charge Plus. It also supports importing various geometric formats such as STEP, IGES, or STL.

2.1.1.5.5 *Boundary conditions*

Boundary conditions in Lumerical Charge play a crucial role in simulating charge accumulation and the electric field distribution in HVDC cables. Proper selection of these conditions ensures

that the models accurately represent the electrical and thermal behavior under real operating conditions. Below are the different types of boundary conditions and their specific implementation for such studies.

Electrical Boundary Conditions

- **HVDC Voltage on the Inner Conductor:**
 - A DC voltage (HVDC) is applied to the central conductor.
 - This voltage can be kept constant or varied over time to simulate transient phenomena such as polarization and depolarization of the insulation.
- **Ground Potential on the Outer Sheath:**
 - The external metallic layer or sheath is fixed at ground potential (0 V), establishing a radial electric field gradient across the insulation.
- **Charge Injection and Extraction:**
 - At the conductor-insulation interfaces and outer insulation layers, charge injection phenomena can be modeled depending on the electric field intensity and local temperature.
 - **Injection Models:** Schottky or Fowler-Nordheim type injection models can be used to represent charge transfer at the conductor-insulation interfaces.

$$J = A^* T^2 \exp\left(-\frac{\phi_B}{kT}\right)$$

- **Surface Recombination:**

In addition to charge injection at the interfaces, surface recombination can be an important effect in space charge distribution. The recombination rate can vary, as in high-quality contacts where the recombination rate is very low due to similar material properties, smooth geometric transitions at the interface, etc. On the other hand, resistive contacts may have a higher trap density, which can increase the recombination rate and affect the overall charge distribution.

Thermal Boundary Conditions

The study of space charge requires an electromechanical coupling, as temperature directly influences the mobility of charges and the characteristics of insulation.

- **Temperature Distribution on the Outer Surface:**
 - A fixed temperature can be imposed on the outer sheath of the cable to simulate environmental conditions or cooling systems.
 - Alternatively, thermal gradients can be applied across the insulation to evaluate the influence of temperature variations on charge accumulation.

- **Internal Heat Generation:**
 - Simulations can include internal heat sources, such as Joule heating in the conductor and dielectric losses in the insulation.
- **Convection and Radiation Conditions:**
 - If the model considers heat dissipation to the environment, convection and radiation conditions can be applied to the outer sheath of the cable.
 - Specific heat transfer coefficients can be adjusted to simulate real-world scenarios.

Symmetry and Periodic Boundary Conditions

To improve computational efficiency, especially in large and complex geometries like HVDC cables, symmetry or periodicity boundary conditions can be leveraged.

- **Axial Symmetry:**
 - If the model is axisymmetric, symmetry conditions can be applied along the central axis. This reduces the problem domain to a 2D model that represents the radial distribution of the electric field and charge.
- **Periodic Boundary Conditions:**
 - In cases where the domain represents a repetitive section of the cable, periodic boundary conditions can be applied to simulate a larger system with reduced computational cost.

2.1.1.5.6 Loads

- **Electrical Load:** The primary load involves the steady-state application of DC voltage on the conductor. However, transient loads play a critical role in studying space charge dynamics, especially during operational events such as polarization, depolarization, and voltage polarity reversals. These transitions create significant electric field distortions, potentially leading to higher stress on the insulation. Voltage spikes, either from switching operations or system disturbances, introduce rapid transients that need to be modeled accurately to assess their impact on space charge accumulation and redistribution.
- **Thermal Load:** Joule heating from the conductor and dielectric losses contribute to a radial temperature gradient within the cable insulation. This thermal gradient influences space charge behavior and must be coupled with electrical simulations to capture its effect on transient and steady-state conditions.
- **Transient Loads:** Operational events like polarity reversals (commonly in line-commutated converter systems) and emergency voltage control measures introduce transient states where the electric field and space charge distribution fluctuate significantly. During these periods, charge carriers' mobility and trap dynamics are particularly important. These transient events can intensify local

electric fields, especially near interfaces, leading to potential degradation or failure of the insulation system.

- **Environmental Loads:** External conditions, such as ambient temperature variations and cooling mechanisms (e.g., convection, radiation), further affect the thermal profile of the cable, indirectly influencing the space charge dynamics during both steady and transient states

2.1.1.5.7 Mesh type

The mesh is a crucial aspect of finite element modelling (FEM), particularly for accurately capturing the electric and thermal fields in HVDC cable simulations. In **Lumerical Charge**, the mesh design significantly impacts the precision and efficiency of the simulation, especially when studying complex phenomena like space charge dynamics.

Element Type

The choice of element type depends on the simulation domain and the problem's dimensionality:

- **3D Models:**

Tetrahedral Elements: These are widely used in 3D simulations due to their flexibility in meshing complex geometries, such as the cylindrical cross-section of a cable or irregular voids within the insulation.

- **2D Models:**

Triangular Elements: Commonly used in 2D cross-sections, providing flexibility in irregular domains.

Mesh Density

Mesh density must be carefully adjusted based on expected gradients in the solution:

- **High-Gradient Regions:**

- Near the conductor, where electric fields are strongest.
- Interfaces between materials, such as insulation and sheath, where discontinuities in material properties (e.g., permittivity, conductivity) cause steep field changes.

- **Critical Defects:**

- Around voids or impurities within the insulation, where localized electric field intensification can occur.
- Higher mesh density in these regions ensures accurate capture of space charge effects and field variations.

Adaptive Meshing

Adaptive meshing refines the mesh during the simulation based on error estimates or gradients in the solution:

- **Void and Defect Detection:**
 - Automatic mesh refinement around detected or pre-defined defects like voids and sharp edges ensures precise calculation of local fields. This is critical for partial discharge studies and aging analysis.
- **Dynamic Refinement:**
 - In transient simulations, areas with rapidly changing fields (e.g., during polarity reversals or voltage spikes) are dynamically refined to maintain accuracy without excessively increasing the computational cost.

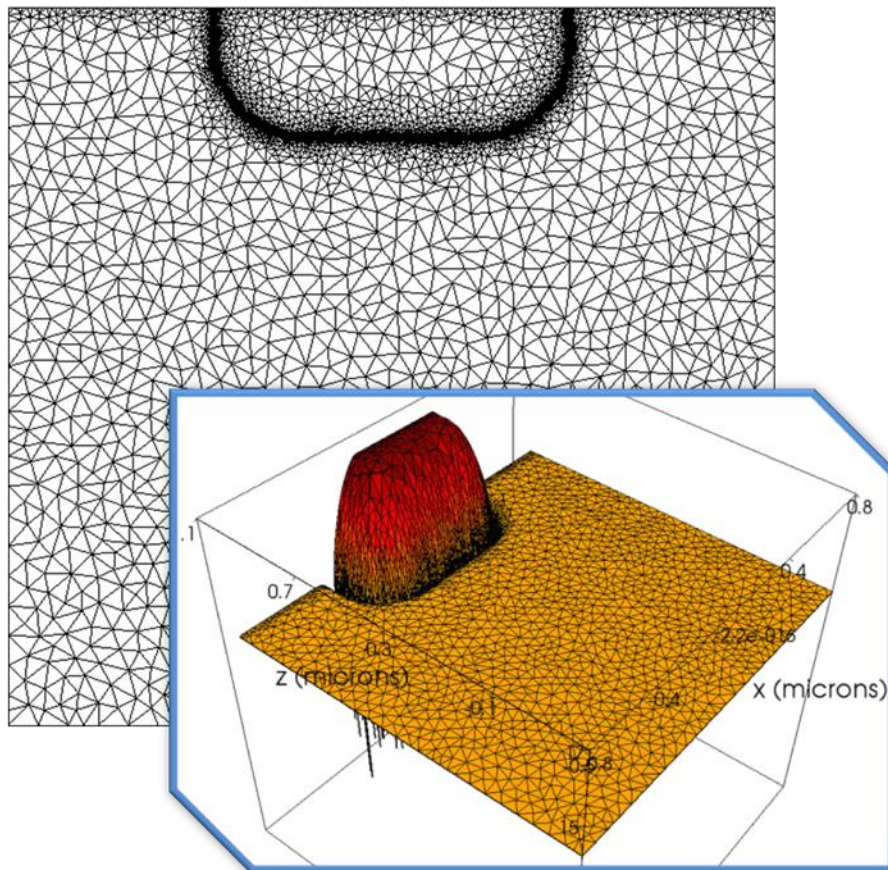


Figure 6 Dynamic Mesh refinement

2.1.1.5.8 Simulation and result analysis

- **Outputs:** Key outputs include the distribution of the electric field, space charge density, and potential gradients throughout the insulation material. These results help identify areas prone to partial discharge or excessive electric stress. In addition, temperature distributions resulting from thermal coupling are analyzed to evaluate hotspots and their impact on space charge behavior.
- **Post-Processing:** Advanced visualization tools in Lumerical enable detailed analysis of electric stress, charge accumulation zones, and temperature gradients. The software can generate field plots, space charge density maps, and time-series data for transient phenomena. These visualizations are crucial for interpreting the long-term reliability and performance of HVDC cable insulation under different operational conditions

2.1.2 Thermal modelling

One of the most critical aspects in the operation of insulated cables is temperature monitoring and management, as overheating of insulated cables can significantly reduce their lifespan and increase the risk of failures. Distributed temperature monitoring using fibre optic sensors has emerged as an advanced and effective solution to address these challenges. This technology enables real-time detection of thermal variations along the cable, providing precise data that is essential for dynamic cable management. Dynamic management of insulated cables involves not only temperature monitoring but also the integration of data on burial depth and environmental conditions, as well as simulation through finite element methods. This comprehensive approach allows for optimising transmission capacity, preventing failures, and extending the infrastructure's lifespan.

2.1.2.1 State-of-the-art

2.1.2.1.1 Standards

The standards developed by IEC are, to this day, the reference standards for ampacity calculation and thermal behaviour calculation in insulated power cables. On one hand, the collection of standards from the IEC 60287 series – Electric cables – Calculation of the current rating - [1], [2], [3], [4], [5], [6], [7], [8], [9] – allows for the calculation of ampacity in insulated power cables. On the other hand, the collection of standards from the IEC 60853 series – Calculation of the cyclic and emergency current rating of cables [10], [11], [12] – supported by the IEC 60287 standards, enables the calculation of the cable's thermal behaviour. Apart from these two series of standards, others define the construction of insulated cables, their testing, or the use of finite element methods for nominal current calculation. These include:

- IEC 62095:2003 Electric cables – Calculations for current ratings – Finite element method [13].
- IEC 60228:2023 Conductors of insulated cables [14].
- IEC 60840:2020+AMD1:2023 CSV Power cables with extruded insulation and their accessories for rated voltages above 30 kV ($U_m = 36$ kV) up to 150 kV ($U_m = 170$ kV) – Test methods and requirements [15].

- IEC 62067:2022 RLV Power cables with extruded insulation and their accessories for rated voltages above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) – Test methods and requirements [16].
- IEC 63026:2019 – Submarine power cables with extruded insulation and their accessories for rated voltages from 6 kV ($U_m = 7.2$ kV) up to 60 kV ($U_m = 72.5$ kV) – Test methods and requirements [17].

The standards developed by IEEE relating to insulated cables do not aim to define ampacity calculations or the thermal behaviour of insulated cables. Instead, they focus on defining testing procedures, the design and installation of terrestrial and submarine lines in a very general manner, fault location, and/or methods for measuring the thermal resistivity of soil and the backfill materials used to cover cables installed underground. An example of these IEEE standards is shown below:

- IEEE Std 1120-2004 Guide for the Planning, Design, Installation, and Repair of Submarine Power Cable Systems [18].
- IEEE Std 1234-2019 Guide for Fault-Locating Techniques on Shielded Power Cable Systems [19].
- IEEE Std 400-2023 Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above [20].
- IEEE Std 442-2017 IEEE Guide for Thermal Resistivity Measurements of Soils and Backfill Materials [21].

A particularly interesting standard in relation to the project topic is IEEE Std 1718-2012 Guide for Temperature Monitoring of Cable Systems [22]. This standard provides an overview of existing and emerging temperature monitoring systems related to power cable installations. It summarises the characteristics, advantages, and limitations of both discrete and distributed temperature monitoring for calculating the nominal capacity of cables.

In the CIGRE framework, numerous references to insulated cables can be found. Some of the most significant are summarised below:

- TB 610 – Offshore Generation Cable Connections [23]: This Technical Brochure (TB), specifically in Chapter 5, addresses the design of submarine cables, particularly the various types of conductors, insulation materials, screens, etc., explaining the function of the different layers. It outlines the main differences between submarine and terrestrial cables and provides general recommendations for the design of submarine lines. Lastly, it briefly explains the various methods available for calculating the nominal capacity of offshore generation connection cables and for determining the necessary dimensions of the cables to achieve the required nominal capacity: analytical/empirical methods (IEC 60287 and IEC 60853) and numerical methods (load simulation, finite difference methods, and finite element methods).
- TB 640 – A Guide for Rating Calculations of Insulated Cables [24]: CIGRE's TB 640 provides a detailed examination of the nominal rating of insulated electric cables, including buried, submarine, and overhead installations, addressing issues related to

establishing the ampacity of both new and existing electric cables. Given the wide variety of types of power cables and installation conditions that influence the nominal rating of a power cable, and although there are well-known standards governing ampacity calculations, such as IEC 60287 or IEC 60853, these standards are not entirely comprehensive. This document assists in calculating the nominal rating of a power cable in a given situation, advising adherence to IEC standards where possible. However, if the cable installation type is not exactly described in the IEC standard, this TB can provide guidance on how to proceed.

- TB 908 – Losses in Armoured Three Core Power Cables [25]: This CIGRE document focuses on the losses occurring in armoured three-core power cables, based on the formulas outlined in IEC 60287-1-1. These formulas were developed from early research on cables with small conductor cross-sections and common metallic screens. However, modern cable designs, especially those for high and very high voltage levels, have evolved to feature larger conductor cross-sections, thicker insulation, and individual metallic covers for each phase, rather than a shared screen. As a result, the IEC 60287-1-1 standard tends to overestimate losses in these cables, which can lead to oversizing. In this document, the formulas from IEC 60287-1-1 are discussed and compared with the current understanding of the physics behind losses in armoured cables. Additionally, two calculation methods are presented: an analytical method and a numerical method. The analytical method, developed by members of the working group, accounts for the proximity effect of the conductor on the magnetic field, providing a more accurate estimate of the induced losses in the screens and the armour, and is suitable for both magnetic and non-magnetic armours. The numerical method tends to slightly overestimate losses as well and is applicable to both types of armours. TB 908 also indicates how finite element models were employed to better understand cable losses and validate the physical phenomena during the development of the analytical method. For cables with double armouring or flat armouring, the 3D FEM method is recommended, as other calculation methods do not cover these options. This is one of the areas identified for further research.

More information on testing, failures, and protection of terrestrial and submarine insulated cable systems can be found in the following CIGRE Technical Brochures:

- TB 379 – Update of service experience of HV underground and submarine cable systems [26].
- TB 398 – Third-party damage to underground and submarine cables [27].
- TB 490 – Recommendations for testing of long AC submarine cables with extruded insulation above 30 kV to 500 kV [28].
- TB 852 – Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to and including 800 kV [29].
- TB 623 – Recommendations for mechanical testing of submarine cables [30].
- TB 722 – Recommendations for additional testing for submarine cables from 6 kV ($U_m = 7.2$ kV) up to 60 kV ($U_m = 72.5$ kV) [31].

- TB 815 – Update of service experience of HV underground and submarine cable systems [32].
- TB 862 – Recommendations for mechanical testing of submarine cables for dynamic applications [33].
- TB 883 – Installation of submarine power cables [34].

In addition to the Technical Brochures, the CIGRE database contains articles published in its journals (ELECTRA and CIGRE Science & Engineering journal – CSE) and papers presented at CIGRE sessions, which will be analysed and discussed in later sections.

2.1.2.1.2 Insulated cables

Figure 7 shows some of the sections outlined in CIGRE's TB640 [24], which correspond to the layers that an insulated cable may contain. Insulated cables consist of one or more stranded/segmental conductors with a combination of sealing layers, insulation, metallic screens, fillers, and protective armour. AC submarine cables have three conductors (one for each phase). AC land cables are single-core and are laid in groups of three, in flat or trefoil formation. DC cables (both land and submarine) are single-core, with two cables—one positive and one negative—per circuit.

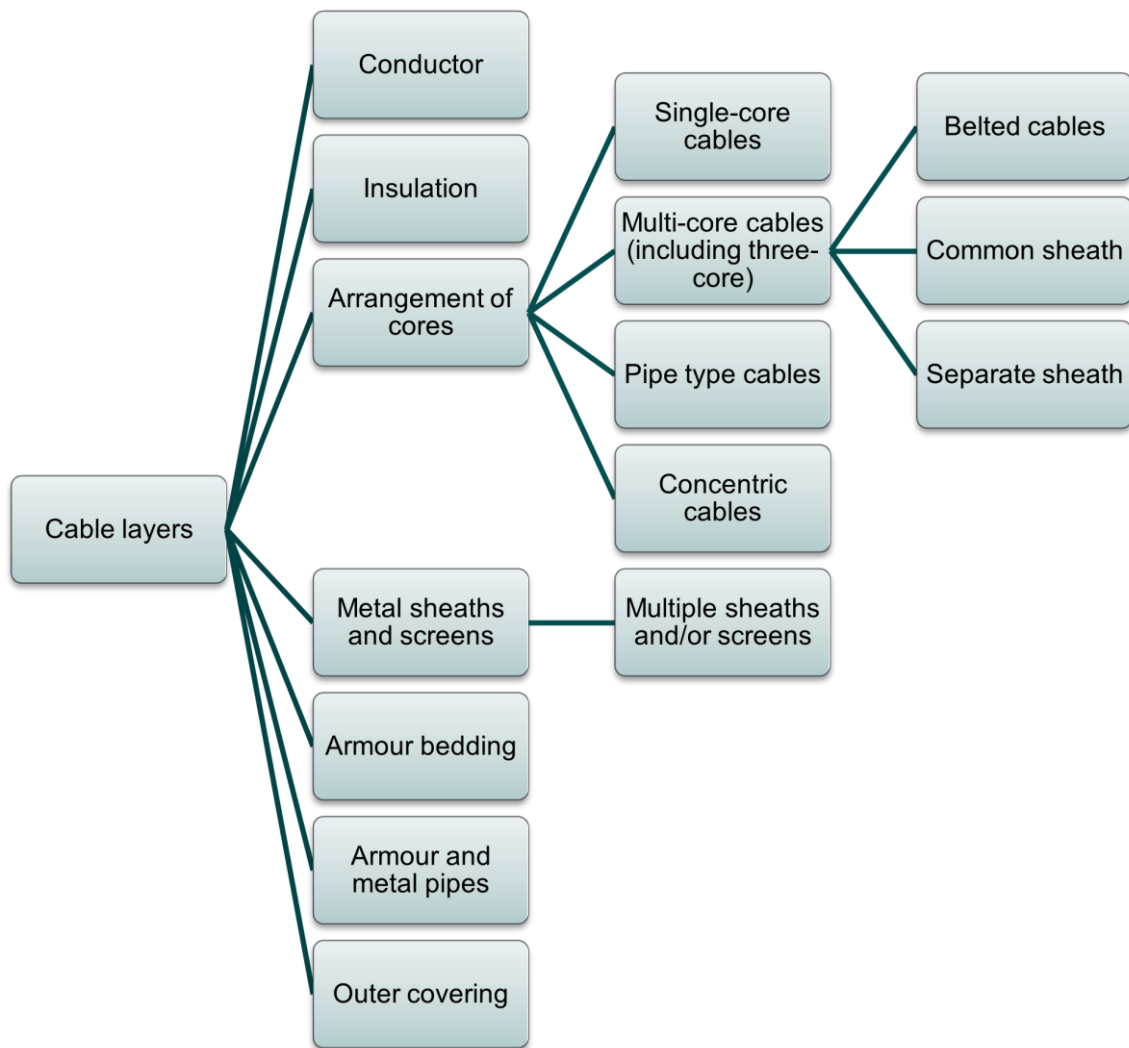


Figure 7 Insulated cable layers according to CIGRE TB640 sections [24]

There are many design variations in the core of insulated cables, but almost all use some type of metallic layer to provide a ground return path for short-circuit currents, load currents, circulating currents and, in some cable constructions, to provide electrical field shielding. These metallic layers may consist of metal sheaths (extruded lead, copper, aluminium or stainless steel, either smooth or corrugated), copper or aluminium wire screens, foil laminates, copper tapes, among others. In addition, this metallic layer can serve another purpose - to prevent water ingress into the cable core. Depending on how this layer is applied, there are three main types of insulated cores:

- Dry: with an extruded lead sheath over the insulation.
- Semi-wet: with a polyethylene sheath over a metallic screen that is not fully waterproof.
- Wet: without a sheath over a metallic screen that is not fully waterproof.

Wet core designs have the advantage of being lighter and more flexible than dry designs. Figure 8 shows the difference in diameter among the various insulated cores, with the wet design having the smallest diameter.

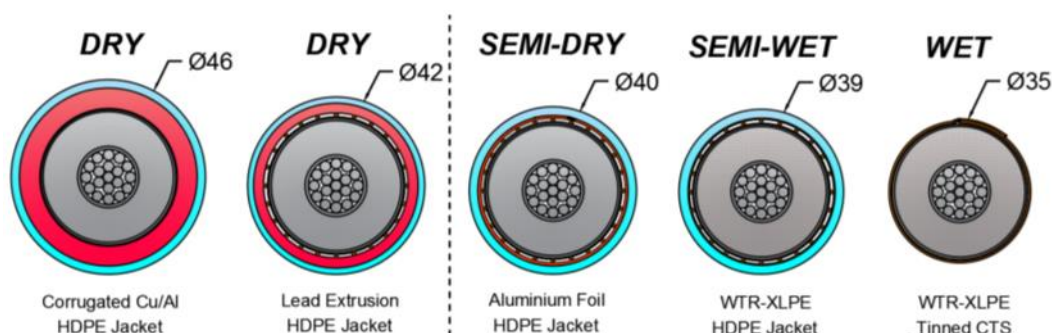


Figure 8 Example of types of submarine cable core design [35]

To illustrate the complexity of some of these insulated power cables, Figure 9 shows the typical hierarchy of a submarine three-core cable. Each core within this submarine cable corresponds to an unarmoured terrestrial insulated cable, consisting of a conductor, insulation, metallic screen, and outer sheath.

