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Thermal Transients in Three-Core Power Cable Systems: First Principle Modelling and Verification

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Abstract

This paper presents research related to developing a thermal model for three-core power cable systems used in offshore wind farms. Three-core power cable systems are a significantly more complicated thermo-electrical system than single-core power cables, primarily due to the geometric asymmetry and the number of heat sources. There are tools available that can model thermal transients in three-core cable systems, but these tools demand a nontrivial level of prerequisite knowledge and training on the part of the user. Therefore, this research aimed at developing and testing a first principle model specifically tuned for thermal transients in three-core cables. The model has been tested by comparing its predictions with empirical temperature data collected from heat cycle testing on three-core cables at Nexans' facilities. To increase the quality of the predictions, part of the research was also to measure the thermal properties of swellable tape and filling compound (used in three-core cables). The first principle model's predictions correspond well with the empirical data, the research results are promising. The model must be tested more thoroughly with different use cases before it can complement or replace current working methods.

Keywords: Three-core cables; Modelling; First principles; Verification; Thermal transients.

1. Introduction

Nexans Halden AS specializes in designing, manufacturing, and installing high-voltage submarine power cables, as well as related transmission system components[1]. Submarine power cables are essential in several different use cases, such as connecting countries that are separated by water or connecting populated islands to the mainland. The cables are commonly engineered specifically for each project, primarily due to the high manufacturing cost relative to the engineering cost.

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1.1. System

For transmission systems running on alternating current (AC), submarine power cables come in two main variants: single-core cables and three-core cables. Single-core cables are better suited for deep waters, due to the weight reduction; the downside is that the number of offshore installation campaigns is tripled, because the transmission system still requires three cores to function. Three-core cables are usually preferred in shallow waters paper[2].

A cable core consists of a conductor in the center, which is covered by a three-layered insulation system. The insulation system is protected with a sheath of lead and a final sheath of polyethylene. Single-core cables are armored directly, while three-core cables need three cores to be combined into a triple helix before being armored (armor consists of a layer or layers of stranded metal wires at the cable exterior). Fig. 1 presents a simplified sketch of the two cable systems.

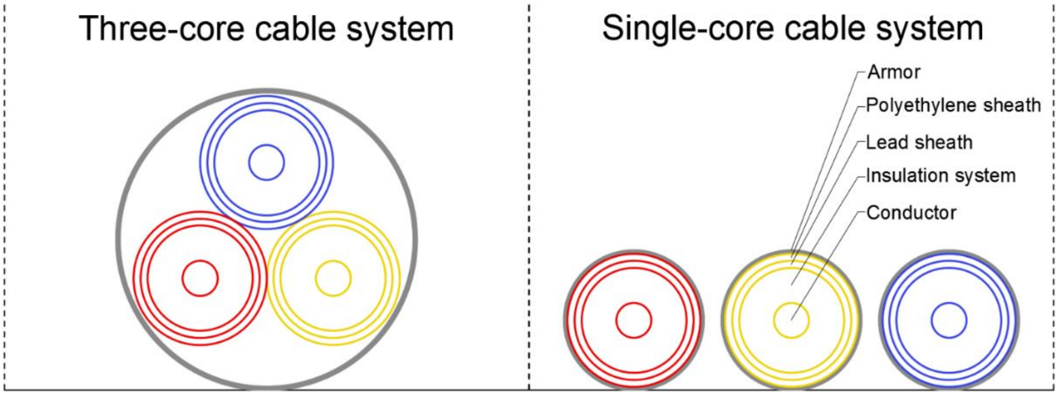

Fig. 1. Sketch of (a) three-core cable system and (b) single-core cable system.

1.2. Design

Broadly speaking, the necessary considerations needed to design a power cable fall into one of two categories: mechanical or electrical. Mechanically, the cable must be able to withstand an offshore installation campaign without suffering permanent damage. Electrically, the cable must be able to carry the load current continuously without heating up to the point of deterioration. The primary heat source is the conductor, which itself is not at risk of damage from heat. However, the conductors' first point of contact is the insulation system; this is made up of crosslinked polyethylene (plastic), which will begin to deteriorate if it is exposed to temperatures above 90 °C for extended periods. This is a universal design constraint.