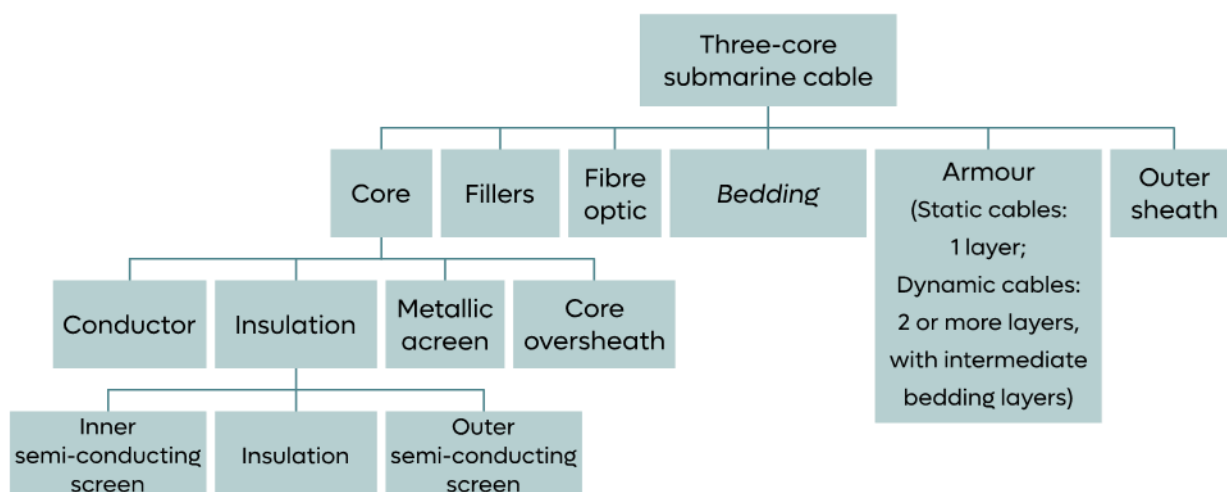


Figure 9 Hierarchy of components in a three-core submarine cable [36]

For long distances of HVDC or HVAC cables, it becomes necessary to perform multiple joints or connectors, either for extending the cable length or for repairs. Cable joints or connectors can be carried out either in the factory or on-site. There are two general types of joints for most cable types: flexible joints and rigid joints. Generally, factory joints are made before the armouring operation, ensuring that the cable section containing the joint is continuously armoured without any noticeable discontinuity or distortion of the armour wires near the joint [28]. The primary characteristic of a factory joint is that it should not impose any restrictions on subsequent cable handling or installation operations, nor cause any variation in the cable's mechanical and electrical performance [23], [28]. This means that factory joints are fully flexible, with the same bending radius, tensile strength limit, and coiling performance as the original cable. The factory joint has approximately the same diameter as the cable, as shown in Figure 10, and can be handled using standard cable-handling equipment. Rigid joints use a prefabricated insulating sleeve. The assembly is completed with watertight barriers (metallic coverings and/or heat-shrink tubes). The outer sheath is typically formed by a metal cylinder firmly attached to the cable's armour. Rigid joints are usually quicker to install than flexible

ones, as they do not require processes that depend on temperature and pressure [23]. Figure 11 shows the final result of a rigid joint with bending reinforcements at the ends.

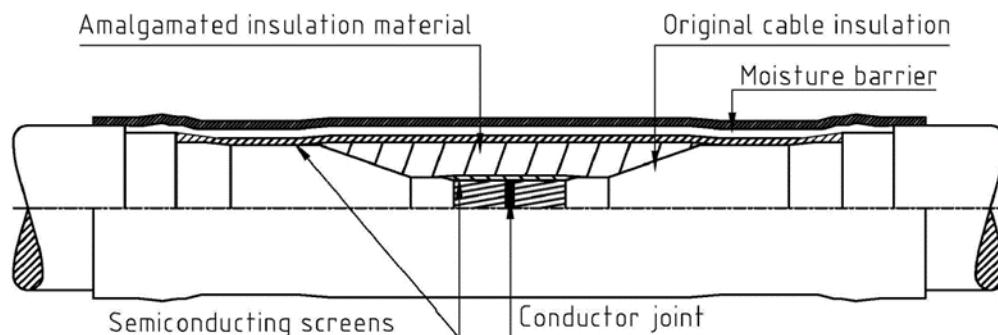


Figure 10 General schematic of a factory joint with the same dimensions as the cable (not to scale) [28]



Figure 11 Rigid joint in a submarine cable and the support structure used for laying the cable [23]

The submarine-to-shore transition joint of an AC cable is typically a rigid joint made from prefabricated elements, similar to the rigid joint used in the installation or repair of an export cable. The mechanical requirements of the transition joint vary from case to case. If the submarine cable is laid in a flat seabed and the joint is placed on land, it may only be necessary to finish the armour. However, in situations where the submarine cable is installed on steep slopes, it may be necessary to secure the submarine cable through its armour [28]. If it is necessary to secure the armour to support the weight of the cable, several designs can be considered; one option is to terminate the armour at a steel fixture rigidly connected to a concrete anchor block.

2.1.2.1.3 Dynamic management of insulated cables

Dynamic management is essential to ensure the safety, efficiency, and durability of power transmission and distribution cables, whether they are submarine, overhead, or underground. Although each type of cable faces specific conditions due to its environment, the principles and benefits of dynamic management are similar. This practice not only enhances operational

reliability and reduces long-term costs but also contributes to making the power grid more sustainable and resilient. The dynamic management of insulated cables allows for the optimisation of their capacity, adjusting it in real-time to handle fluctuations in load, ensuring efficient and safe transmission, and preventing overloads by detecting and mitigating situations that could cause significant damage to the cable.

The insulated cables have the structure previously discussed (Figure 7) and in more detail for the case of a static submarine three-core cable in Figure 12. The layers defined in Figure 12 are:

- l_1 : Conductor
- l_2 : Inner semi-conducting screen
- l_3 : Insulation
- l_4 : Outer semi-conducting screen
- l_5 : Semi-conductor water blocking tape
- l_6 : Metallic screen
- l_7 : Outer jacket of each conductor
- l_8 : Bedding
- l_9 : Armour
- l_{10} : Outer jacket
- f_1 : Fibre optic
- f_2 : Filler

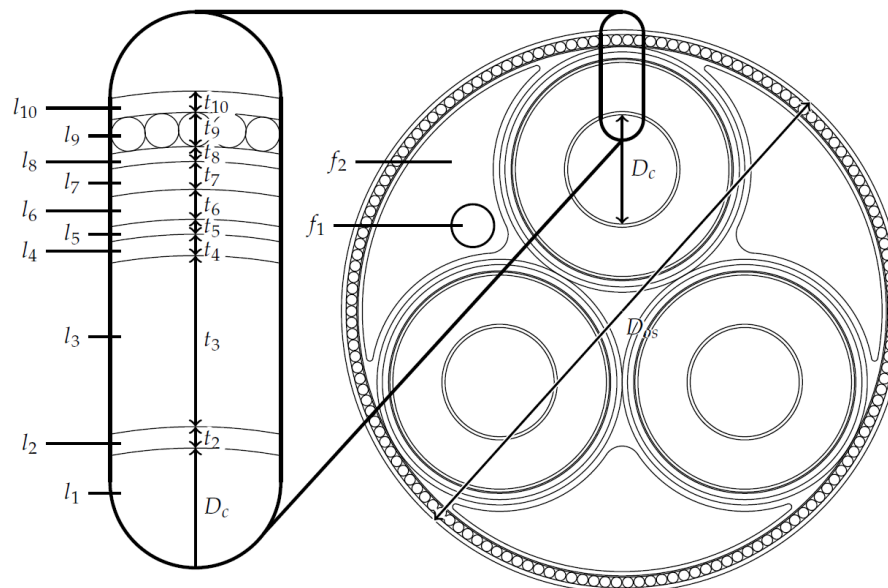


Figure 12 Common construction of a three-core submarine cable with XLPE insulation, metallic sheath on each conductor, and armouring [37]

This structure is similar to that of insulated cables used for the transmission and distribution of electrical energy on land. For this reason, CIGRE TB 640 [24] indicates that the analytical/empirical methods contained in IEC 60287 [1] and IEC 60853 [11] can be used to calculate the nominal capacity of submarine cables and the necessary cable dimensions to achieve the required nominal capacity. These standards are the most widely used for the dynamic management of insulated cables and are based on the equivalent thermal circuit

method. The equivalence between the electrical and thermal parameters used in this method is shown in Table 4. Figures 13 and 14 show the static and dynamic thermal circuit models for a three-core armoured cable. In these circuits, thermal resistance represents the ability of the material to impede heat flow and thermal capacity is defined as the ability to store heat. This method is only applicable in cases where the thermal parameters do not change as a function of temperature variations, as it solves the heat flow equations using the superposition principle, which is only used for linear systems [37].

Table 4 Equivalence of parameters in the thermoelectric analogy [38]

Electrical parameter	Units	Electrical parameter	Units
Resistance, R	Ω	Thermal resistance, T	$K \cdot m/W$
Capacitance, C	F	Heat capacity, Q	$J/K \cdot m$
Voltage, U	V	Temperature, θ	$^{\circ}\text{C}$
Current, I	A	Heat flux, ω	W/m

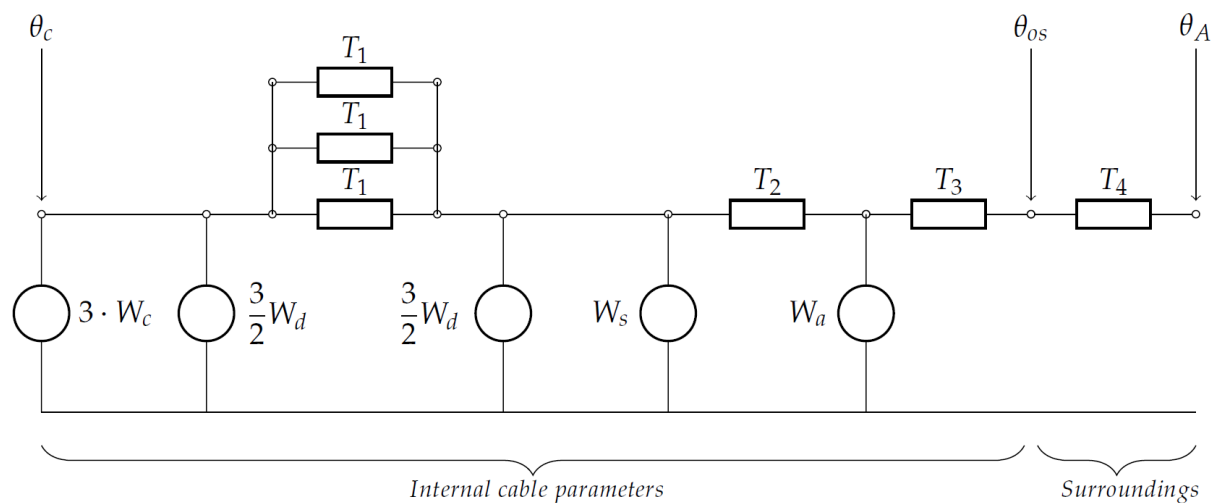


Figure 13 Static thermal circuit model of a three-core submarine cable [37]

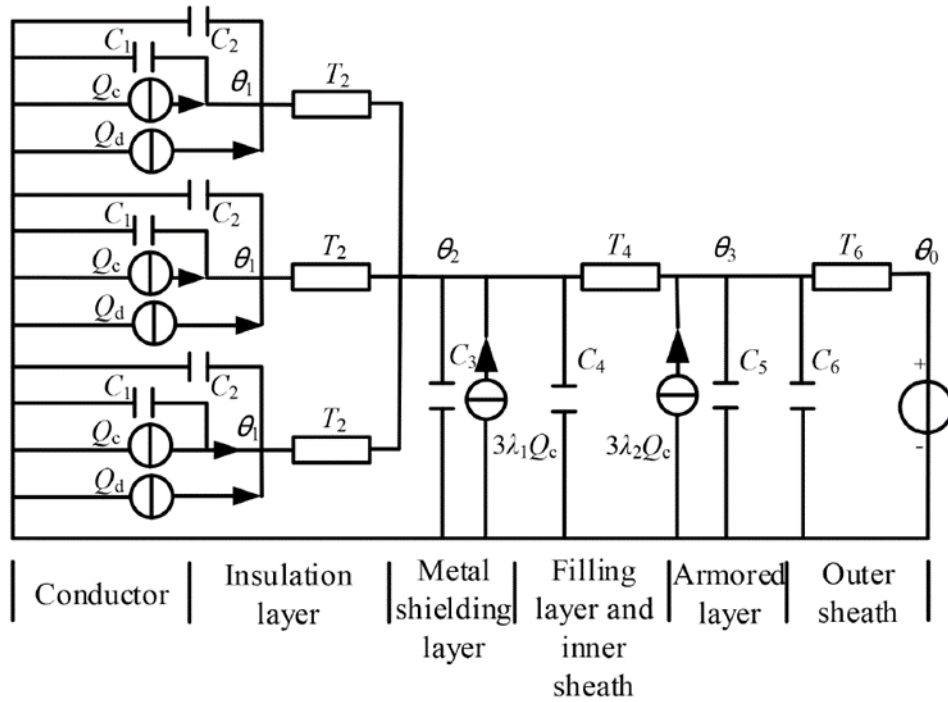


Figure 14 Transient thermal circuit model of a three-core submarine cable [39]

The first step in IEC 60287-1-1 [1] is to calculate the cable losses: conductor losses (Q_c [W/m^3] or W_c [W/m]), dielectric losses (Q_d [W/m^3] or W_d [W/m]), sheath losses (Q_s [W/m^3] or W_s [W/m]), and armour losses (Q_a [W/m^3] or W_a [W/m]). The calculation of the losses in the metallic screen and in the armour is made in relation to the losses in the conductors, so in Figure 14 they are represented as $\lambda_1 Q_c$ and $\lambda_2 Q_c$ respectively.

The expression given in IEC 60287-1-1 [1] for calculating the permissible temperature rise in the conductor above the ambient temperature is defined as:

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

where $\Delta\theta$ is the temperature rise of the conductor above the ambient temperature (K), I is the current flowing in a conductor (A), R is the resistance per unit length of the conductor at the maximum operating temperature (Ω/m), W_d is the dielectric loss per unit length (W/m), T_1 is the thermal resistance per unit length between the conductor and the sheath ($K \cdot m/W$), T_2 is the thermal resistance per unit length between the sheath and the armour ($K \cdot m/W$), T_3 is the thermal resistance per unit length of the outer sheath ($K \cdot m/W$) and T_4 is the thermal resistance per unit length between the cable surface and the surrounding medium ($K \cdot m/W$), n is the number of insulated conductors in service in the cable (conductors of the same cross section and carrying the same load), λ_1 is the ratio of the losses in the metallic sheath to the total losses in all the conductors of this cable and λ_2 is the ratio of the losses in the armour to the total losses in all the conductors of this cable.

The ampacity (I) in conductors is obtained from Equation 1 as follows:

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

To use equations 1 and 2, it is necessary to know the losses in the different components of the cable. The losses in the conductors per unit length are given by $I^2 R$, where R is calculated as

$$R = R'(1 + y_s + y_p) \quad (3)$$

where R' is the conductor resistance per unit length in direct current at maximum operating temperature (Ω/m), and y_s and y_p are the skin effect and proximity factor respectively.

The conductor resistance per unit length in direct current at maximum operating temperature is calculated as

$$R' = R_o[1 + \alpha_{20}(\theta - 20)] \quad (4)$$

where R_o is the resistance of the conductor per unit length in direct current at 20 °C (Ω/m), α_{20} is the coefficient of variation at 20 °C of the resistivity as a function of temperature per Kelvin, and θ is the maximum operating temperature of the cable (°C).

The dielectric losses per unit length and in each phase are calculated as follows

$$W_d = \omega \cdot C \cdot U_o^2 \cdot \tan \delta \quad (5)$$

where $\omega = 2\pi f$, C is the capacitance per unit length (F/m) and U_o is the voltage to earth (V).

Finally, the calculation of the losses in the metallic sheaths and armour, given by the ratios of the losses to the total losses in all the conductors of the cable, λ_1 and λ_2 respectively, are calculated using the equations given in IEC 60287 [1], which depend on the construction and materials of the cable.

Regarding the calculation of cable losses, more recent publications such as CIGRE TB 908 [25], or conference papers [40], [41], [42], [43], [44], [45], [46], [47], indicate that the loss calculation in IEC 60287 is inaccurate. On the contrary, also recent publications [37], [39], [48], [49], [50], [51], [52], [53], [54], [55], continue to use the loss calculation method as shown in IEC 60287.

CIGRE TB 908 [25] contains two methods for the calculation of losses in a three-core submarine cable. Method 1, starting from the cable geometry, calculates the magnetic field of three stranded conductors with or without armour, the permeability of the cable armour, and presents the formulae for calculating the losses in the conductors, sheath and armour, and also studies the mutual influence between the armour losses and the sheath and conductor losses. The equations and results presented were validated using FEM models.

Articles and conference papers [40], [41], [42], [44], [45], [45], [46], [47] which suggest that the calculation of losses using the IEC 60287 equations is inaccurate use FEM models to calculate losses in conductors, metallic sheaths and armour. An example of the results of losses in a three-core submarine cable with armour obtained using a FEM model is shown in Figure 15. Using steady-state loading conditions and external conditions defined in FEM model simulations, it is possible to obtain the fitting curves for losses in conductors, metallic sheaths, and armour [40], as shown in Figure 16.

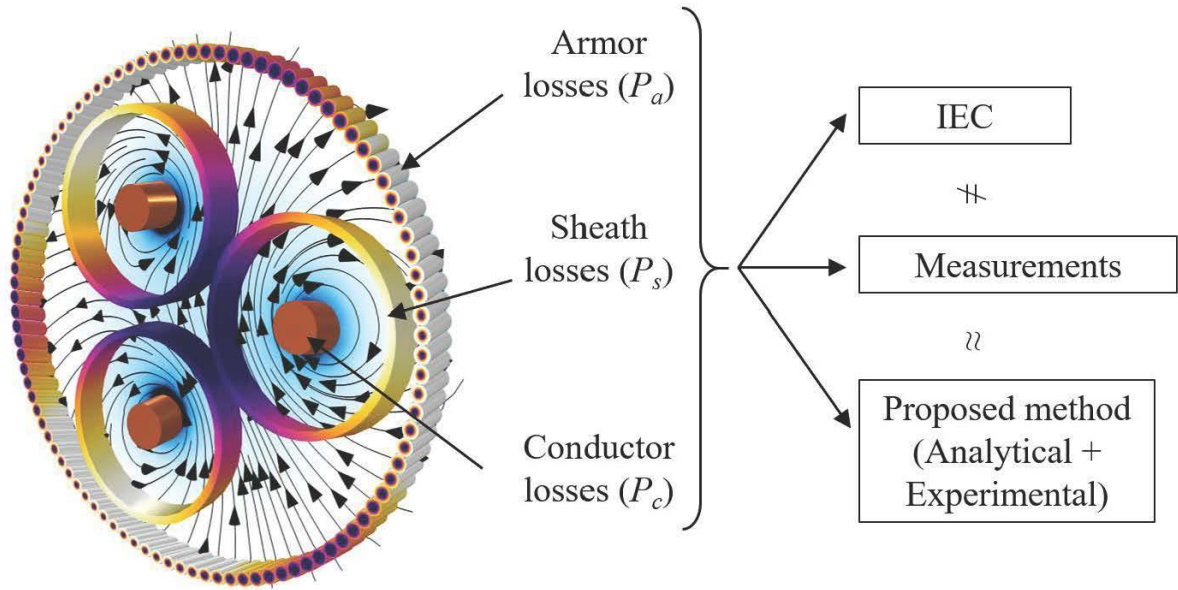


Figure 15 Electromagnetic losses in a simplified 3D model [42]

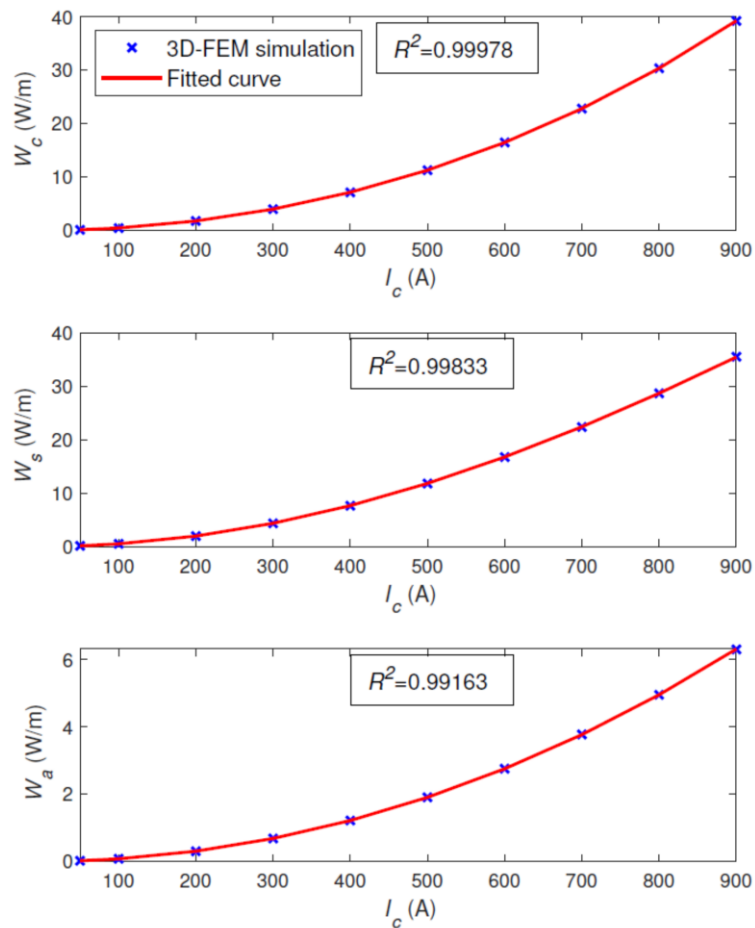


Figure 16 Fitting curves of losses (W_c , W_s , and W_a) in a cable model obtained in simulations for defined external conditions ($\theta_{amb} = 15^\circ\text{C}$, depth of burial = 1m, and seabed thermal conductivity of $\rho_{soil} = 1 \text{ W/K} \cdot \text{m}$) in [40]

The calculation of the thermal resistances (T_1 , T_2 , T_3 , and T_4) of the elements that make up an insulated cable is also the subject of the study, since the IEC 60287-2-1 standard [4], [6], [9] provides different equations depending on the cable design.

As with the calculation of losses using the equations in IEC 60287-1-1 [1], some authors use different equations to calculate the thermal resistances of the elements that make up an insulated cable.

For example, in [40], to calculate the thermal resistance between the conductor and the metallic screen (T_1) in a three-core submarine cable, the authors take into account the different materials that make up these layers: inner semi-conducting screen + insulation + outer semi-conducting screen; unlike the IEC 60287-1-1 standard, which considers the three layers of the insulation material. Also, in this same publication [40], there is another difference for the calculation of the thermal resistance of the outer jacket (T_3), in this case, the authors calculate the thermal resistance between the armour and the outer jacket using a slightly more complex formula, where the different thermal resistivities of the materials that compose it are taken into account.

In [39], an alternative method for calculating the thermal resistance between the filler material and the bedding under the armour (T_2) is presented. As with IEC 60287-2-1, this resistance cannot be treated as a ring-shaped heat-conducting medium due to its irregular shape. In contrast to the equation used in IEC 60287-2-1, this publication introduces the shape factor method from heat transfer theory, which aims to calculate the thermal resistance between two isothermal surfaces with irregular shapes. After presenting the thermal resistance equation T_2 based on the shape factor, the authors note that, in the case of a three-core cable, there is an error in this assumption, which makes the calculation of the thermal resistance inaccurate. Subsequently, in this work, the initial result of T_2 was modified by the value obtained from a FEM model.

Finally, depending on the study being reviewed, different formulas outlined in the IEC 60287-2-1 [4] are used for calculating the thermal resistance between the cable surface and the surrounding medium (T_4). This is because this thermal resistance depends on the installation conditions of the insulated cables, namely: directly buried (either on land or subsea), exposed to the air (protected or unprotected from solar radiation), or in ducts filled with air or water.

The thermal analysis of insulated power cables under transient conditions is covered by IEC 60853-2 [11]. This standard states that:

The transient temperature response of a cable to a step-function of current in its conductor (or conductors) depends on the combination of thermal capacitances and resistances formed by the constituent parts of the cable itself and its surroundings. On the other hand, when the response for long times is required, the thermal capacitances associated with the cable may be negligible and the most important factor is the thermal transient in the surrounding soil. The method for calculating the temperature response of a cable to a suddenly applied constant value of conductor current is to consider that the whole thermal circuit is divisible into two independent parts. One part is made up of the cable components out to the outer surface of the cable, the second part is

the environment of the cable. The individual responses of these two parts are partial transients, with which the total transient for the complete system can be built up.

This standard [11] gives two ways of calculating the emergency transport capacity factors depending on the duration of the emergency regime. The first method is used when the duration of the emergency regime is longer than 1 hour (according to IEC 60853-2 these are known as long duration transients) and the second when the duration is between 10 minutes and 1 hour. A modified version of the first case is used to calculate the second case.

The first part of the thermal circuit simulating the behaviour of the insulated cable, which includes all the layers of the cable inside its outer surface, is represented by a network of two cells, as shown in Figure 11. The first cell includes the thermal capacity of the conductor and the inner part of the insulation (Q_A) with the thermal resistance of the insulation (T_A), while the second cell includes the thermal capacity (Q_B) and the thermal resistance (T_B) of the rest of the cable. The equations for calculating the thermal capacities and thermal resistances in Figure 11 for the different types of insulated cables are given in IEC 60853-2 [11].

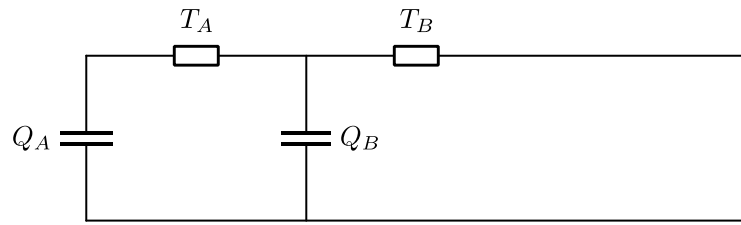


Figure 17 Cable equivalent network for transient response calculations [11].

Once the thermal representation of the cable is done, the partial transient response of the cable is calculated. The transient heating of the conductor, $\theta_c(t)$, above the temperature of the outer surface of the cable, and the approximation factor, $\alpha(t)$, relative to the heating of the conductor relative to the outer surface of the cable, are given by the following equations:

$$\theta_c(t) = W_c [T_a(1 - e^{-at}) + T_b(1 - e^{-bt})] \quad (5)$$

$$\alpha(t) = \theta_c(t) / [W_c(T_A + T_B)] \quad (6)$$

$$M_o = \frac{1}{2} (Q_A \{T_A + T_B\} Q_B T_B N_o = Q_A T_A + Q_B T_B$$

$$a = \frac{M_o + \sqrt{M_o^2 - N_o}}{N_o} \quad b = \frac{M_o - \sqrt{M_o^2 - N_o}}{N_o} \quad (7)$$

$$T_a = \frac{1}{a - b} \left[\frac{1}{Q_A} - b(T_A + T_B) \right] \quad T_b = T_A + T_B - T_a$$

where W_c is the linear loss in a conductor, or in the conductor of an equivalent cable, calculated at the maximum temperature reached by the conductor. These losses are assumed to be constant during the transient regime.

Next, the partial transient response of the cable environment, the second part of the thermal circuit, is calculated. For example, for cables laid in open air, it is not necessary to calculate the separate response for the cable(s) environment, the full transient regime is obtained by replacing T_B by $(T_B + T_C)$ in equation 7 (for the equation of T_C , see IEC 60853-2 [11]). For cables buried directly or in ducts, the transient heating ($\theta_e(t)$) of the outer surface of the cable above the ambient temperature is given by:

$$\theta_e(t) = \frac{\rho_T W_1}{4\pi} \left\{ \left[-Ei\left(\frac{-D_e^2}{16t\delta}\right) - \left[-Ei\left(\frac{-L^2}{t\delta}\right) \right] \right] + \sum_{k=1}^{k=N-1} \left[-Ei\left(\frac{-(d_{pk})^2}{4t\delta}\right) - \left[-Ei\left(\frac{-(d'_{pk})^2}{4t\delta}\right) \right] \right] \right\} \quad (8)$$

where W_1 is the total power loss per unit length of each cable in the group, ρ_T is the soil thermal resistivity, D_e is the external surface diameter of cable, δ is the soil thermal diffusivity, t is the time from moment of application of heating, L is the axial depth of burial of hottest cable, d_{pk} is the distance from centre of cable k to centre of hottest cable p , d'_{pk} is the distance from image of centre of cable k to centre of hottest cable p , N is the number of cables, and $-Ei(x)$ is the exponential integral function calculated using the scales given in IEC 60853-2 [11] or using the following equation for all values of $x > 0$ (assuming $-Ei(x)$ to be equal to 0 for values of $x \geq 8$ and equal to $-\ln(x) - 0.5772 + x$ for $x < 0.01$):

$$-Ei(x) = 0.5772 - \ln(x) - \sum_{n=1}^{\infty} \frac{(-1)^n x^n}{n(n!)} \quad (9)$$

The full transient temperature response of the cable is calculated from the two partial transient regimes (cable and its surroundings) and the approximation factor relative to the conductor relative to the cable surface. The total transient heating ($\theta(t)$) above ambient temperature is given by the following equation:

$$\theta(t) = \theta_c(t) + \alpha(t) \cdot \theta_e(t) \quad (10)$$

When it is necessary to calculate the temperature response for variations in multiple and discrete current intervals, IEC standard 60653-2 [36] specifies that the calculations described above should be repeated for each partial current interval. In calculating these partial transients, the effective heat source (the heat gained or lost in the partial current interval) and the effective temperature (for the calculation of electrical resistances) should be used in the previous formulas. One way to proceed is to perform iterative calculations for each load interval, as outlined below:

1. Start with the temperature obtained at the end of the previous load interval.

2. Calculate the electrical resistances corresponding to this temperature and determine the power losses.
3. Using these losses, calculate the temperature at the end of the interval.
4. Use this temperature to recalculate the electrical resistances and power losses, then return to step 3.
5. Repeat steps 3 and 4 until convergence is reached, then proceed to the next load interval.

The complete total temperature response of the cable circuit will be obtained by summing all the partial transients, taking into account the time differences between the partial intervals.

An example of the application of this methodology for calculating the full transient temperature response of a submarine cable is provided in [37], [38]. Figure 18 shows a daily current profile used by the authors, where I_a is the actual current and I_s is the average value of the actual current, with a total number of constant load steps of 4 hours ($\Delta\tau$). In Figure 19, three different load steps can be observed individually following the application of the current, resulting in the complete temperature response (θ_Σ).

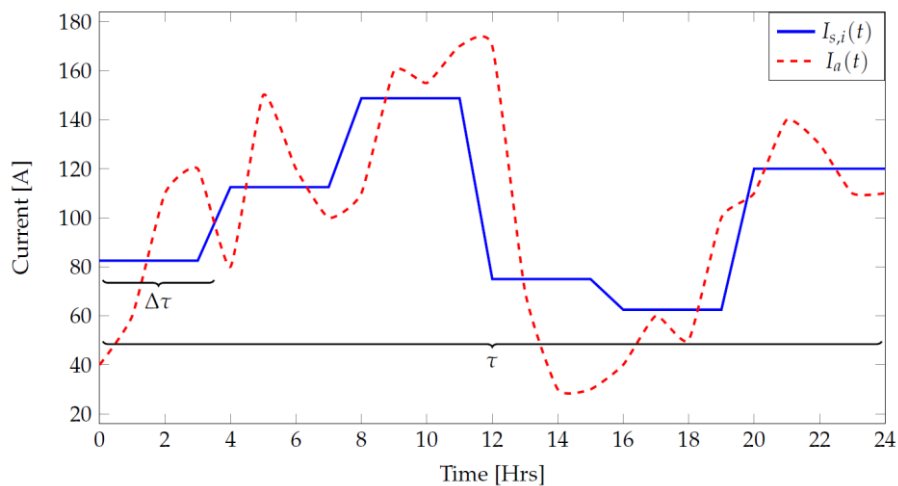


Figure 18 Construction of the step function for a current profile [37]

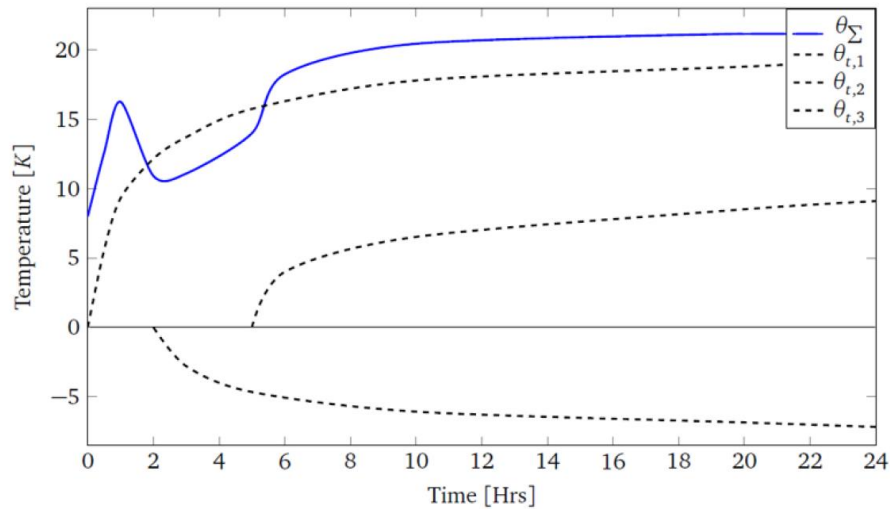


Figure 19 Complete transient temperature response with multiple load steps [37]

Similarly to previous studies [37], [38], the authors in [56] compare the measured temperatures in the conductors with results obtained using the IEC 60853-2 methodology [11], as well as through FEM simulations. The top of Figure 20 shows a comparison of the results obtained by the authors using the IEC standard methodology with those obtained experimentally, while the bottom part compares the measured temperatures with the results from FEM simulations.

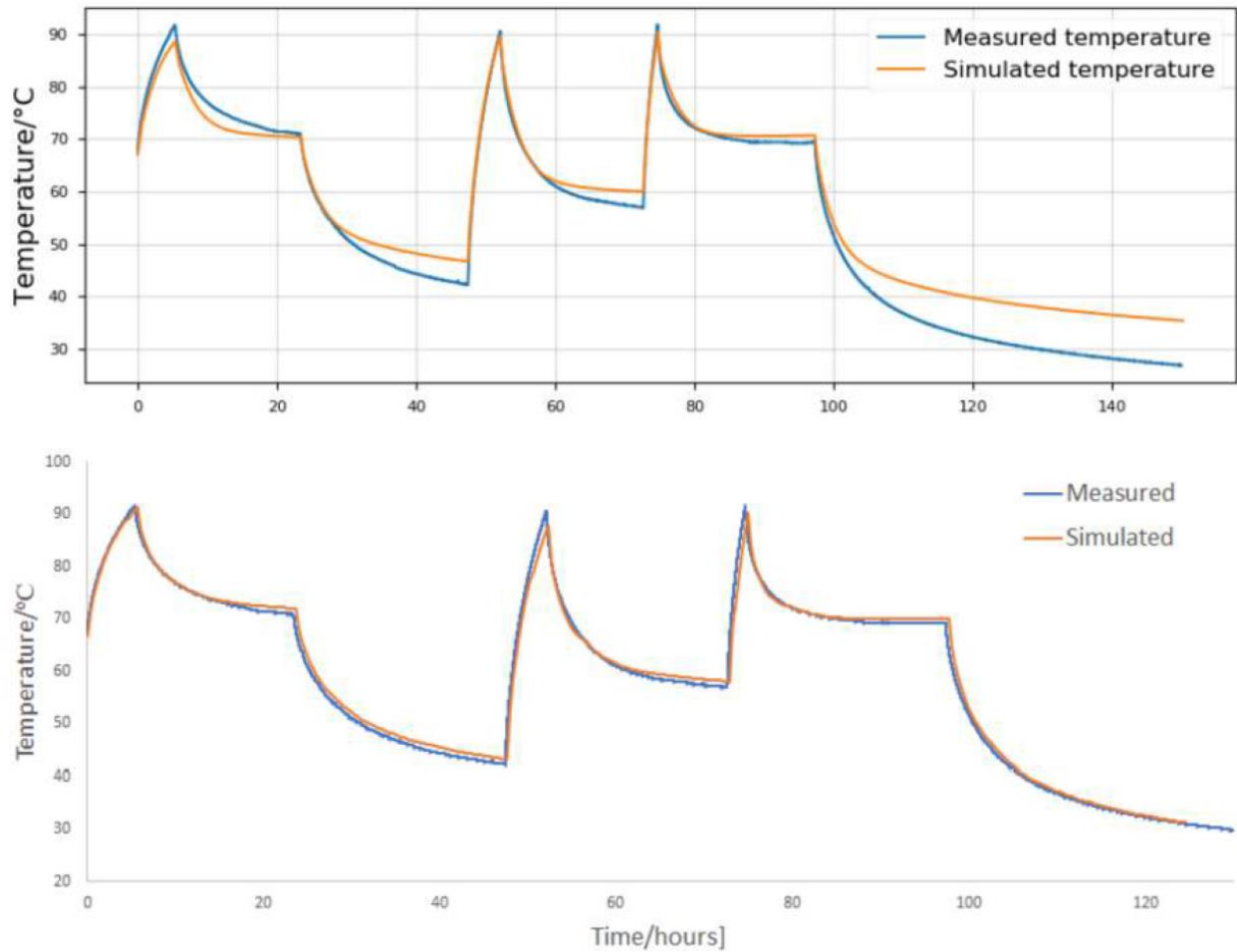


Figure 20 Comparison of the measured conductor temperatures with those calculated using the IEC 60853-2 method (top) and with results from FEM model simulations (bottom) [56]

Lastly, the final part of IEC 60853-2 [11] presents the calculation of emergency current-carrying capacity. This calculation begins with the assumption that a constant current, I_1 , flows through the cable over a long enough period to ensure steady-state conditions are reached. From this point, defined as $t = 0$, a higher current, I_2 , is applied for a specific period t . The IEC standard addresses the value of current I_2 such that the conductor temperature does not exceed a specified value at the end of period t , taking into account the variation in the conductor's electrical resistivity with temperature. The calculation of I_2 is given by:

$$I_2 = I_R \left\{ \frac{h_1^2 R_1}{R_{max}} + \frac{(R_R/R_{max})(r - h_1^2[R_1/R_R])}{\theta_R(t)/\theta_R(\infty)} \right\}^{1/2} \quad (11)$$

where r is the ratio $\theta_{max}/\theta_R(\infty)$, I_R is the continuous rated current with which the conductor reaches, without exceeding, the maximum permissible temperature, h is the ratio I_1/I_R , R_1 is the AC resistance of the conductor before applying the emergency current, that is, at the conductor temperature corresponding to I_1 , R_{max} is the AC resistance of the conductor at the end of the emergency load period, R_R is the AC resistance of the conductor under the continuous rated current I_R , at the maximum permissible temperature, θ_{max} is the maximum permissible temperature rise above ambient at the end of the emergency load period, $\theta_R(t)$ is

the temperature rise of the conductor above ambient after applying I_R , disregarding the conductor resistance variation, and $\theta_R(\infty)$ is the steady-state value of $\theta_R(t)$, representing the maximum permissible temperature rise of the cable. This method is valid when $I_2 \leq 2.5I_R$.

For the calculation of the emergency rating capacity (I_2) (Equation 11), it is necessary to consider the heating due to dielectric losses, disregarding any variation of these with temperature and calculating the permanent heating of the conductor $\Delta\theta_d$ due to these losses using the following equation:

$$\Delta\theta_d = W_d \left[\frac{1}{2} + T_1 + n(T_2 + T_3 + T_4) \right] \quad (12)$$

Once the value of $\Delta\theta_d$ is obtained, it should be deducted from θ_{max} , $\theta_R(t)$, and $\theta_R(\infty)$. The calculation of I_2 will be performed using the modified values of θ_{max} , $\theta_R(t)$, and $\theta_R(\infty)$, while the values of R_R , R_{max} , and R_1 , remain unchanged.

2.1.2.1.4 Simulation using finite element methods (FEM)

As discussed throughout this section, the simulation of power cables using FEM models is crucial for determining loss values across the various layers of the cable, understanding the thermal behaviour of submarine cables, and validating the different analytical models developed. FEM simulation of insulated cables can be divided into two types of studies: on the one hand, electromagnetic simulation, which aims to examine the cable's electromagnetic behaviour, and on the other, thermal simulation, which seeks to understand the cable's thermal performance under different operating conditions.

As previously indicated, calculating cable losses according to IEC 60287 [1] has been shown by various authors to be inaccurate [25], [40], [41], [42, p. 3], [43], [44], [45], [46], [47], [57]. For this reason, many publications employ FEM models to calculate losses in conductors, metallic screens, and armour of insulated cables, as shown in the previous example (Figure 15). From these studies, FEM modelling enables more reliable determination of cable losses, which can then be calculated analytically by adjusting the values obtained from the FEM model (Figure 16).

Another approach involves using an FEM model to validate the analytical proposals presented in each publication, as is the case with Method 1 described in CIGRE's TB 908 [25], or the partial element equivalent circuit (PEEC) formulation developed by Giussani et al. [58], [59], [60], [61] and Cambareri et al. [62].

A thermal FEM model is based on the geometry of the cable and the type of installation, making it possible to represent any of the different installation configurations through which an insulated cable runs [6], [41], [53], [63], [64], [65], [66], [67], [68], [69], [70].

Figure 21 [66] shows two geometries used in FEM models representing the cable directly buried (a) and resting on the ground (b). By varying the type of material in the fluid layer (blue layer) — either air or water — it is possible to represent the installation of the submarine cable on land or in the sea, respectively. The study of the ampacity of the submarine cable in different installation configurations enables obtaining the most restrictive value for the submarine line, as shown in [63], [66].

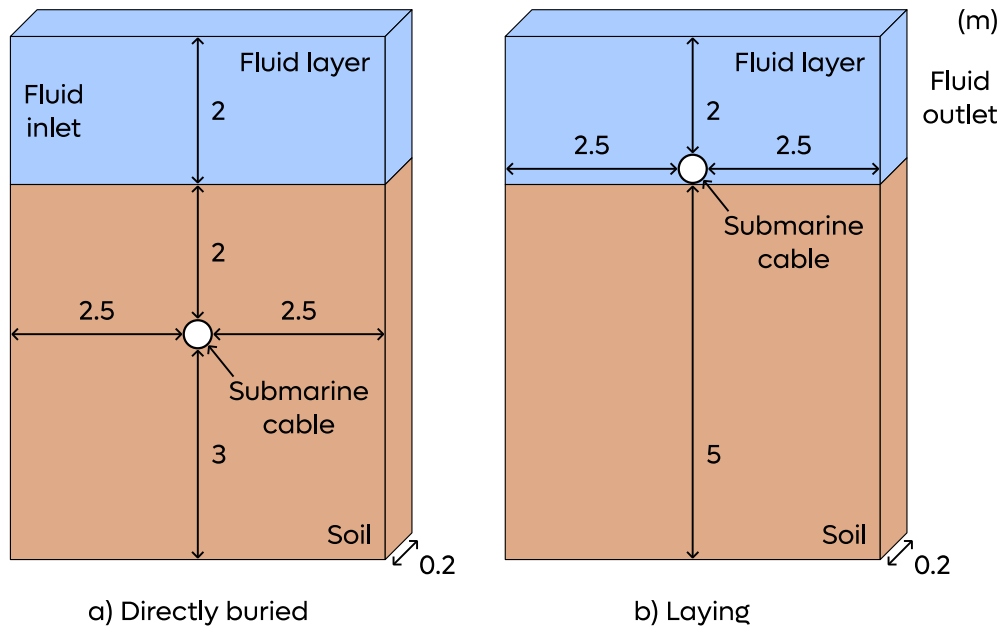


Figure 21 Geometries of a FEM model under different laying conditions: (a) directly buried; (b) laying on the ground (adapted from [66])

After generating the geometry, it is necessary to define the boundary conditions of the FEM model. These boundary conditions include isothermal zones, natural or forced convection at the air-soil, water-soil, cable-air, or cable-water interfaces (defined by the convective coefficient h and the ambient temperature of the air or water (θ_{amb}), radiation (defined by the emissivity of the cable surface), and the cable losses, represented by heat generation in the different cable layers. These losses are calculated using an electromagnetic FEM model or by applying the equations presented in Section 2.1.2.1.3.

An example of the boundary conditions established in a thermal FEM model is shown in Figure 16. In the FEM model, the isothermal or thermally insulated zones are defined on the sides and at the base of the geometry, located far enough from the cable so that cable losses do not affect their temperature. The top part of the model represents the interface between the seabed and the water, where forced convection conditions are applied through the convective coefficient and the ambient water temperature, as previously discussed. This same model could be used for a cable directly buried on land, with only the boundary conditions related to convection changing; in this case, natural convection and ambient air temperature would be applied.

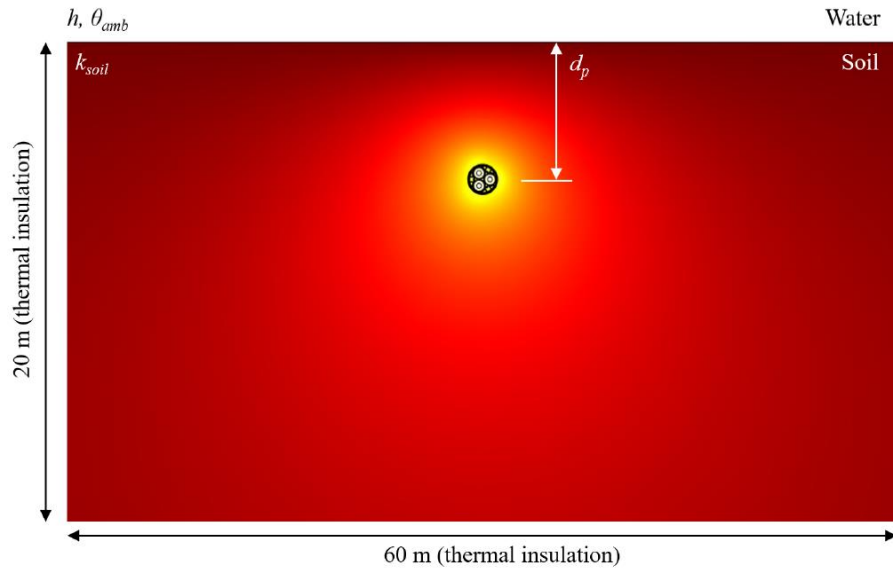


Figure 22 Boundary conditions established in the FEM model developed in [40]

Once the FEM model is defined, it becomes possible to study and simulate the thermal behaviour of the cable under numerous conditions. For instance, the thermal behaviour of the cable can be analysed in steady-state [41], [64] or in transient state [37], [40], [49] (Figure 23) under various cable load levels, observing the influence of burial depth, ambient temperature, or convective coefficient on conductor temperatures. Additionally, it is possible to study the thermal behaviour of the cable when modifying the thermal properties of the materials that make up the cable, with the goal of improving the manufacturing processes or examining how the thermal conductivity of the seabed affects the load capacity of the submarine cable.

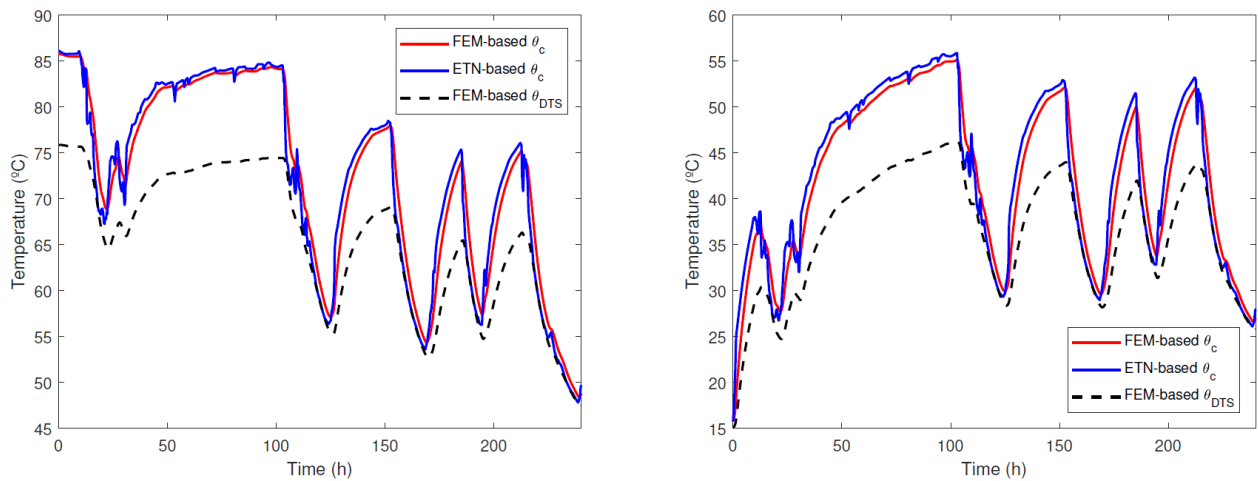


Figure 23 Estimation of conductor temperature results (θ_c) in [40]

FEM models are also used to simulate both electromagnetic and thermal behaviour in the joints of insulated cables [71], [72], [72], [73], [74]. As with the case of FEM models of cables, losses in the different layers of the cable can be calculated using the equations from Section 2.1.2.1.3 or from electromagnetic models. These models are conducted in 3D to obtain an accurate cable and joint model, which may lead to computer memory and convergence limitations [72], [73], other authors use 2D FEM models [54], and also, there are works in which possible defects in the joints are simulated [74], [75]. Figure 24 shows the structure of the 110 kV

insulated cable joint used by the authors in [54], and Figure 25 shows the steady-state temperature distribution at the joint.

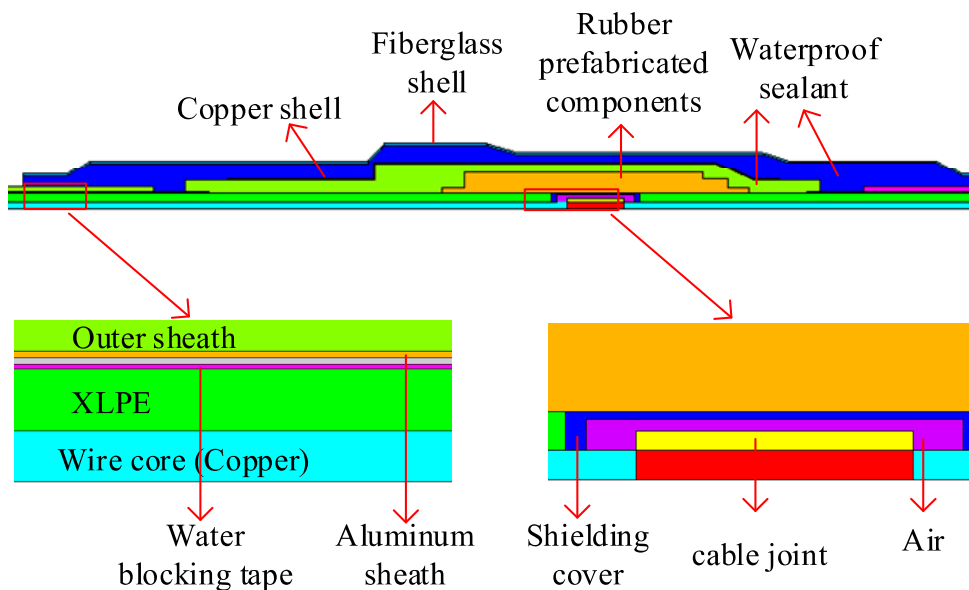


Figure 24 Structure of 110 kV cable joint [54]

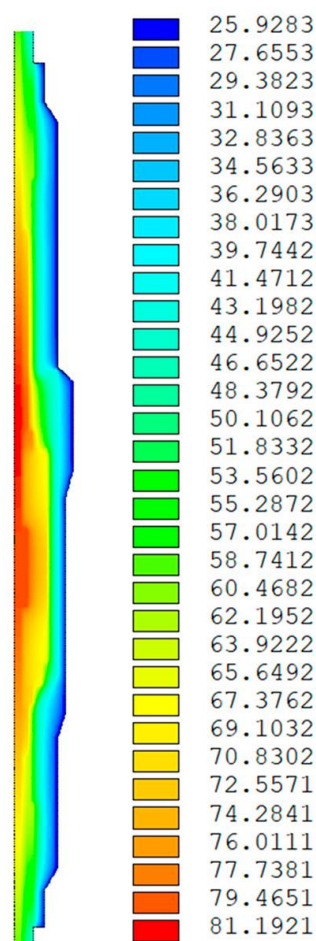


Figure 25 Steady-state temperature distribution of the cable joint [54]

2.1.2.2 Use cases, experimental data, and thermal models

The number of thermal models to be developed in WP5 (Predictive models for cable system ageing, life, and reliability) will be directly related to the different installations to be monitored. The project includes two use cases (WP8 - Integration of the different technologies, use cases, and assessment) and the development of a new HVDC cable (WP4 - Development of new, power-dense, and sustainable HVDC cable systems), which means the number of thermal models will be three, corresponding to the number of monitored installations. One of the use cases will involve an HVAC cable system belonging to STATNETT, while the other use case (ENERGINET) and the new cable development (NEXANS) will be HVDC cable systems.

The use case for the HVAC cable system will be a new 420kV cable system installation project (Øygardskabel 2), set to take place in the municipality of Øygarden in 2025. Øygardskabel 2 utilises a Cross-Linked Polyethylene (XLPE) 420kV AC underground cable system connecting Solsvik-N Blomøy, planned for installation in 2025. The cable system is approximately 15 km long and consists of 5 major sections (15 minor sections) in a cross-bonding configuration. The cable will be installed on four islands connected by bridges. It will be placed inside and beneath the different bridges connecting the four islands, as shown in Figure 26. The cable system will include a fibre-optic infrastructure to integrate the various sensor and monitoring technologies developed in the project, as shown in Figure 27. The system will initially operate at 300kV for the first few years and then at 420kV at a later stage. The type of cable to be used will be a 2500mm² Cu Enameled, XLPE 220/400(420) kV, with a maximum current at 90 °C, according to laying conditions, of 1925 A.

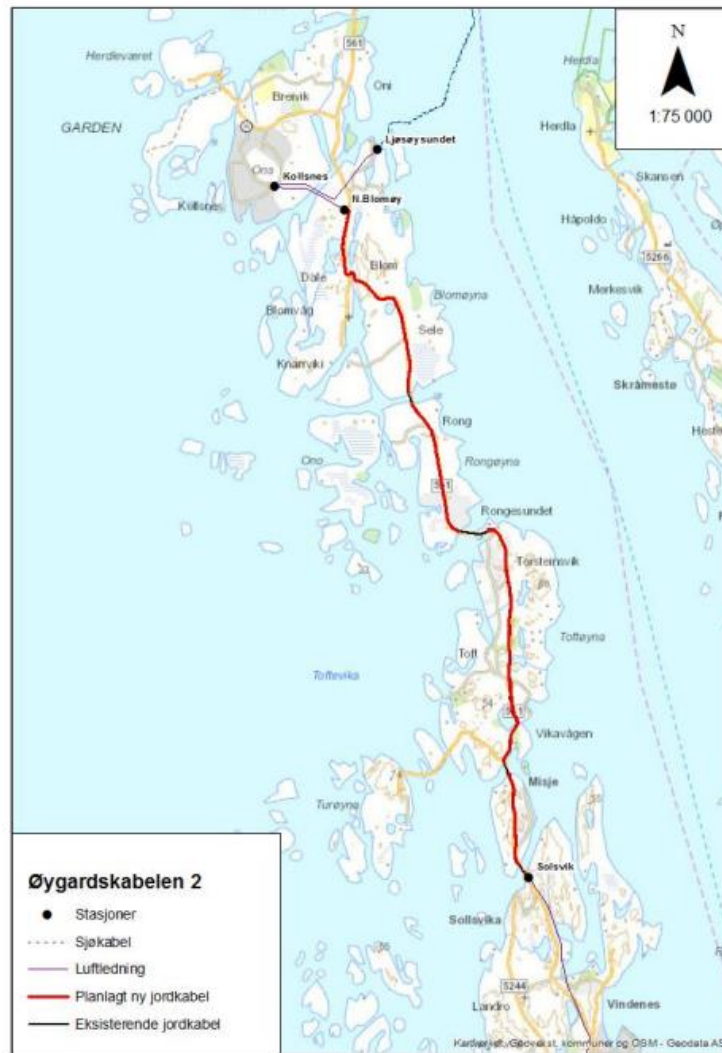


Figure 26 The Øygarden 2 project, connecting 4 islands with bridges [76]

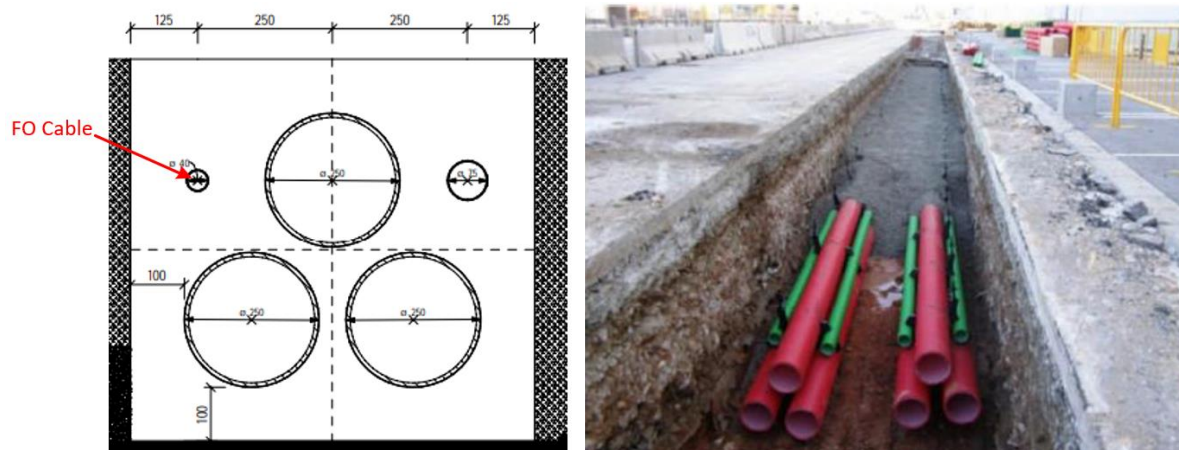


Figure 27 UG Cable cross section with FO cable [77]

The cable system will be monitored through various sensors integrated into the fibre-optic infrastructure that will be installed along the cable (Figure 27). The experimental data to be used in the thermal models will include:

- Ambient temperature data along different sections of the cable route.
- Cable load data over time, particularly under different operational conditions.
- Sensor data from various locations on the cable, providing temperature measurements at different depths, cable layers, and junction points.

The second use case will be the COBRACable belonging to ENERGINET. COBRACable is a 700 MW interconnector cable system from Denmark to the Netherlands, consisting of approximately 15 km of underground cable on the Danish side and 300 km of submarine cable. Figure 22 shows the cable route, where it is evident that the cable system on the Danish side is of a land-submarine-land-submarine type due to the crossing of the island of Fanø – the end termination is marked in red and the three transition joints are marked in purple. The COBRACable utilises a 320 kV, bipole HVDC, cross-linked polyethylene (XLPE) combined underground and submarine cable system connecting the Danish town of Endrup (substation EDR) with the Dutch Eemshaven substation. On the Danish land side (mainland and island), the cable system consists of 14 cable sections, each approximately 1500 m in length, 12 straight joints, 3 transition joints, and 1 end-termination joint. Figure 29 shows the different technologies and installation conditions of the interconnection cable between the Netherlands and Denmark.



Figure 28 Route of the COBRACable on the Danish side [78]

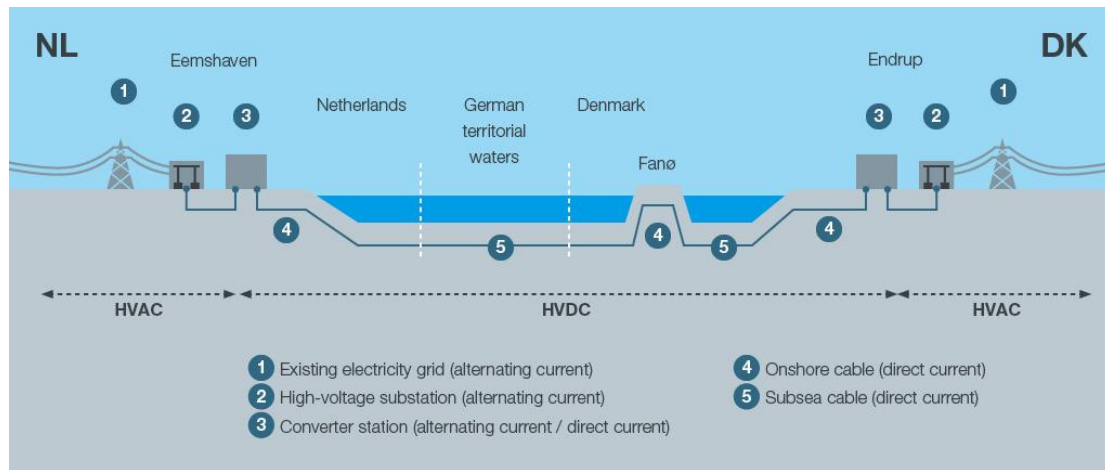


Figure 29 COBRACable diagram [79]

The data used in the thermal model of the COBRACable will come from the underground cable on the Danish side and the submarine cable, with sensors deployed along the cable route to capture the following parameters:

- Temperature data from the underground sections and the submarine sections, accounting for varying thermal conditions along both land and sea environments.
- Load data, including the operational parameters of the HVDC system.
- Transition joint temperature data and end-termination joint temperature measurements, as these are critical points for assessing the thermal behaviour of the system.

The last cable to be monitored will be the new HVDC cable developed by NEXANS in this project. In Deliverable D3.1 Cable system specification [80], the initial description of the cable design is presented together with the performance to be expected from the cables. The cable monitoring will take place during the qualification tests of the new HVDC cable at NEXANS' facilities. These tests will monitor the temperature reached by the cable under different load tests, as well as the temperature reached at the joints. The experimental data for the new HVDC cable model will be derived from:

- Temperature measurements of the cable and joints under different load tests.
- Data on the performance of the cable under various test conditions, including temperature at different points of the cable during operation.

According to the use cases and the new HVDC cable to be developed in the project, as well as the different locations of the monitoring sensors to be installed on them, the thermal models to be developed in WP5 are described in Table 5.

Table 5 Thermal modelling according to different use cases and scenarios

Thermal model	Use case	Cable system	Partner	Scenarios depending on cable/joint type/installation
Thermal Model Øygarden 2	Øygarden 2	HVAC	STATNETT	1. Cables installed in tubes in a trefoil formation 2. Cables exposed to air under bridges in a flat formation 3. Cables exposed to air under bridges in a trefoil formation 4. Joint bays
Thermal Model COBRACable	COBRACable	HVDC	ENERGINET	1. Land cables installed in tubes 2. Submarine cables 3. Transition joint
Thermal Model New HVDC Cable Nexans	New HVDC Cable	HVDC	NEXANS	1. Air-exposed cable protected from solar radiation 2. Joints

2.1.2.3 Analytical model

2.1.2.3.1 Hypothesis

The analytical model to be developed in WP5, in conjunction with the FEM thermal models, will calculate the heat losses in each of the cable layers. As indicated in Section 2.1.2.1.3, the first step outlined in the IEC 60287-1-1 [1] is to calculate the cable losses: conductor losses (Q_c [W/m^3] or W_c [W/m]), dielectric losses (Q_d [W/m^3] or W_d [W/m]), sheath losses (Q_s [W/m^3] or W_s [W/m]), and armour losses (Q_a [W/m^3] or W_a [W/m]). The calculation of the losses in the metallic screen and in the armour is made in relation to the losses in the conductors as $\lambda_1 Q_c$ and $\lambda_2 Q_c$ respectively.

Depending on the cable technology (HVAC or HVDC), different losses need to be calculated for the cables. For the calculation of conductor losses in HVDC cables, the resistance per unit length in direct current at operating temperature (R') is used, while for HVAC cables, the resistance per unit length in alternating current at the operating temperature (R) is used. Another aspect to consider is the dielectric losses, which are not present in HVDC cables but present in HVAC cables. The same applies to losses in the metallic screens and armour, which are only present in HVAC cables.

Both the DC resistance and the AC resistance are temperature-dependent, so the temperature of the conductors when calculating heat losses is a very important parameter. The analytical algorithms developed for each of the models will take this parameter into account.

2.1.2.3.2 Number of analytical models

The number of analytical models corresponds to the number of cable types and installation conditions used in the different use cases. Table 6 shows the analytical models according to different cable types and installation conditions of the use cases to be developed in WP5 and to be used in the FEM thermal models. For each type of cable and installation there must be at least one analytical model. For this reason, in the Øygarden 2 project, although there is only one type of cable, because there are different installation conditions, three analytical models must be developed to take into account the different installation conditions. One is for cables in ducts in a trefoil formation and the other two are for cables exposed to air in a flat or trefoil formation.

Table 6 Analytical models according to different cable types and installation conditions of the use cases

Analytical model	Use case	Cable system	Partner	Scenarios depending on cable type/installation
Analytical Model Øygarden 2	Øygarden 2	HVAC	STATNETT	1. Cables installed in tubes in a trefoil formation 2. Cables exposed to air under bridges in a flat formation 3. Cables exposed to air under bridges in a trefoil formation
Analytical Model COBRACable	COBRACable	HVDC	ENERGINET	1. Land cables installed in tubes 2. Submarine cables
Analytical Model New HVDC Cable Nexans	New HVDC Cable	HVDC	NEXANS	1. Air-exposed cable protected from sunlight

2.1.2.3.3 Inputs

The inputs for the development of the analytical models are similar to those used in the FEM thermal model (Section 2.1.2.4.4) and in the real time thermal rating (Section 2.2.2.2.2). These parameters for each high-voltage cable system are:

Circuit Data

- Circuit type (AC or DC)
- Circuit Frequency, if AC
- Line Voltage
- Current
- Sheath bonding

- Cable type name

Cable Data

- List of layers of the cable including properties of each layer
 - Layer name
 - Material type
 - Cross section of sheath/armour
 - Thickness
 - Outer Diameter
- Conductor temperature
- Phase-to-phase distance for single-core cable circuits
- Material properties
 - Thermal resistivity/conductivity
 - Dielectric loss tangent of the main insulator

2.1.2.3.4 Outputs

As indicated above, the output of these analytical models will be the losses in the different layers of the cable(s).

- **HVDC cables:** the point value of losses in the conductor will be obtained when a steady-state FEM thermal model is to be studied, or the evolution of losses in the conductor over time when a transient FEM thermal model is to be studied.
- **HVAC cables:** the losses in conductors, insulation, screen, and armour (if applicable) will be obtained in a point value for use in a steady-state FEM model, or the evolution over time of the losses in conductors, screen, and armour (if applicable) (the losses in the insulation are constant so it would not be necessary to recalculate them) when a transient FEM thermal model is to be studied.

2.1.2.4 Finite element method (FEM)

The Finite Element Method (FEM) is a key tool in the thermal analysis of electrical cables, allowing the simulation of heat distribution in complex multi-component systems. This type of model provides a detailed representation of the thermal interactions between the different parts of a cable, which is essential for evaluating the thermal behaviour under different operating conditions.

2.1.2.4.1 Hypothesis

The FEM thermal model must take into account the geometry of the cable, i.e. the spatial arrangement of its components (conductor, insulation, metal screen, armour, etc.). This includes both the material layers and the joints between the different elements. This approach makes it possible to simulate the thermal interaction between the different parts of the cable. In addition to the FEM model of the cable(s), FEM models of the joints, which are much more complex than those of the cables, are developed. These simulations will be used to study the thermal behaviour of each layer of a joint.

The model will include the thermal properties of the materials that make up the cable, such as thermal conductivity (how the material transfers heat), heat capacity (how the material stores heat) and density. These properties vary depending on the type of material, so obtaining and selecting the values to be used in the model is crucial for accurate modelling.

Depending on the properties of the materials and the conditions to which they are subjected, the thermal behaviour of the system can be linear or non-linear. For example, as discussed above, the resistance of the conductors used to calculate the losses in the conductors, metal screens, and armour are temperature-dependent. The FEM model must consider these possible non-linearities in order to correctly represent the thermal effects under different load and temperature conditions.

2.1.2.4.2 Methods and physical events

The cable will be modelled to ensure that all layers comprising the cable are accurately represented. Additionally, the cable's surrounding environment will be modelled according to the different installation conditions. Each layer of the cable, as well as each element of the environment, will be defined with its specific thermal properties, such as thermal conductivity and heat capacity, which may be temperature-dependent.

The FEM model solves the equations of heat conduction, convection, and radiation in both steady-state and transient regimes. In the steady-state regime, the temperature distribution is determined under constant load conditions, whereas in the transient regime, the changes in temperature over time in response to load variations or external condition changes are evaluated.

In the FEM model, the heat losses calculated analytically in the conductor, insulation, metallic screen, and armour (if applicable) will be incorporated as an internal heat source. Since these losses are temperature-dependent, it is necessary to run an iterative loop between the analytical model and the FEM model until the results converge.

2.1.2.4.3 Number of FEM models

According to the use cases and the new HVDC cable to be developed in the project, as well as the different locations of the monitoring sensors to be installed on them, the FEM thermal models to be developed in WP5 are described in Table 5 of Section 2.1.2.2.

2.1.2.4.4 Inputs

The inputs for the development of the FEM models are similar to those used in the real time thermal rating (Section 2.2.2.2). These parameters for each high-voltage cable system are

Cable/Joint Data

- List of layers of the cable including properties of each layer
 - Layer name
 - Material type
 - Number of elements per layer and their cross-section (conductor, sheath, and armour)
 - Pitch length and lay direction (conductor, sheath, and armour)

- Thickness
- Outer Diameter
- Material properties
 - Thermal resistivity/conductivity
 - Specific heat capacity
 - Density
 - Emissivity

Thermal Section Data

- Cross-section drawing (example shown in Figure 36), including:
 - Material types (thermal resistivity, specific heat capacity, and density if not standard materials) for all elements such as pipes, pipe medium, backfill, native soil etc
 - All geometry parameters including cable laying depth, dimensions of environment materials (width and height of backfill layers etc)
 - Dimensions (inner and outer diameter) of pipes and ducts, also sensor ducts if used
 - Phase-to-phase distance for single-core cable circuits; if multiple circuits are present, circuit distance as well
 - Indication of the fibre optic sensor position(s)

2.1.2.4.5 CAD model

From the input data of the cable(s) and the environment, the geometry of the model is generated, either using the simulation software itself or through other CAD software.

For FEM models of cables, the geometry of the model is 2D, given a small thickness, to which linear periodic symmetry is then applied. This linear periodic symmetry is used to simulate translationally symmetric models, where the structure is assumed to repeat infinitely in a particular direction. The thickness assigned to the geometry is necessary for creating the linear periodic symmetry.

As indicated in Section 2.1.2.1.4, the geometries used in FEM models of joints can be either 2D or 3D. For a detailed and accurate FEM model of the joints, 3D geometries will be used.

2.1.2.4.6 Mesh type

As indicated in Section 2.1.1.5.7, meshing used in an FEM model is a crucial factor in ensuring the accuracy of thermal or electrical simulations. The choice of mesh type and its resolution directly impacts the model's ability to capture thermal variations, especially in critical areas such as joints and regions of high thermal dissipation. Section 2.1.1.5.7 also discussed the different types of meshing based on element types, mesh density, and adaptive meshing.

As noted, the FEM model of the cable will be 2D, with a thickness added to apply linear periodic symmetry, so for meshing purposes, the geometry is considered 3D. With this in mind, the meshing of both the cable models and the joints will use a mesh composed of tetrahedral elements, providing greater flexibility to adapt to complex geometries. The mesh resolution should be adjusted according to the areas of most thermal interest. High thermal dissipation areas, such as near the conductors or material interfaces, require a higher-density mesh to

correctly capture thermal variations. The node density should be sufficiently high in these critical points to ensure that temperature gradients are well represented in the simulation. The mesh should be refined in these critical areas to ensure that the thermal simulation can accurately capture temperature variations, allowing for precise modelling of both transient and steady-state thermal phenomena.

One aspect not addressed in the CAD model is that all bodies forming the geometry of the model must be part of a single part (geometry composed of multiple bodies in a part). This will ensure that all bodies are meshed together, or in other words, the faces of two bodies in contact will form a single shared face between the two bodies.

2.1.2.4.7 Boundary conditions

The boundary conditions available in either steady-state or transient thermal analysis are shown in Table 7. As discussed throughout this document, for losses in conductors, insulation, metal screen and armour (if applicable), the **internal heat generation** boundary condition is used, in units of W/m^3 . For surfaces in contact with air, **convection** and **radiation** are used as boundary conditions. It is necessary to define the convective coefficient and ambient temperature for convection and the emissivity and ambient temperature for radiation. When the FEM model involves a submarine cable/joint, convection is also applied as a boundary condition for the surfaces in contact with the water. In this case, the ambient temperature and the convective coefficient are also defined, with the latter being set to a high value to simulate marine currents. The boundary conditions of the surfaces farthest from the cable/joint are defined as either **perfectly insulated** or assigned a constant **temperature**, as their distance from the cable/joint being simulated means they have no effect on it. In transient FEM models, it is sometimes necessary to define a **temperature** boundary condition at the start of the simulation for certain elements of the model. This is done to ensure that the model reaches the desired initial thermal state before beginning to analyse transient changes. This condition allows the model to stabilise and reach the correct initial state, ensuring that simulations of temperature variations over time are based on a realistic starting point.

Table 7 Boundary conditions available in thermal analysis in ANSYS [81]

Boundary Condition	Definition	Parameter	Units
Internal heat generation 	Applies a uniform generation rate internal to a body.	Energy per unit time per unit volume (Power per unit volume)	W/m^3

Boundary Condition	Definition	Parameter	Units
Convection 	Causes convective heat transfer to occur through one or more flat or curved faces (in contact with a fluid).	Convective coefficient	$W/m^2 \cdot ^\circ C$
		Ambient temperature	$^\circ C$
Radiation 	Applies thermal radiation to a surface of a model (an edge in a 2D model). The exchange of radiation between a body and the ambient temperature or between two surfaces can be defined.	Emissivity	-
		Ambient temperature	$^\circ C$
Temperature 	Simulates a uniform, time-dependent, or spatially varying temperature over the selected geometry.	Temperature	$^\circ C$
Heat flow 	Simulates the transmission of heat across flat or curved surfaces or edges or across a vertex or vertices and as a result adds energy to a body over time.	Heat flow	W
Perfectly insulated 	Specifies a perfectly insulated load wherein a "no load" insulated condition is applied to the Face: that is, zero heat flow. The heat flow rate is 0 across this face.	-	-

Tables 8, 9, and 10 show the different boundary conditions to be applied to a buried cable (terrestrial or submarine), a cable exposed to air, and a cable in a duct (terrestrial or submarine), respectively. As can be seen, the internal heat generation and temperature/perfect insulation boundary conditions are similar in both FEM models. The convection and radiation boundary conditions and their surface areas differ between the three models.

Table 8 Boundary conditions used in the FEM model of a buried cable (terrestrial or submarine)

Boundary Condition	Application	Part of the Model
Internal heat generation 	Volume	Conductor (Q_c)
		Insulation (Q_d) (if applicable)
		Metallic sheath (Q_s) (if applicable)

Boundary Condition	Application	Part of the Model
		Armour (Q_a) (if applicable)
Convection 	Surface	Land surface in contact with air (land cable) or seabed surface in contact with water (submarine cable)
Temperature / perfectly insulated 	Surface	Bottom, left, and right sides of the model, representing the land or seabed

Table 9 Boundary conditions used in the FEM model of an air-exposed cable

Boundary Condition	Application	Part of the Model
Internal heat generation 	Volume	Conductor (Q_c)
		Insulation (Q_a) (if applicable)
		Metallic sheath (Q_s) (if applicable)
		Armour (Q_a) (if applicable)
Convection 	Surface	Cable surface in contact with air
		Land surface in contact with air
Radiation 	Surface	Cable surface in contact with air
Temperature / perfectly insulated 	Surface	Bottom, left, and right sides of the model, representing the land and the air

Table 10 Boundary conditions used in the FEM model of a cable in a duct (terrestrial or submarine)

Boundary Condition	Application	Part of the Model
Internal heat generation 	Volume	Conductor (Q_c)
		Insulation (Q_d) (if applicable)
		Metallic sheath (Q_s) (if applicable)
		Armour (Q_a) (if applicable)
Convection 	Surface	Cable surface in contact with air (land cable) or water (submarine cable)
		Inner surface of the tube in contact with air (terrestrial cable) or water (submarine cable)
		Land surface in contact with air (land cable) or seabed surface in contact with water (submarine cable)
Radiation 	Surface	Cable surface in contact with air
		Inner surface of the tube in contact with air
Temperature / perfectly insulated 	Surface	Bottom, left, and right sides of the model, representing the land or seabed

2.1.2.4.8 Simulation results

Once the FEM model has been defined, taking into account the points discussed above, it is time to run the simulation and observe the results. Depending on the type of thermal analysis performed, steady-state or transient, different temperature results will be obtained. The main difference between the two analyses is that the steady-state result will be a single temperature value/distribution, whereas the transient result will be a temperature value/distribution over time.

As mentioned above, one of the results of the simulations is the temperature distribution in the model geometry, as shown in Figure 30. With this temperature distribution it is possible to see at a glance how the thermal behaviour of the cable varies when any parameter of the cable or the environment is modified.

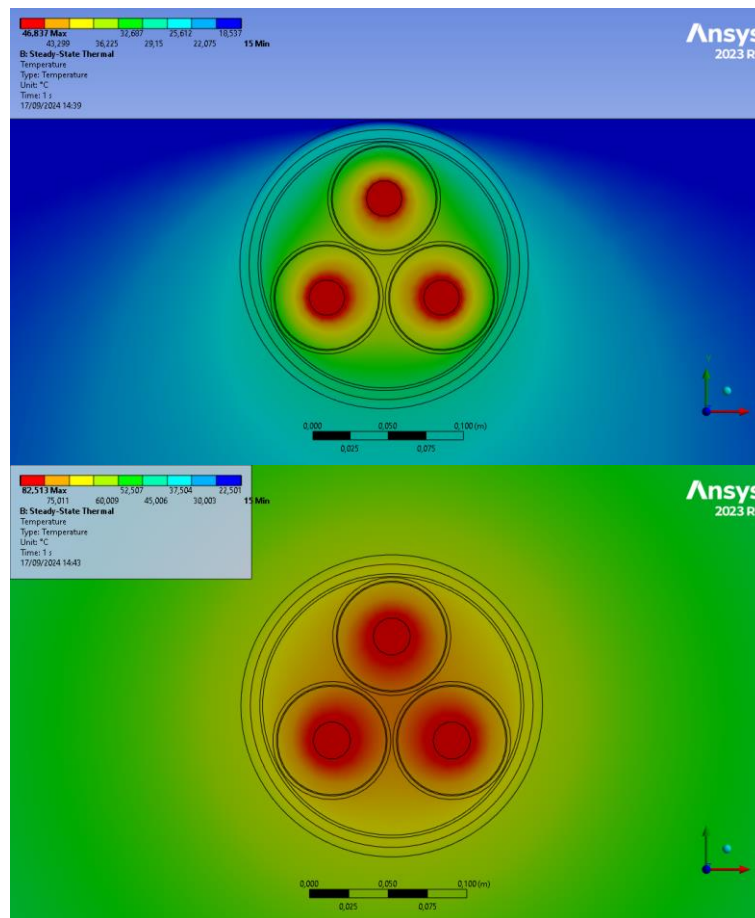


Figure 30 Temperature distribution in a steady-state analysis of a submarine cable for different burial depths

Although the results of the temperature distribution in the geometry of the model are very visual and easy to check, the most important feature of this type of simulation is to obtain the temperature values at critical points of the cable, for example the temperature reached by the insulation in contact with the conductor(s). Once the FEM model has been simulated, it is possible to place a probe object at any point on the geometry (Figure 31) that calculates the temperature at that point, either pointwise for a steady-state analysis or time-varying for a transient. Figure 32 shows the result of one of these probes in a transient analysis.

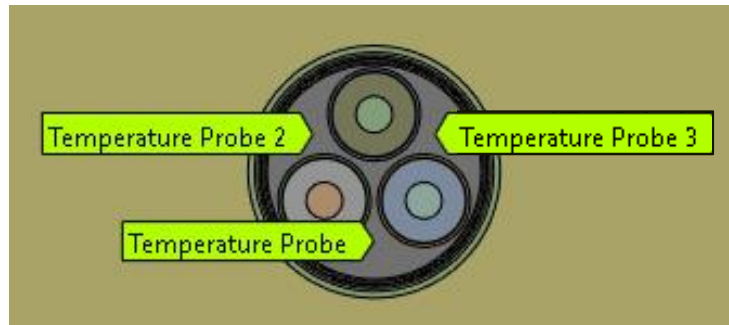


Figure 31 Example of the location of temperature probes in a FEM model at the position of the optical fibres of a submarine cable.

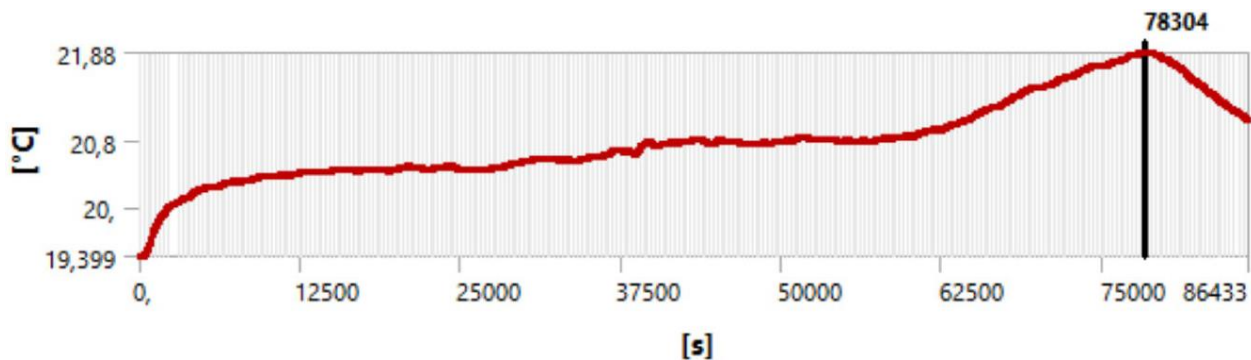


Figure 32 Probe temperature result in a transient analysis

2.1.2.5 Integration of analytical and FEM models and experimental data – Thermal model validation

Sections 2.1.2.3 and 2.1.2.4 have explained separately the analytical and FEM models to be developed in WP5 for the different use cases and the new HVDC cable. This section shows how the analytical and FEM models will be related to the monitored experimental data of the cable systems and how the validation of the thermal models will be performed.

Figure 33 shows the flow chart of the analytical and FEM models with the experimental data. Based on the cable system data and its installation conditions, both the analytical model and the FEM model will be developed. The analytical model will provide the losses in the different components of the cable, which will be used in the FEM model as boundary conditions (internal heat generation). Since the losses in the conductors depend on their temperature, it will be necessary to establish an iterative loop between the FEM model and the analytical model until the results converge. In parallel, the monitored current data will be used by the analytical model, and the monitored ambient temperature data will be used by the FEM model.

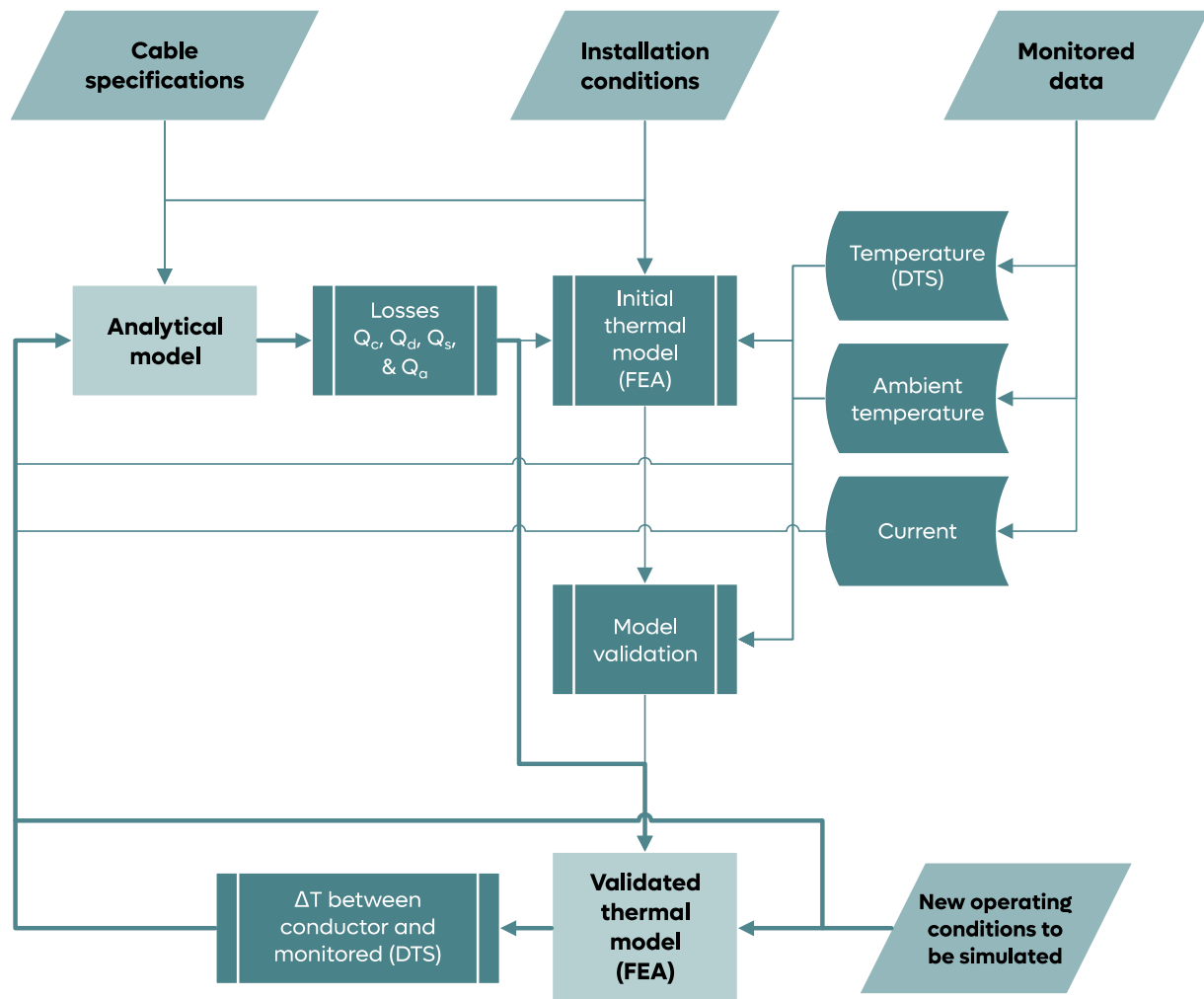


Figure 33 Flowchart of the integration of analytical and FEM models with experimental data

Once the simulation results are obtained, after the iterative loop between the analytical and FEM models, it is time to compare them with the experimental temperature data from the cable system. Ideally, it would be best to compare the simulated and experimental temperatures of the conductors. However, this is quite rare since the cable systems installed or to be installed (use cases) do not typically monitor conductor temperatures. Therefore, the temperature results from the probe in the FEM model, positioned at the same location as the monitored temperature using DTS, will be compared with the experimental data.

After completing the comparison, the next step is to fine-tune the model parameters to bring the simulation results closer to the actual temperature measurements. This process must take into account that any adjustments made will affect multiple simulations, each subject to different environmental conditions and load scenarios for the cable system. It is essential that these variables are taken into account to ensure the accuracy of the model over a wide range of operational contexts. Through iterative refinement, the model is optimised to accurately reflect the thermal behaviour of the cable system under varying conditions. When the difference between the simulated temperature and the actual measured temperature is sufficiently small to be practically negligible, the FEM model is considered validated. This process ensures that the thermal model accurately represents real world conditions. The

validation phase is critical as it confirms the reliability of the model in predicting temperature distribution under varying operational scenarios. By achieving this level of accuracy, the validated FEM model can be confidently used for future simulations, enabling accurate thermal analysis and optimised design considerations for cable systems and joints.

The integration process between the analytical and FEM models with the monitored data will be conducted for all the thermal models defined in Section 2.1.2.2. The objective is to develop and validate a thermal model for each of these cable systems to ensure that the models accurately reflect the real world thermal performance based on the monitored data.

2.2 Algorithms

2.2.1 Aging

2.2.1.1 State-of-the-art

Cross-linked polyethylene (XLPE) cables are widely used in DC transmission lines. This type of cables possess a great insulation performance, which makes them an excellent candidate for transmission applications [82]. However, this insulation degrades over time. One of the hottest topics in the power system is the detection of insulation degradations before the cable failure occurs. Several methods have been proposed to address this issue: (i) dielectric loss factor ($\tan \delta$) method, (ii) partial discharge detecting method and (iii) temperature measurement method, among others [83]. Additionally, aging detection based on machine learning (ML) has been also started to develop, as it can make models that can detect insulation degradations on the cable [84].

Machine learning is a field of study in artificial intelligence (AI) that allows computers to learn without being explicitly programmed. The most common types of ML are supervised learning and unsupervised learning. In supervised learning, data is labelled, and the purpose of the system is to generalize a pattern, between the entry and the expected exit, so that it may function well in cases where they are not in the training group. Although it's an effective form of learning, it's not suitable to learn from interaction. On the other hand, unsupervised learning consists in finding a pattern of unlabelled data, in which case the output is unknown.

There are several types of ML techniques such as Decision Trees (DT), Logistic Regression (LR), Support-vector Machines (SVM), Naïve Bayes (NB) and Artificial Neural Networks (ANNs), among others. All of them are part of supervised learning. These methods allow to deduce patterns from data and build automatic inference systems [85].

These techniques can perform univariate or multivariate data analysis. In univariate analysis, each observation point corresponds to a single variable. In other words, it involves the measurement or observation of a single characteristic or attribute for each individual or item in the dataset. On the other hand, multivariate analysis each observation point is composed of two or more variables. These variables can represent different aspects, characteristics, or measurements related to the observed phenomenon. Sometimes, when performing multivariate analysis, it is necessary to adequate the different types of variables (qualitative, quantitative, etc.) to be able to train the ML algorithms.

Firstly, Logistic Regression (LR) is used to estimate the probability that an event will occur or, in the electrical field, that a cable will have a particular outcome using, usually, intensity and voltage data. LR is based on a mathematical model that computes the just mentioned probabilities.

Secondly, a Support-vector Machine (SVM) consists on a linear separator between two differently annotated groups of data points that serves to identify two different classes in a multidimensional environment [86]. In case the problem to deal with has more than two classes, it must be reduced to a set of multiple binary classification problems. Some of the advantages of SVMs are (i) little probability of overfitting, (ii) high accuracy in their task and (iii) the fact that they can be used both for classification and prediction [87]. Nevertheless, SVM algorithms are considered black-box techniques which means their internal procedure is complex to understand and therefore the reasoning behind the algorithm cannot be easily traced. The regression algorithm associated with SVMs is the Support Vector Regressor, in which the function that best approximates the evolution of the input data is found. In the case of SVR, the function is given by the hyperplane containing most of the points. Figure 34 shows a regression result using SVM.

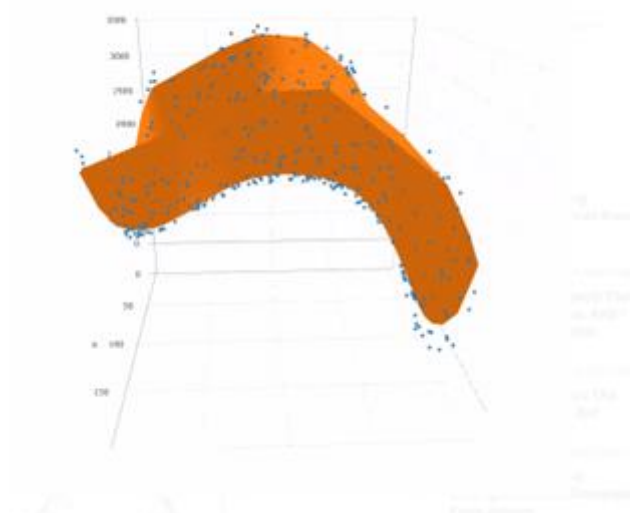


Figure 34 Regression result using Support Vector Machine

Decision trees are tree-like models that can be used both for classification and regression tasks too. They are formed by nodes, branches and leaves, where nodes represent attributes where data is split into two or more branches, whose end is called a leaf [88]. One of the main advantages of trees is their easy interpretation.

KNearest Neighbours Regressor approximates a function that associates the independent variables with the dependent variables without the need for parameters from a mean of the observations present in the same group or neighbourhood. The size of the groups is selected by cross-validation so as to minimise the mean squared error [89]. The figure below shows how increasing the size of the clusters gives a much more accurate result.

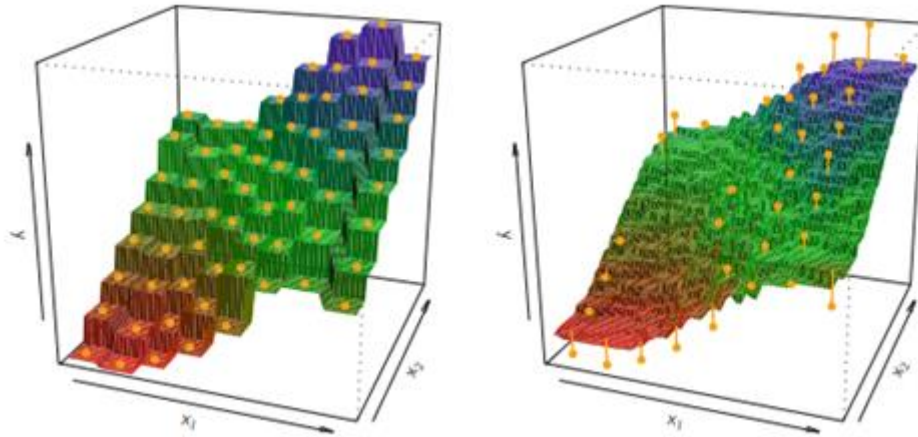


Figure 35 Result of KNN with group size 1 (left) and group size 9 (right).

Lastly, Bayesian networks (BN) are probabilistic models that represent variables and their conditional dependencies in a directed acyclic graph (DAG) [90]. It has been discussed that to build an effective BN model a combination of data and expert knowledge is required [91]. However, there have been many models that, in practice, have been built either learning purely from data or using solely expert knowledge [92]. In Bayesian networks the knowledge is modelled as a set of conditional probabilities and inference is made musing those probabilities. Bayesian networks rely on the Bayes' Theorem, which describes how to update the probabilities of hypotheses when given evidence.

2.2.1.2 Methodology

The proposed method is based on ML techniques. The outputs of the FEA models developed by RDT and UCA will serve as input data for the planned aging algorithm. The algorithm shall predict the remaining life of the cable based on different factors previously specified. The execution of the algorithm may be planned once a fixed time period, so it would give the remaining life capacity of the cable before it fails. In case the remaining life capacity is lower than a previously specified value, an alarm should be given so that the cable operator could make a decision about it and replace it, in case it is necessary.

After reading the existing literature presented on the section above, several ML methods will be considered to develop the algorithm. Each one's performance will be calculated the same way, so in this way it will be easier to see which one has performed best.

Before training the algorithm, data exploration shall be done. Data exploration consists of preprocessing and cleaning data. Usually, given data is not optimal to work with it. On the one hand, the data provided will be analysed and it will be decided which data can be used for the generation of the models by analysing the relationship between them. This is done by using a correlation matrix.

The correlation matrix measures the degree of linear relationship between each pair of elements or variables using Pearson's correlation values. These values are between -1 and 1, with variables with a relationship greater than 0.7 or less than -0.7 being considered highly correlated.

On the other hand, a data cleaning and adaptation process will be carried out, in which the data used will be adapted to be used as input for the models, eliminating possible erroneous data and adding new data from the combination of existing data.

In fact, accuracy, precision, recall and F1-score are the most used metrics to evaluate algorithms. In addition, the ROC curve can also be plotted to see in a graphical way each algorithm's performance:

Accuracy: is a metric that measures how often a machine learning model correctly predicts the outcome.

$$Accuracy = \frac{TP + TN}{TP + TN + FP + FN}$$

Precision: is a metric that measures how often a machine learning model correctly predicts the positive class.

$$Precision = \frac{TP}{TP + FP}$$

Recall: it is measured on the scale of 0 to 1 as a percentage. The higher the recall the better the model is. If a perfect recall (1.0) is achieved the model can find all instances of the target class in the dataset.

$$Recall = \frac{TP}{TP + FN}$$

F1-score: it provides a balanced measure of a model's precision and recall. This metric is particularly useful in scenarios where class distributions are imbalanced.

$$F1 = 2 * \frac{Precision * Recall}{Precision + Recall}$$

ROC curve: This curve is plotted using the True Positive Rate (TPR) and False Positive Rate (FPR) of the model. The Area Under the Curve (AUC) quantifies the performance of the model.

$$TPR = \frac{TP}{TP + FN} \quad FPR = \frac{FP}{FP + TN}$$

After training and testing every algorithm, each one of these metrics will be calculated. This will serve as a determination to decide which is the algorithm with the best performance.

2.2.1.3 Inputs

The aging algorithm should receive the inputs resulting from the SPC model previously developed. The model developed by RDT will receive different operation modes or environmental conditions as inputs and will try to determine whether partial discharges will appear or not. In the cases that partial discharges arise, the model could give their amplitude and frequency. As the inputs for the developing of the model are variable, a maximization of the partial discharges of the cable could be searched in order to have more data to train the algorithm.

The algorithm may try to reverse this process. Receiving the partial discharges measured by the installed sensors as inputs, it might give the conditions of the cable based on those inputs. The partial discharges could be characterized differently according to different factors such as overvoltage or the aging of the cable.

2.2.1.4 Outputs

Due to the innovative character of the algorithm, the actual outputs may vary of the expected outputs of the algorithm. Therefore, several possibilities are presented:

Scenario 1. In this scenario, the output of the algorithm is a remaining life percentage of the cable. This could be established as an absolute value or percentage ranges. This would suppose to establish some ranges and classify the outputs of the algorithm according to them. For instance, a possible output could be ratios of 20% each so the output could be 0%, 20%, 40%, 60%, 80% and 100%.

Scenario 2. The second scenario would reduce the possible outputs of the algorithm. In this case, three different groups would be specified: healthy, damaging and broken. This may be subject to changes to obtain a better result of the algorithm.

2.2.1.5 Results and validation

To validate the algorithm, the RDT model could be also used. This model is designed to detect partial discharges, a critical indicator of insulation degradation and potential faults in electrical systems. Similarly, the developed algorithm is planned to be able to identify partial discharges, analyzing signal patterns to pinpoint these occurrences with precision. By comparing the outputs from both the RDT model and the algorithm, we aim to assess their alignment and consistency in detecting partial discharges. This comparison is crucial to validate the reliability and accuracy of our algorithm against the established RDT model, helping us refine detection processes, reduce false positives, and ultimately ensure the safety and efficiency of the electrical systems being monitored.

2.2.2 Real time thermal rating (RTTR)

2.2.2.1 State-of-the-art

Due to the increasing demand of electricity and the limitation capacity of transmission lines conductor temperature forecasting is an essential part of an efficient power system [93]. If this temperature can be predicted, it could be used as a reference for calculating the capacity of the cable to transport the power without incurring into a problem. Some of the techniques used to predict this temperature are Finite Element Models (FEM), Kalman filters or Neural Networks [94], [95].

Kalman filters are recursive algorithms designed to estimate the state of a dynamic system from noisy and uncertain measurements. They operate in two primary phases: prediction, where the next state is estimated using a thermal network model, and update, where the prediction is refined based on real-time temperature sensor data. These real-time data are measured values, they are subject to noise. Due to their ability to provide accurate, dynamic state estimation while accounting for uncertainties and noise of input data, Kalman filters have emerged as one solution among other methodologies for RTTR,

Artificial Neural Networks (ANNs) are computer programs inspired by biology and designed to mimic the way the human brain processes information [96]. They are composed by neurons, which are interconnected between each other. These neurons receive data as input and they are trained using a learning process. Once trained, they may be used to predict outputs for

new data. Neural networks are made up of interconnected layers, which in turn are made up of processing units (neurons). A neural network usually consists of three parts: an input layer, one or more hidden layers and an output layer. The input layer is the one that receives the input data, and the output layer is the one that gives the prediction made by the model. Between those two layers are the hidden layers, which are the ones in charge of updating the weights of the connection that exist between the different layers. The network's last layer is the output layer. This layer is the one that gives the model's result, i.e., the prediction. When talking about time series prediction, the output layer is composed of as many neurons as the number of time steps to be predicted.

Recurrent Neural Networks (RNNs) are a type of neural network that have recurrent connections, meaning that outputs from previous layers are fed back to previous layers, allowing them to maintain state information throughout the sequence. This makes them particularly suitable for processing sequential data, such as time series. Nevertheless, traditional RNNs can suffer from a problem known as *vanishing* or *exploding gradient*, which can negatively affect their ability to learn long-term patterns in sequential data. This is where LSTM and GRU architectures offer effective solutions. This kind of networks has been widely used for both natural language processing and time series prediction due to their ability to remember information over long periods of time [97], [98].

2.2.2.2 Cable thermal rating

2.2.2.2.1 Methodology

Generally, RTTR for cable ratings is based on a physical model of the cable and its environment.

The basic idea of a dynamic model-based conductor temperature monitoring system has already been described in an IEEE paper in 1979 [99]. This paper proposed to use a state-space formulation, a thermal ladder network model and a Kalman Filter. A similar general approach for conductor temperature calculation is in RTTR.

In addition to conductor temperature, RTTR also calculates steady-state ampacity and transient ratings. To calculate dynamic ratings, temperature predictions are internally made for varying load values and a root-finding algorithm is used to determine the load related to a pair of prescribed values of (1) time ("emergency period") and (2) final conductor temperature.

The physical problem of heat transfer from an underground power cable systems can often be treated as two-dimensional.

However, beyond very simple situations, the approach to solve this problem using a one-dimensional thermal network model would only provide approximate solutions. Therefore, RTTR combines one-dimensional thermal network models with stationary and transient 2d Finite Element simulations and model parameter tuning via evolutionary algorithms. Guidance for cable modelling is provided by IEC 60287, IEC 60853 and CIGRE Technical Brochure 880 "Power cable rating examples for calculation tool verification".

2.2.2.2.2 Inputs



The RTTR software applies model-based conductor temperature calculation which requires a detailed model of the power cable as minimum input. In addition, details of the environment in which the cable is installed need to be available as inputs for calculating the steady state ampacity and the transient rating. The required inputs can be divided into the three categories circuit data, cable data and thermal section data. These must be provided for each high voltage cable system for which RTTR shall be deployed.

Circuit Data

- Circuit type (AC or DC)
- Circuit Frequency, if AC
- Line Voltage
- Sheath bonding
- Cable type name
- Sensor position (position of the optical fiber to be used by the DTS), possible are:
 - Internal with specification in which layer fiber is located
 - Attached to power cable
 - Remotely with a distance to power cable

Cable Data

- List of layers of the cable including properties of each layer
 - Layer name (e.g. Conductor)
 - Material type (e.g. Cu)
 - Cross section of sheath/armour
 - Thickness
 - Outer Diameter
- Maximum conductor temperature
- Maximum Insulation Temperature Drop (ITD)
- Cable data sheet
- Fiber optic sensor cable and data sheet

Thermal Section Data

- Cross-section drawing (example shown in Figure 36), including:
 - Material types (thermal resistivities if not standard materials) for all elements such as pipes, pipe medium, backfill, native soil etc
 - All geometry parameters including cable laying depth, dimensions of environment materials (width and height of backfill layers etc)
 - Dimensions (inner and outer diameter) of pipes and ducts, also sensor ducts if used
 - Phase-to-phase distance for single-core cable circuits; if multiple circuits are present, circuit distance as well
 - Indication of the fiber optic sensor position(s)

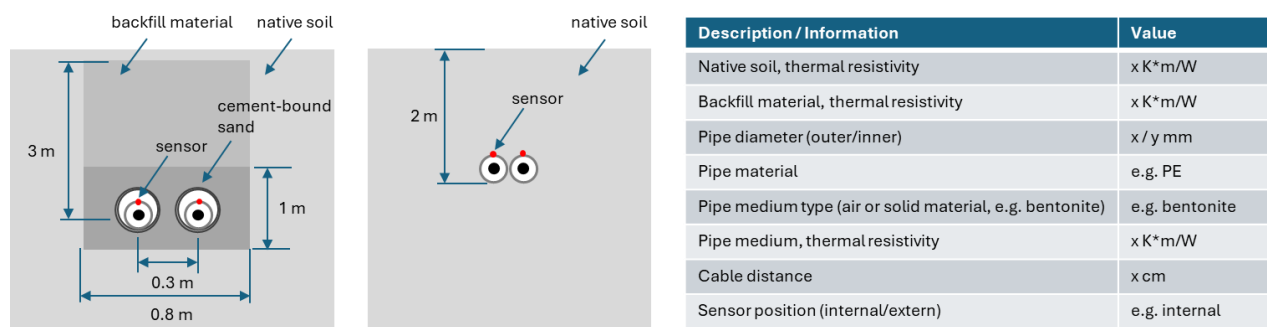


Figure 36 Schematic cross section of HVDC installed onshore (left) and directly buried offshore (right)

2.2.2.2.3 Outputs

RTTR for cable calculations provides various output values, some of which are interdependent and are described in detail hereafter.

Conductor Temperature

- The conductor temperature can be calculated either only for the hotspot of the cable (single point rating) or for each DTS sensor temperature sample point and is then available as conductor temperature trace (CTT).

Load Factor

- Based on the history of load data, the RTTR software also calculates a load factor as the average of one week of hourly load data divided by the hourly peak load during this period. The load factor is not used to derive further rating results but serves as an indication of how dynamically the cable load changes.

Steady-State Ampacity

- The (steady-state) ampacity is defined as the current in Ampère a circuit can carry indefinitely without exceeding the maximum conductor temperature (e.g. 90°C for a typical XLPE cable) for any of its phases. The steady-state ampacity can be calculated for RTTR models which include an explicit environment model. If the environment of the cable is not considered, the ampacity cannot be calculated.

Emergency Ratings (Transient Ratings)

- The **emergency temperature** is calculated from a given load current as well as time and is the temperature the cable will reach when applying the given load and time. The emergency temperature is the basis for the calculation of transient ampacity and emergency time ratings.
- The **emergency time** is calculated for a given load current and maximum conductor temperature. When the specified load current is applied for the calculated emergency time, the conductor temperature will increase but not exceed the specified max. conductor temperature for the rating.
- The **transient ampacity** is calculated for a given time and max. conductor temperature and is the maximum load current which, when applied for the specified time, will lead

to an increase of the conductor temperature without exceeding the specified max. conductor temperature for the rating.

2.2.2.2.4 Results and validation

To validate RTTR on high-voltage cables, the temperatures of the conductor, the various cable layers and the environmental parameters can be measured and compared with the calculated results of the RTTR.

In order to be able to measure the reference temperatures required for validation, the sensors must be inserted into the corresponding cable layers. However, in real cable installations for which RTTR is to be used, this is not practically feasible, making it impossible to validate the RTTR algorithm and the thermal model directly in the field.

Even if validation in the field is not practically possible, the RTTR algorithm can be validated on a real cable in laboratory tests, e.g. as part of the HV cable PQ test. There, the temperature sensors can be integrated into the individual cable layers and the temperature history of the individual cable layers can be recorded for different time variant load profiles. At the same time, the RTTR is carried out for the cable and the results are recorded so that the calculation results are available for the same loads and load profiles as the measured temperature values. Both measured values are then compared with the calculated values. If the deviation between the RTTR results and the measured values are within a defined tolerance, the validation of the algorithm has been successfully completed.

A laboratory test to validate the RTTR algorithm is not practically necessary for every cable, but it is also not absolutely essential. If the functionality of the RTTR algorithm has already been validated, the accuracy of the thermal models used for RTTR can be validated using simulation data.

Therefore, the rating results are compared with results of stationary and transient 2D simulations using COMSOL Multiphysics®, where the 2D COMSOL model of the HV cables and their environment reflects actual geometry and thermal parameters. The simulation results are then compared to those of the thermal models and must fall within defined tolerances to be successfully validated.

2.2.2.3 Connectors thermal rating

2.2.2.3.1 Methodology

Cable joints are one of the most critical points of the cable. In fact, they are prone to breaks due to different factors such as temperature or space charge loads. Therefore, monitoring these points can make a difference when talking about predictive maintenance. The connectors real time thermal rating will be done using LMK Bragg sensors located in the cables' joints. These sensors measure wavelengths that change with temperature variations. As temperature is not an extremely rapid magnitude, measurements can be made every minute or every five minutes since instant changes are not likely to happen.

As mentioned above, ANNs require to be trained. In order to be trained, first data must be splitted into training and test data. Usually, the training/test ratio is 70/30 which allows the neural network to be trained efficiently and avoid the possible overfitting of the network. Additionally, the remaining 30% of the data is used to train the trained network. This ratio can be changed if the network's performance is not adequate, or the available data is not great.

Furthermore, when training ANNs hyperparameters must be set. A hyperparameter is a constant parameter whose value is set before the learning process begins. The values of parameters are derived via learning. Examples of hyperparameters include learning rate, the number of hidden layers and batch size. The values of some hyperparameters can be dependent on those of other hyperparameters. These parameters can be initially set but they can be tuned during the training process to acquire a better performance of the network.

Due to the problem presented, two different NN architectures are proposed. The first of them is the Long Short-Term Memory (LSTM) neural network. LSTM networks are a special type of RNNs capable of learning long-term dependencies in prediction problems in data sequences. These networks have 3 types of gates: input, forget and output (Figure 37).

- **Input Gates:** decide which input values will be used for a memory change.
- **Forget gate:** find all the details to be deleted by the block.
- **Output Gate:** The output of the block is determined by the block's input and memory.

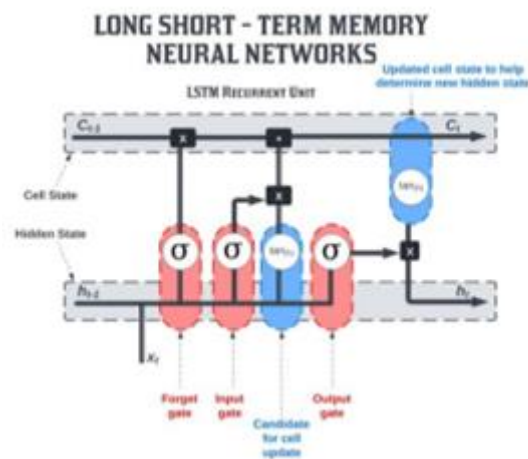


Figure 37 Architecture of a LSTM neuron

The second proposal is a GRU (Gated Recurrent Unit) neural network. These networks are a variant of the classical recurrent networks, proposed for first time in [100] and are designed to deal with the vanishing gradient problem. Unlike RNNs, GRU networks have a reset gate that allows them to remove unnecessary information and retain the information to be transmitted to the next neuron in the network (Figure 38).

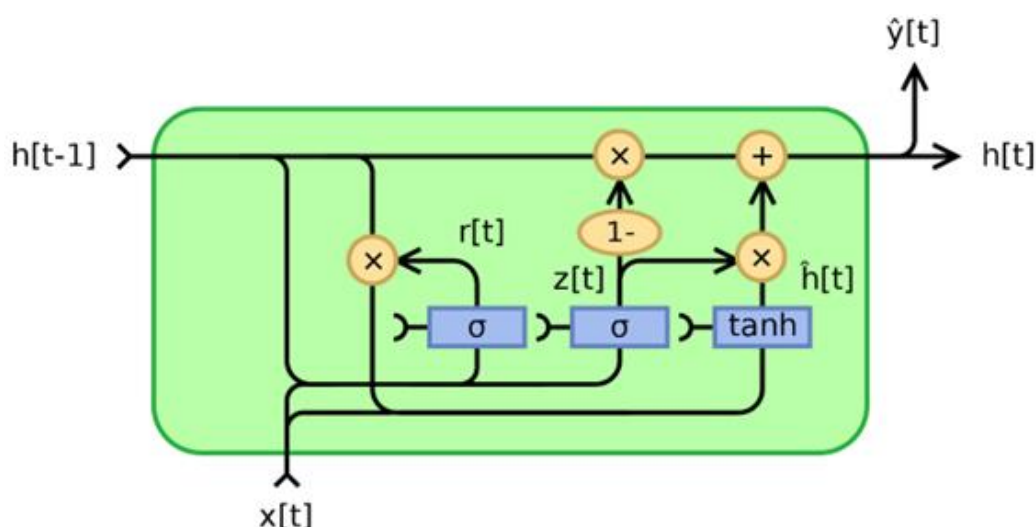


Figure 38 Architecture of a GRU neuron

As for the training of the algorithm, the models previously developed by UCA will be used. These models will provide some of the necessary data to feed the algorithm. The models' outputs will serve as inputs for the algorithm. The given temperature can be thought of as the prediction of the algorithm whose inputs will be several factors such as current passing through the cable, the ambient temperature and other factors that will be discussed in the next section.

2.2.2.3.2 Inputs

The algorithm will receive as an input the following data:

- **Temperature measured at the connectors.** This temperature will be measured using LMK Bragg sensors which will be located at each connector of the cable.
- **Current passing through the cable.** This data will be provided by the TSOs, as there are no current sensors installed on the cables. This data is crucial to do a good development of the algorithm, indeed, the current passing through the cable has a direct impact on the temperature.
- **Ambient temperature at the connection point.** Apart from the connectors' temperature, the surrounding temperature should also be recorded as it impacts directly on the connectors.
- **Environmental variables near the cable installation.** To optimize the algorithm's performance, gathering environmental variables would be interesting as to have more data that could be helpful for the algorithm's development. Such data could involve humidity, ground resistivity, or other bonding conditions of the cable.

2.2.2.3.3 Outputs

The expected outputs for the model are the temperatures on the cable connectors. The algorithm may provide predicted temperatures on the different connectors of the cable. The temperatures may be provided in time windows, with the possibility of defining different time

windows (1h, 6h, 8h). Depending on the expected time window, the input data amount may increase or decrease according to the wanted output.

2.2.2.3.4 Results and validation

The connectors' RTTR algorithm may be validated using both the thermal models developed by UCA and the real data measured in the connectors.

1. **Real data validation:** to validate the algorithm with real the procedure can be as follows: the model is deployed on the edge and is left hosted there. At first, instead of predicting a future time period, the prediction can be done with a time period that has already been passed. Therefore, the actual data is available to compare the results of the algorithm with the data measured by the sensors. This can be extremely useful as it is a direct result of the algorithm's performance.
2. **Thermal model validation:** the second option consists of validating the algorithm using the thermal model. As the model's outputs are the connectors' temperature depending on several factors, simulations can be done with the algorithm. For instance, a simulated situation could involve a current value for the cable, an ambient temperature and some temperature of the connectors. This would suppose an input to the algorithm and the expected temperature given by it could be compared with the outputs of the model.

2.2.3 Fault location

2.2.3.1 State-of-the-art

Fault detection and location is crucial to maintain good operability of high voltage transmission lines. Faults in cables can lead to outages, safety risks, and increased operational costs. The goal of fault location techniques is to detect, identify, and precisely locate faults so that repair teams can respond quickly, minimizing downtime and service disruption.

In alternating current (AC) cable systems, fault location has been widely studied leading to several different technologies to deal with this type of problem. The faults occurring in power lines and cables can be classified into four main categories: (i) short circuit to another conductor in the cable, (ii) short circuit to earth, (iii) high resistance to earth and (iv) open circuit [101]. There are different methods commonly used to locate the fault in underground cable such as Blavier Test, Murray loop test, Varley loop test, earth overlap test, and potential fall test [102]. Murray loop test is based on Wheatstone bridge principle [103]. The test consists of making one Wheatstone bridge in an underground cable. Then, after comparing the resistance between the two cables the fault should be located. The Varley loop test is similar to the Murray loop test, however, the circuit schema varies adding an additional variable resistor in the faulted cable.

Additionally, another method for fault location in underground cables is the Thumper Test. This technique involves injecting high-voltage surge pulses into the cable to generate mechanical vibrations or "thumps" at the fault location. These vibrations can be detected using acoustic or seismic equipment, enabling precise fault localization. The main advantage of this method is its ability to locate faults over long cable lengths with high accuracy. However, repeated

application of high-voltage surges may further damage the cable insulation, making this method more suitable for specific fault scenarios or as a complementary approach.

Furthermore, the CAMOS system developed by Lumiker uses differential protection to detect and locate a fault in the HVAC cable. The fault locator searches for the cable phase; discriminates first the major part, then the minor part and lastly, it indicates the exact point of the fault. The main advantages of this system are: (i) the speed of the result, practically in real time; (ii) unambiguous determination of the minor fault part as it determines it from the short-circuit values and (iii) the exact point of fault only requires a simple cable and ground model.

Nevertheless, in direct current (DC) cable systems, fault location is in a very early stage of development as well as the installations themselves. There have been some slight attempts to develop fault location systems for HVDC cables [104]. Even though staged faults showed promising outcomes, single-ended fault locators were found to be not dependable for HVDC lines in the long term, leading to their replacement by double-ended solutions. This project aims to develop a system that can perform fault location in DC lines using vibration patterns generated both throughout the cable and in its joints.

2.2.3.2 Methodology

The proposed methodology to develop a fault location system in this project is based on vibrations that are detected both along the cable (distributed) and in its joints (localised). Both LMK and APS will cooperate to develop an algorithm that can detect a fault and find it with a <10m precision. Figure 39 depicts the process followed to determine the location of the fault detected on the cable. First, LMK vibration sensors will detect a possible fault matching pattern and the developed algorithm will communicate an approximate location to APS interrogator. Then, the DAS will look into that location for anomalous values. In case the fault is validated, the algorithm deployed on the edge node will provide a segment or distance estimation for the fault.

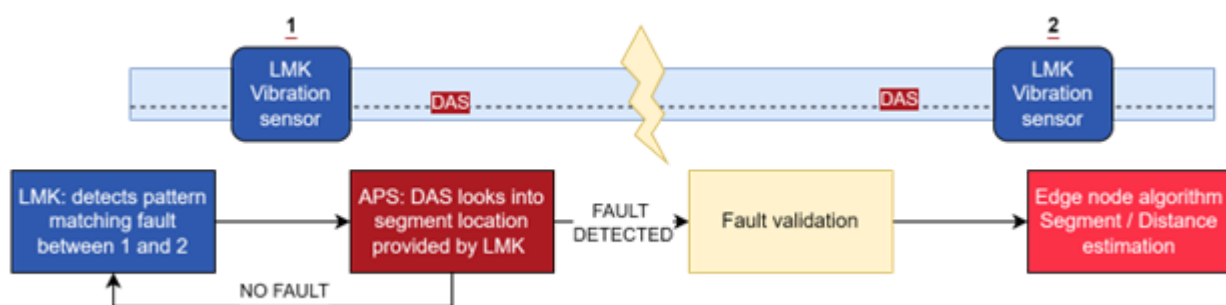


Figure 39 Fault location algorithm schema

The first algorithm of the combined algorithm will be based on the detection of vibration patterns in the cable joints. The first step for the development of the algorithm is its training. For this purpose, faults in the cable will be simulated and vibration data will be collected from sensors placed at the cable joints. These patterns will be classified as faults.

In addition to this, there will also be data that will correspond to vibration patterns generated with the correct functioning of the cable. Later, once the algorithm is trained, it can be used as a first approximation for the location of the fault.

Faults could be classified as anomalies occurring in the cable. Therefore, the proposed algorithm will be based on anomaly detection. Anomaly detection is an unsupervised data processing technique to detect anomalies from the data set. An anomaly can be broadly classified into different categories:

- **Outliers:** Short/small anomalous patterns that appear in a non-systematic way in data collection.
- **Change in events:** Systematic or sudden change from the previous normal behavior.
- **Drifts:** Slow, unidirectional long-term change in the data.

Some of the most notable anomaly detection algorithms include One-Class support vector machine (SVM), isolation forest (IF), K-nearest neighbour (KNN) algorithm and local outlier factor (LOF). A brief explanation of each algorithm is now presented and each one will be studied in order to decide which fits better with the purpose of the algorithm.

1. One-Class support vector machine (SVM)

It is like the SVM algorithm presented in Section 2.2.1.1. Nevertheless, it is primarily designed for outlier, anomaly, or novelty detection. The objective behind using one-class SVM is to identify instances that deviate significantly from the norm. It has one class of data points, and its task is to predict a hypersphere that separates the cluster of data points from the anomalies.

2. Isolation Forest (IF)

This type of anomaly detection algorithm uses unsupervised data. It uses a random forest algorithm, or decision trees, under the hood to detect outliers in the data set. The algorithm tries to split or divide the data points such that each observation gets isolated from the others.

3. K-nearest neighbour (KNN) algorithm

As presented in Section 2.2.1.1, this algorithm tries to cluster similar data points through a mathematical equation. It functions through the assumption that similar data points will be found near each other. If a data point appears further away from a dense section of points, it is considered an anomaly.

4. Local Outlier Factor (LOF)

This algorithm is similar to the k-NN algorithm. However, while KNN makes assumptions based on data points that are closest together, LOF uses the points that are furthest apart to draw its conclusions. The local outlier factor computes an anomaly score that measures how isolated the point is with respect to the surrounding neighborhood.

Convolutional Neural Networks

Convolutional Neural Network (CNN) for Anomaly Detection
In addition to traditional anomaly detection methods, the proposed methodology will explore the use of Convolutional Neural Networks (CNN) for detecting and classifying anomalies in

vibration data. CNNs are particularly effective for processing spatial and temporal data, making them suitable for vibration patterns recorded along the cable and at joints.

The CNN model will process spectrograms or time-series data derived from vibration measurements. It will consist of convolutional layers to extract relevant features from the vibration data and fully connected layers to classify patterns as either normal or anomalous.

Furthermore, an autoencoder-based CNN will also be considered to learn the normal behavior of the cable and identify anomalies based on reconstruction errors. This method provides a robust unsupervised approach to anomaly detection. By integrating CNN-based techniques, the system will enhance its precision and adaptability to various fault scenarios.

Another advanced method under consideration is the use of Convolutional Neural Networks (CNNs) for pattern recognition in vibration data. CNNs are widely recognized as state-of-the-art tools for identifying and classifying intricate patterns in spatial and temporal datasets. By training the network on both fault and normal vibration patterns, the model can accurately detect deviations and classify anomalies.

2.2.3.3 Inputs

LMK's algorithm's inputs will mainly be the data gathered by vibration sensors. These sensors will be installed on the cable joints, and they will be constantly registering the cable's behaviour. The interrogator will be the one in charge of processing the data. At first, the data analysed will be the vibrations between the first and second header of the cable. Then, in case a first anomalous behaviour is detected, the interrogator will start analysing the data more thoroughly. This means it will start analysing vibrations section by section, i.e. between joints, and that data will be the final input for the algorithm.

For the DAS system, the input will include continuous vibration data along the entire cable. These signals, captured at a high spatial resolution, will be processed into time-series data or spectrograms to feed the model (e.g. CNN model). The preprocessing stage will extract key features, such as amplitude, frequency, and location of anomalies.

2.2.3.4 Outputs

When an anomalous behaviour is detected, LMK's algorithm will send an alarm to APS's algorithm via the installed edge node. Along with the alarm, as LMK's algorithm checks vibrations between specific points, it will communicate to the APS's algorithm the cable section where the anomalous behaviour is happening. This will facilitate the DAS's work, as it will not have to check the full cable and it will be able to focus on a smaller section.

The DAS system, powered by the CNN model, will deliver precise fault localization with <10m accuracy. The outputs will include the exact fault location, the type of anomaly detected, and a visual representation of the affected section. Additionally, anomalies will be prioritized based on their criticality to ensure timely intervention. This output will be integrated with the edge node, facilitating seamless communication with other monitoring systems.

2.2.3.5 Results and validation

The validation of the Fault Detection Algorithm is a structured process aimed at ensuring both the robustness and reliability of the system. To this end, it is important to use data collected under various environmental conditions, including vibration noise, moisture, and temperature fluctuation. The validation process is divided into two distinct parts:

1. **Model validation:** This phase focuses on the model (e.g., CNN model) itself during the training and development stage of the algorithm. A diverse dataset will be used, with a clear split between training and validation data to avoid overfitting and enhance generalizability. Ground truth data is essential, including fault locations and criticality scores. Ground truth can be collected via simulated fault scenarios or through manual inspection or other diagnostic tools in real-world settings. Validation metrics include classification metrics such as accuracy, recall, precision, and F1-score as well as localization and criticality errors to evaluate the system's ability to pinpoint faults and assess their criticality accurately. Simpler methods for fault localization like pattern matching may additionally serve as a baseline to compare against.
2. **End-to-end validation:** This phase involves validating the entire algorithm, from data input to the final output, in a real-world or simulated operational setting. Validation may be conducted using data from deliberately introduced faults or through long-term monitoring of cables in real-world installations. Data used in end-to-end validation must be distinct from model training and validation datasets, ensuring unbiased evaluation. It is possible to use previously collected datasets from multiple test sites for faster and diverse validation. The validation metrics include all metrics from model validation (e.g., accuracy, recall, localization error). Additional measures are false positives and negatives for both the LMK's algorithm and the trained model, the error margin for fault locations and the detection latency. These metrics ensure localization precision and reliability and assess real-time performance. Alerts and visual outputs must be validated for clarity and usability, ideally by end-users. Feedback will help fine-tune the system's interfaces and outputs. Performance should be tested on cable networks of varying lengths to ensure the system scales effectively while maintaining accuracy and speed. End-to-end validation serves to identify any gaps or failure modes in the CNN model or the overall algorithm, facilitating iterative improvements in the model architecture and training pipeline.

By dividing the validation into these two stages, the process ensures that the CNN model functions effectively in isolation and integrates seamlessly into the full fault detection system. This comprehensive approach confirms that the system is accurate, reliable, and capable of operating under diverse and challenging environmental conditions.

3 CONCLUSIONS

The deliverable encompasses the development of detailed models and predictive algorithms for both HVAC and HVDC cable systems, integrating various conditions and key performance factors. These models will enable improved design, monitoring, and fault detection capabilities for innovative HVDC systems, as outlined in the EasyDC-FOS project.

Models

1. Space Charge Modelling

Led by RDT, the space charge modelling aims to simulate the behavior of electrical charge accumulation in cable insulation under different operating conditions. The models will take various environmental and operational factors as inputs and predict the occurrence of partial discharges (PDs) as outputs. Special emphasis is placed on maximizing the appearance of partial discharges to generate extensive data sets. These data sets are crucial for the subsequent training and refinement of algorithms, ensuring accurate simulation and understanding of insulation aging and its failure modes.

2. Thermal Modelling

UCA is responsible for developing comprehensive thermal models for cables and connectors. These models will simulate the thermal behavior under varying load conditions, producing critical outputs such as temperature distributions, ampacity, and emergency rating. By considering the unique properties of the cable system materials and their interactions, these models will guide design optimizations and inform real-time operational decisions.

Predictive Algorithms

1. Aging Algorithm

LMK will spearhead the development of an aging prediction algorithm based on partial discharge measurements. By utilizing the PD data from the space charge model, the algorithm will estimate the cable's current aging status as a percentage of its lifespan. Training and validation of the algorithm will rely on both simulated data and experimental results. This approach ensures accurate representation of real-world conditions and enhances the reliability of the algorithm in predicting the degradation of cable insulation over time.

2. Real-Time Thermal Rating (RTTR)

- **Cable RTTR:** APS will create a model focusing on the real-time assessment of the cable's thermal behavior. The outputs—such as conductor temperature, load factor, steady-state ampacity, and emergency rating—will be validated against sensor measurements, ensuring robust and accurate performance in operational scenarios.
- **Connector RTTR:** LMK will extend the RTTR framework to connectors using Artificial Neural Networks (ANNs). Inputs will include thermal model outputs and other relevant parameters, while validation will incorporate both modeled data and real-world measurements. This integration will support comprehensive thermal management across the entire cable system.

3. Fault Location Algorithm

APS and LMK will collaborate on a two-stage fault detection and location algorithm. LMK's component will monitor cable vibrations at connector points, identifying anomalies indicative of potential faults. When detected, LMK's system will notify APS via edge nodes, pinpointing the specific cable section requiring further analysis. APS will then employ Distributed Acoustic Sensing (DAS) to validate faults or categorize them as false positives. This end-to-end system promises enhanced accuracy and efficiency in fault detection and response, crucial for maintaining operational reliability.

By delivering robust models and algorithms under Deliverable 3.2, the project aligns with its broader goals of advancing the reliability, efficiency, and sustainability of HVDC and HVAC systems. These tools will also serve as foundational elements for later validation and deployment phases across laboratory and field environments.

4 REFERENCES

- [1] IEC 60287-1-1:2023, 'Electric cables - Calculation of the current rating - Part 1-1: Current rating equations (100 % load factor) and calculation of losses - General'. 2023.
- [2] IEC 60287-1-2:2023, 'Electric cables - Calculation of the current rating - Part 1-2: Current rating equations (100 % load factor) and calculations of losses - Sheath eddy current loss factors for two circuits in flat formation'. 2023.
- [3] IEC 60287-1-3:2023, 'Electric cables - Calculation of the current rating - Part 1-3: Current rating equations (100 % load factor) and calculation of losses - Current sharing between parallel single-core cables and calculation of circulating current losses'. 2023.
- [4] IEC 60287-2-1:2023, 'Electric cables - Calculation of the current rating - Part 2-1: Thermal resistance - Calculation of thermal resistance'. 2023.
- [5] IEC 60287-3-1:2017, 'Electric cables - Calculation of the current rating - Part 3-1: Operating conditions - Site reference conditions'. 2017.
- [6] IEC 60287-2-3:2024, 'Electric cables - Calculation of the current rating - Part 2-3: Thermal resistance - Cables installed in ventilated tunnels'. 2024.
- [7] IEC 60287-3-2:2012, 'Electric cables - Calculation of the current rating - Part 3-2: Sections on operating conditions - Economic optimization of power cable size'. 2012.
- [8] IEC 60287-3-3:2007, 'Electric cables - Calculation of the current rating - Part 3-3: Sections on operating conditions - Cables crossing external heat sources'. 2007.
- [9] IEC 60287-2-2:1995, 'Electric cables - Calculation of the current rating - Part 2: Thermal resistance - Section 2: A method for calculating reduction factors for groups of cables in free air, protected from solar radiation'. 1995.
- [10] IEC 60853-1:1985, 'Calculation of the cyclic and emergency current rating of cables - Part 1: Cyclic rating factor for cables up to and including 18/30(36) kV'. 1985.
- [11] IEC 60853-2:1989, 'Calculation of the cyclic and emergency current rating of cables - Part 2: Cyclic rating of cables greater than 18/30 (36) kV and emergency ratings for cables of all voltages'. 1989.
- [12] IEC 60853-3:2002, 'Calculation of the cyclic and emergency current rating of cables - Part 3: Cyclic rating factor for cables of all voltages, with partial drying of the soil'. 2002.
- [13] IEC TR 62095:2003, 'Electric cables - Calculations for current ratings - Finite element method'. 2003.
- [14] IEC 60228:2023, 'Conductors of insulated cables'. 2023.
- [15] IEC 60840:2020/AMD1:2023, 'Power cables with extruded insulation and their accessories for rated voltages above 30 kV ($U_m = 36$ kV) up to 150 kV ($U_m = 170$ kV) - Test methods and requirements'. 2020.
- [16] IEC 62067:2022, 'Power cables with extruded insulation and their accessories for rated voltages above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) - Test methods and requirements'. 2022.
- [17] IEC 63026:2019, 'Submarine power cables with extruded insulation and their accessories for rated voltages from 6 kV ($U_m = 7,2$ kV) up to 60 kV ($U_m = 72,5$ kV) - Test methods and requirements'. 2019.
- [18] IEEE, 'IEEE Guide for the Planning, Design, Installation, and Repair of Submarine Power Cable Systems'. IEEE, Nov. 2024. doi: 10.1109/IEEESTD.2005.95937.

- [19] IEEE, 'IEEE Guide for Fault-Locating Techniques on Shielded Power Cable Systems'. IEEE, Nov. 2024. doi: 10.1109/IEEESTD.2019.8748246.
- [20] IEEE, 'IEEE Guide for Field Testing and Evaluation of the Insulation of Shielded Power Cable Systems Rated 5 kV and Above'. IEEE, Nov. 2024. doi: 10.1109/IEEESTD.2023.10336851.
- [21] IEEE, 'IEEE Guide for Thermal Resistivity Measurements of Soils and Backfill Materials'. IEEE, Nov. 2024. doi: 10.1109/IEEESTD.2018.8353815.
- [22] IEEE, 'IEEE Guide for Temperature Monitoring of Cable Systems'. IEEE, Nov. 2024. doi: 10.1109/IEEESTD.2012.6214562.
- [23] CIGRE Working Group B1.40, 'TB 610 - Offshore Generation Cable Connections'. Feb. 2015.
- [24] CIGRE Working Group B1.35, 'TB 640 - A Guide for Rating Calculations of Insulated Cables'. 2015.
- [25] CIGRE Working Group B1.64, 'TB 908 - Losses in Armoured Three Core Power Cables'. Jun. 2023.
- [26] CIGRE Working Group B1.10, 'TB 379 - Update of service experience of HV underground and submarine cable systems'. 2009.
- [27] CIGRE Working Group B1.21, 'TB 398 - Third party damage to underground and submarine cables'. 2009.
- [28] CIGRE Working Group B1.27, 'TB 490 - Recommendations for testing of long AC submarine cables with extruded insulation above 30 (36) kV to 500 (550) kV'. Feb. 2012.
- [29] CIGRE Working Group B1.32, 'TB 496 - Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 500 kV'.
- [30] CIGRE Working Group B1.43, 'TB 623 - Recommendations for mechanical testing of submarine cables'. 2015.
- [31] CIGRE Working Group B1.55, 'TB 722 - Recommendations for additional testing for submarine cables from 6 KV (UM=7.2 KV) up to 60 KV (UM = 72.5 KV)'. Apr. 2018.
- [32] CIGRE Working Group B1.57, 'TB 815 - Update of service experience of HV underground and submarine cable systems'. Sep. 2020.
- [33] CIGRE Working Group B1.63, 'TB 862 - Recommendations for mechanical testing of submarine cables for dynamic applications'. Jan. 2022.
- [34] CIGRE Working Group B1.65, 'TB 883 - Installation of Submarine Power Cables'. Oct. 2022.
- [35] Maria Ikhennicheu *et al.*, 'Review of the state of the art of dynamic cable system design', INNOSEA, D3.1, Feb. 2020. [Online]. Available: <https://corewind.eu/wp-content/uploads/files/publications/COREWIND- D3.1- Review- of- the- state- of- the- art- ofdynamic-cable-system-design.pdf>
- [36] 2H Offshore (edited by ORE Catapult), 'DYNAMIC CABLE TECHNOLOGY QUALIFICATION FRAMEWORK AND CASE STUDIES', ORE Catapult, Sep. 2022.
- [37] T. V. M. Nielsen, S. Jakobsen, and M. Savaghebi, 'Dynamic Rating of Three-Core XLPE Submarine Cables for Offshore Wind Farms', *Appl. Sci.*, vol. 9, no. 4, p. 800, Feb. 2019, doi: 10.3390/app9040800.
- [38] T. V. M. Nielsen, S. Jakobsen, and M. Savaghebi, 'Dynamic Rating of Three-Core XLPE Submarine Cables Considering the Impact of Renewable Power Generation', in *2019 IEEE 13th International Conference on Compatibility, Power Electronics and Power*

- Engineering (CPE-POWERENG)*, Sonderborg, Denmark: IEEE, Apr. 2019, pp. 1–6. doi: 10.1109/CPE.2019.8862377.
- [39] Q. Zhan *et al.*, ‘Real-time calculation of three core cable conductor temperature based on thermal circuit model with thermal resistance correction’, *J. Eng.*, vol. 2019, no. 16, pp. 2036–2041, Mar. 2019, doi: 10.1049/joe.2018.8739.
- [40] M. González-Cagigal, J. del-Pino-López, A. Bachiller-Soler, P. Cruz-Romero, and J. Rosendo-Macías, ‘A Thermal Model for Three-Core Armored Submarine Cables Based on Distributed Temperature Sensing’, *Energies*, vol. 14, no. 13, p. 3897, Jun. 2021, doi: 10.3390/en14133897.
- [41] H. Jiang *et al.*, ‘Operating Ampacity and Calculation Method for AC Submarine Cables Considering Sheath Circulation’, in *2023 10th International Forum on Electrical Engineering and Automation (IFEEA)*, Nanjing, China: IEEE, Nov. 2023, pp. 612–616. doi: 10.1109/IFEEA60725.2023.10429597.
- [42] J. C. del-Pino-López and P. Cruz-Romero, ‘Use of 3D-FEM Tools to Improve Loss Allocation in Three-Core Armored Cables’, *Energies*, vol. 14, no. 9, p. 2434, Apr. 2021, doi: 10.3390/en14092434.
- [43] Juan Carlos del-Pino-López and Pedro Cruz-Romero, ‘A 3D parametric thermal analysis of submarine three-core power cables’, Jun. 2020.
- [44] Juan Carlos del-Pino-López and Pedro Cruz-Romero, ‘Hybrid 2D/3D fully coupled electrothermal model for three-core submarine armored cables’, Oct. 2020.
- [45] J. C. del-Pino-Lopez, M. Hatlo, and P. Cruz-Romero, ‘A 3D Parametric Analysis of Three-core Armored Power Cables Series Impedance’, in *2018 International Conference on Smart Energy Systems and Technologies (SEST)*, Sevilla: IEEE, Sep. 2018, pp. 1–6. doi: 10.1109/SEST.2018.8495728.
- [46] NOE VIOLLEAU, GUO ENGELKEN, BISSONNETTE Longas, and ZICHANOWICZ POLAK, ‘Measurements and FEA Results of Steel Armour Losses in Three-core Submarine XLPE Cables’, 2016. [Online]. Available: <https://www.e-cigre.org/publications/detail/b1-206-2016-measurements-and-fea-results-of-steel-armour-losses-in-three-core-submarine-xlpe-cables.html>
- [47] Filipe Miguel Faria da Silva, Thomas Ebdrup, Claus Leth Bak, and Christian Flytkjær Jensen, ‘Understanding losses in three core armoured submarine cables’, 2016. [Online]. Available: <https://www.e-cigre.org/publications/detail/b1-304-2016-understanding-losses-in-three-core-armoured-submarine-cables.html>
- [48] R. D. Chippendale, J. A. Pilgrim, K. F. Goddard, and P. Cangy, ‘Analytical Thermal Rating Method for Cables Installed in J-Tubes’, *IEEE Trans. Power Deliv.*, vol. 32, no. 4, pp. 1721–1729, Aug. 2017, doi: 10.1109/TPWRD.2016.2571844.
- [49] C.-H. Bonnard, A. Blavette, S. Bourguet, and A. Charmetant, ‘Modeling of a wave farm export cable for electro-thermal sizing studies’, *Renew. Energy*, vol. 147, pp. 2387–2398, Mar. 2020, doi: 10.1016/j.renene.2019.09.135.
- [50] X. Tao *et al.*, ‘Comparative Study on the Ampacity of 500 kV Single-Core and Three-Core Submarine Cable’, *J. Phys. Conf. Ser.*, vol. 2731, no. 1, p. 012014, Mar. 2024, doi: 10.1088/1742-6596/2731/1/012014.
- [51] D. Chatzipetros and J. A. Pilgrim, ‘Review of the Accuracy of Single Core Equivalent Thermal Model for Offshore Wind Farm Cables’, *IEEE Trans. Power Deliv.*, vol. 33, no. 4, pp. 1913–1921, Aug. 2018, doi: 10.1109/TPWRD.2017.2770321.

- [52] Q. Li *et al.*, 'A Method for Detecting the Burial Depth of ± 500 kV XLPE DC Submarine Cables Based on Equivalent Thermal Circuit and Optical Fiber Monitoring Temperature'. Preprints, Apr. 2023. doi: 10.22541/au.168062563.34122386/v1.
- [53] X. Yu *et al.*, 'Simulation Study on Steady-State Ampacity of ± 400 kV J-tube DC Submarine Cable', in *2022 4th International Conference on Electrical Engineering and Control Technologies (CEEECT)*, Shanghai, China: IEEE, Dec. 2022, pp. 546–551. doi: 10.1109/CEEECT55960.2022.10030564.
- [54] Z. Zhang, X. Deng, L. Liang, X. Wang, Y. Chen, and J. Ruan, 'Temperature Field Calculation and Thermal Circuit Equivalent Analysis of 110 kV Core Cable Joint', *Processes*, vol. 12, no. 3, p. 463, Feb. 2024, doi: 10.3390/pr12030463.
- [55] F. He *et al.*, 'An Improved Analytical Thermal Rating Method for Cable Joints', *Energies*, vol. 17, no. 9, p. 2040, Apr. 2024, doi: 10.3390/en17092040.
- [56] E. OLSEN, F. BRYNEM, and M. HATLO, 'Dynamic Current Rating – Thermal Transient Response', *CIGRE Sci. Eng.*, vol. 23, Dec. 2021, [Online]. Available: <https://cse.cigre.org/cse-n023/dynamic-current-rating-thermal-transient-response.html>
- [57] S. STURM, A. KÜCHLER, and J. PAULUS, '3D-FEM modelling of losses in armoured submarine power cables and comparison with measurements', 2020. [Online]. Available: <https://www.e-cigre.org/publications/detail/b1-215-2020-3d-fem-modelling-of-losses-in-armoured-submarine-power-cables-and-comparison-with-measurements.html>
- [58] L. Giussani, L. D. Rienzo, M. Bechis, and C. D. Falco, 'Computation of Armor Losses in AC Submarine Cables', *IEEE Trans. Power Deliv.*, vol. 36, no. 5, pp. 3014–3021, Oct. 2021, doi: 10.1109/TPWRD.2020.3031735.
- [59] L. Giussani, L. Di Rienzo, M. Bechis, P. Cambareri, and C. De Falco, 'Efficient PEEC Computation of Losses and Currents in Shields of Round Wires in Submarine Tripolar Cables', *IEEE Trans. Magn.*, vol. 58, no. 9, pp. 1–4, Sep. 2022, doi: 10.1109/TMAG.2022.3161840.
- [60] L. Giussani, L. D. Rienzo, M. Bechis, and C. De Falco, 'Fully Coupled Computation of Losses in Metallic Sheaths and Armor of AC Submarine Cables', *IEEE Trans. Power Deliv.*, vol. 37, no. 5, pp. 3803–3812, Oct. 2022, doi: 10.1109/TPWRD.2021.3137661.
- [61] L. Giussani, C. De Falco, M. Bechis, P. Cambareri, and L. Di Rienzo, 'Integral Coupled Formulation for Modeling Tripolar Submarine Cables with Shield Wires', in *2022 IEEE 20th Biennial Conference on Electromagnetic Field Computation (CEFC)*, Denver, CO, USA: IEEE, Oct. 2022, pp. 1–2. doi: 10.1109/CEFC55061.2022.9940872.
- [62] P. Cambareri, L. Di Rienzo, M. Bechis, and C. De Falco, 'Losses Computation in Double Armored AC Submarine Cables', in *2022 IEEE 20th Biennial Conference on Electromagnetic Field Computation (CEFC)*, Denver, CO, USA: IEEE, Oct. 2022, pp. 1–2. doi: 10.1109/CEFC55061.2022.9940839.
- [63] Y. Zhang, X. Chen, H. Zhang, J. Liu, C. Zhang, and J. Jiao, 'Analysis on the Temperature Field and the Ampacity of XLPE Submarine HV Cable Based on Electro-Thermal-Flow Multiphysics Coupling Simulation', *Polymers*, vol. 12, no. 4, p. 952, Apr. 2020, doi: 10.3390/polym12040952.
- [64] Y. Zhang, X. Tang, Y. Huang, M. Xia, X. Du, and J. Sui, 'Analysis of Thermal Field Distribution Characteristics of Different Structure Submarine Cables in Diverse Laying Environments', in *2023 2nd International Conference on Optical Imaging and Measurement (ICOIM)*, Xi'an, China: IEEE, Oct. 2023, pp. 120–126. doi: 10.1109/ICOIM60566.2023.10491451.

- [65] M. Callewaert, R. Vanthillo, C. Fojtek (Marlinks), and B. Mampaey (Elia), 'Deriving an experimental and analytical relation between the core and fiber temperatures of a 3P XLPE cable', *J. Phys. Conf. Ser.*, vol. 2151, no. 1, p. 012012, Jan. 2022, doi: 10.1088/1742-6596/2151/1/012012.
- [66] J. Wei, G. Liu, L. Zhang, M. He, Y. Yang, and D. Liu, 'Analysis and Research on Transmission Limit and Emergency Capability of Three-Core Submarine Cable', in *2023 Panda Forum on Power and Energy (PandaFPE)*, Chengdu, China: IEEE, Apr. 2023, pp. 1183–1187. doi: 10.1109/PandaFPE57779.2023.10140330.
- [67] G. Callender, D. Ellis, K. F. Goddard, J. K. Dix, J. A. Pilgrim, and M. Erdmann, 'Low Computational Cost Model for Convective Heat Transfer From Submarine Cables', *IEEE Trans. Power Deliv.*, vol. 36, no. 2, pp. 760–768, Apr. 2021, doi: 10.1109/TPWRD.2020.2991783.
- [68] G. Callender, K. F. Goddard, J. K. Dix, and P. L. Lewin, 'A Flexible Model to Calculate Buried Cable Ampacity in Complex Environments', *IEEE Trans. Power Deliv.*, vol. 37, no. 3, pp. 2007–2015, Jun. 2022, doi: 10.1109/TPWRD.2021.3102414.
- [69] M. A. Hamdan, J. A. Pilgrim, and P. L. Lewin, 'Analysis of thermo-mechanical stress in three core submarine power cables', *IEEE Trans. Dielectr. Electr. Insul.*, vol. 27, no. 4, pp. 1288–1296, Aug. 2020, doi: 10.1109/TDEI.2020.008750.
- [70] Yao Liu *et al.*, 'Insulation Design of the UHVDC Submarine Cable under the Background of Global Energy Interconnection', 2020, pp. 233–236.
- [71] F. Jin *et al.*, 'Investigation of the effects of insulation defects on the 3-D electromagnetic-thermal coupling fields of power cable joint', in *2016 IEEE 11th Conference on Industrial Electronics and Applications (ICIEA)*, Hefei, China: IEEE, Jun. 2016, pp. 1436–1439. doi: 10.1109/ICIEA.2016.7603811.
- [72] A. Zhao and L. Gu, 'Study on the temperature distribution of the outer surface of the cable intermediate joint based on ANSYS simulation', in *2018 IEEE 4th Information Technology and Mechatronics Engineering Conference (ITOEC)*, Chongqing, China: IEEE, Dec. 2018, pp. 20–23. doi: 10.1109/ITOEC.2018.8740397.
- [73] H. Brakelmann and G. J. Anders, 'Thermal Analysis of Cable Routes with Joints or Other Discontinuities', *Energies*, vol. 17, no. 16, p. 4029, Aug. 2024, doi: 10.3390/en17164029.
- [74] X. Lu *et al.*, 'Effect of Interface Defects on the Electric–Thermal–Stress Coupling Field Distribution of Cable Accessory Insulation', *Energies*, vol. 17, no. 17, p. 4498, Sep. 2024, doi: 10.3390/en17174498.
- [75] A. A. Bhatti *et al.*, 'Simulation of Temperature Distribution Behavior of High Voltage Cable Joints with Typical Defects', in *2021 6th Asia Conference on Power and Electrical Engineering (ACPEE)*, Chongqing, China: IEEE, Apr. 2021, pp. 1139–1143. doi: 10.1109/ACPEE51499.2021.9436866.
- [76] Statnett, 'Øygardkabelen - Construction License', *Statnett*. Nov. 2024. Accessed: Nov. 22, 2024. [Online]. Available: <https://www.statnett.no/globalassets/her-er-vare-prosjekter/region-vest/oygardskabelen/anleggskonsesjon.pdf>
- [77] Statnett, 'Øygardkabelen - Konsesjonssøknad', *Statnett*. Nov. 2024. Accessed: Nov. 22, 2024. [Online]. Available: <https://www.statnett.no/globalassets/her-er-vare-prosjekter/region-vest/oygardskabelen/konsesjonssoknad-for-oygardskabelen.pdf>
- [78] Energinet, 'COBRACable: Interconnector to the Netherlands'. Jun. 2019. Accessed: Nov. 22, 2024. [Online]. Available: <https://en.energinet.dk/infrastructure-projects/finished-projects/cobracable/>

- [79] TenneT, 'COBRACable', *TenneT*. Accessed: Nov. 22, 2024. [Online]. Available: <https://www.tennet.eu/projects/cobracable>
- [80] S. ALBOGHOBEISH, E. Doedens, T. Slaný, O. H. Ashrakat, and H. Kvarme, 'Cable system specification'.
- [81] ANSYS Inc., 'Mechanical User's Guide'. Accessed: Nov. 22, 2024. [Online]. Available: https://ansyshelp.ansys.com/account/secured?returnurl=/Views/Secured/corp/v231/en/wb_sim/ds_Home.html
- [82] G. Li *et al.*, 'The Lifetime Prediction and Insulation Failure Mechanism of XLPE for High-Voltage Cable', *IEEE Trans. Dielectr. Electr. Insul.*, vol. 30, no. 2, pp. 761–768, Apr. 2023, doi: 10.1109/TDEI.2022.3215605.
- [83] Z. Li, Z. Jiao, A. He, and N. Xu, 'A Denoising-Classification Neural Network for Power Transformer Protection', *Prot. Control Mod. Power Syst.*, vol. 7, no. 4, pp. 1–14, Oct. 2022, doi: 10.1186/s41601-022-00273-8.
- [84] S. Ida Evangeline, S. Darwin, K. Baskaran, and E. Fantin Irudaya Raj, 'A machine learning-based assessment model for defect diagnosis in XLPE power cables', *E-Prime - Adv. Electr. Eng. Electron. Energy*, vol. 8, p. 100530, Jun. 2024, doi: 10.1016/j.prime.2024.100530.
- [85] D. B. Dwyer, P. Falkai, and N. Koutsouleris, 'Machine Learning Approaches for Clinical Psychology and Psychiatry', *Annu. Rev. Clin. Psychol.*, vol. 14, pp. 91–118, May 2018, doi: 10.1146/annurev-clinpsy-032816-045037.
- [86] C. Vaghela, N. Bhatt, and D. Mistry, 'A Survey on Various Classification Techniques for Clinical Decision Support System', *Int. J. Comput. Appl.*, vol. 116, no. 23, pp. 14–17, Apr. 2015, doi: 10.5120/20498-2369.
- [87] M. Gudadhe, K. Wankhade, and S. Dongre, 'Decision support system for heart disease based on support vector machine and Artificial Neural Network', in *2010 International Conference on Computer and Communication Technology (ICCCCT)*, Sep. 2010, pp. 741–745. doi: 10.1109/ICCCCT.2010.5640377.
- [88] J. M. Hardin and D. C. Chhieng, 'Data Mining and Clinical Decision Support Systems', in *Clinical Decision Support Systems*, E. S. Berner, Ed., in Health Informatics. , New York, NY: Springer New York, 2007, pp. 44–63. doi: 10.1007/978-0-387-38319-4_3.
- [89] G. James, D. Witten, T. Hastie, and R. Tibshirani, *An Introduction to Statistical Learning: with Applications in R*. Springer Science & Business Media, 2013.
- [90] I. Ben-Gal, 'Bayesian Networks', in *Encyclopedia of Statistics in Quality and Reliability*, 1st ed., F. Ruggeri, R. S. Kenett, and F. W. Faltin, Eds., Wiley, 2007. doi: 10.1002/9780470061572.eqr089.
- [91] N. Fenton and M. Neil, *Risk Assessment and Decision Analysis with Bayesian Networks*, 2nd ed. New York: Chapman and Hall/CRC, 2018. doi: 10.1201/b21982.
- [92] A. C. Constantinou, N. Fenton, and M. Neil, 'Integrating Expert Knowledge with Data in Bayesian Networks: Preserving Data-Driven Expectations when the Expert Variables Remain Unobserved', *Expert Syst. Appl.*, vol. 56, pp. 197–208, Sep. 2016, doi: 10.1016/j.eswa.2016.02.050.
- [93] T. Senjyu, H. Takara, K. Uezato, and T. Funabashi, 'One-hour-ahead load forecasting using neural network', *IEEE Trans. Power Syst.*, vol. 17, no. 1, pp. 113–118, Feb. 2002, doi: 10.1109/59.982201.
- [94] Q. Li, M. Musavi, and D. Chamberlain, 'Overhead conductor thermal rating using neural networks', in *2011 IEEE International Conference on Smart Measurements of Future*

- Grids (SMFG) Proceedings*, Nov. 2011, pp. 139–142. doi: 10.1109/SMFG.2011.6125757.
- [95] D. Aegerter and S. Meier, *Model-based predictive control for use in RTTR temperature sensing systems of high voltage cables*. 2019.
- [96] A.-K. S and B. R, 'Basic concepts of artificial neural network (ANN) modeling and its application in pharmaceutical research', *J. Pharm. Biomed. Anal.*, vol. 22, no. 5, Jun. 2000, doi: 10.1016/S0731-7085(99)00272-1.
- [97] Z. Che, S. Purushotham, K. Cho, D. Sontag, and Y. Liu, 'Recurrent Neural Networks for Multivariate Time Series with Missing Values', *Sci. Rep.*, vol. 8, no. 1, Art. no. 1, Apr. 2018, doi: 10.1038/s41598-018-24271-9.
- [98] P. T. Yamak, L. Yujian, and P. K. Gadosey, 'A Comparison between ARIMA, LSTM, and GRU for Time Series Forecasting', in *Proceedings of the 2019 2nd International Conference on Algorithms, Computing and Artificial Intelligence*, Sanya China: ACM, Dec. 2019, pp. 49–55. doi: 10.1145/3377713.3377722.
- [99] R. N. Patton, S. K. Kim, and R. Podmore, 'Monitoring and Rating of Underground Power Cables', *IEEE Trans. Power Appar. Syst.*, vol. PAS-98, no. 6, pp. 2285–2293, Nov. 1979, doi: 10.1109/TPAS.1979.319428.
- [100] K. Cho *et al.*, 'Learning Phrase Representations using RNN Encoder-Decoder for Statistical Machine Translation', Sep. 03, 2014, *arXiv*: arXiv:1406.1078. doi: 10.48550/arXiv.1406.1078.
- [101] 'Modified Murray Loop Method for Underground Cable Fault Location Detection Using GSM', *Int. J. Sci. Res. IJSR*, vol. 5, no. 6, pp. 1892–1894, Jun. 2016, doi: 10.21275/v5i6.NOV164688.
- [102] A. Nag, A. Yadav, A. Y. Abdelaziz, and M. Pazoki, 'Fault Location in Underground Cable System Using optimization Technique', in *2020 First International Conference on Power, Control and Computing Technologies (ICPC2T)*, Jan. 2020, pp. 261–266. doi: 10.1109/ICPC2T48082.2020.9071462.
- [103] V. M. & R. Mehta, *Principles of Power System: Including Generation, Transmission, Distribution, Switchgear and Protection : for B.E/B.Tech., AMIE and Other Engineering Examinations*. S. Chand Publishing, 2005.
- [104] M. Ando, E. O. Schweitzer, and R. A. Baker, 'Development and Field-Data Evaluation of Single-End Fault Locator for Two-Terminal HVDV Transmission Lines-Part 2 : Algorithm and Evaluation', *IEEE Trans. Power Appar. Syst.*, vol. PAS-104, no. 12, pp. 3531–3537, Dec. 1985, doi: 10.1109/TPAS.1985.318906.