1.3. Case

Several European countries are committed to phasing out fossil fuels and turn to renewable energy sources, such as solar and wind[3]. This has led to a shift in the market for submarine power cables, due to the rapid rise in offshore wind power. A challenge when designing power cables intended for offshore wind power is that the load pattern is literally as difficult to predict as the weather is. There is a known theoretical maximum load (based on the turbines), but that is rarely reached and maintained for extended periods. As a result, the power cables are often designed to cover most, but not all, load patterns. Whether the power cable should cover a particular load case is usually based on wind pattern measurements combined with a cost-benefit analysis. This design choice offers a reduction in initial costs, but the current will have to be throttled intentionally if the wind speed surpasses permissible levels, because it would cause overloading.

Overloading is not in itself intrinsically harmful for the cable system; the source of damage is rising temperatures. An overload can be defined as running a current through the cable that will cause the temperature to rise above safe levels, eventually. A cable can safely be overloaded for a while, such as during a wind speed burst, given that the cable starts at a sufficiently low temperature. The issue is that the cable's internal temperature in operation is not known with enough detail to make that judgement; the safe option is to throttle the current.

Three-core cables are usually the go-to solution in offshore wind power projects, because it is more convenient to install the turbines in shallow water. The thermal profile of three-core cables is difficult to model precisely, because the cables are fundamentally asymmetric and every metal component acts as a heat source. The International Electrotechnical Commission (IEC) provides a model that is convenient and works well with static or cyclic load patterns, but not with sporadic load patterns[4]. To achieve the necessary level of detail with an arbitrary load pattern, one must turn to finite element analyses i.e., a way to use first principle models for more complicated constructs, such as cables. These tools are powerful and flexible, but they require a high level of prerequisite knowledge, as well as significant effort.

1.4. Need

Nexans Halden AS needs a reliable and convenient method or tool for calculating and visualizing the thermal profile in high voltage submarine power cables, given an arbitrary load pattern.

1.5. Goal

Build and test a thermal model based on first principles for three-core submarine power cable systems, capable of predicting the cable's thermal profile, given an arbitrary load profile.

1.6. Research questions

The stated need and goal, as well as a few known unknowns, led to the following research questions:

- How do the first principle model predictions compare to empirical measurements in transient periods and steady state conditions?
- How do the first principle model predictions compare to predictions made by models given in the prevailing standards?
- How do the swellable tapes and the filling compound influence system performance thermally?

Furthermore, the research explores how the developed model fits in the design phase of the systems engineering lifecycle.

1.7. Definitions

- Reliable: The model's predictive power is not predicated on a specific set of input parameters; it gives reliable predictions for a realistic range of input parameters.
- Convenient: The level of usability should be such that using the model does not require specialized training; a basic understanding of power cables should be sufficient.
- Arbitrary: Can change sporadically with time, without showing signs of periodicity.

The developed model will assume that the input parameters are realistic during normal operation. It will not cover situations outside the scope of normal operation, such as short circuits, where the power cables experience a surge of current for a short duration (typically tens of thousands of amperes for a second or less).

2. Research method

The research will primarily rely on testing via collecting empirical data and comparing it to the model built on first principles. The project has constructed a testing rig, designed to heat up cables by running a current (up to 3000 ampere) through the conductor. This setup will be used to gather empirical data on thermal transients in cables, which can be compared to the model's predictions.

The model's predictions will also be compared to the predictions made by the IEC model, which is used to calculate steady state temperatures when designing cables[4].

Swellable tape's thermal properties are currently taken from IEC 60853-2 Table E1[5]. Note that the thermal properties for swellable tape, according to Table E1, are the same as that of several other materials, such as the thermal capacity of rubber and asbestos. Materials with vastly different compositions rarely share the exact same thermal properties. Thus, there is reason to suspect that the values given in IEC 60853-2 are conservative estimates.

Regarding the thermal properties of the filling compound, Nexans' material experts asked for that information from the supplier, but the supplier confirmed that they had not performed measurements on thermal properties. Therefore, as part of the research, the thermal properties of swellable tape and filling compound were measured through testing, to quantify their overall influence on the system's performance.

3. Theoretical background

3.1. Thermodynamics

Thermodynamics is the science of energy and energy transformation. The model is based on the underlying principles of thermodynamics, specifically the principles related to heat transfer. The phenomena that are key to the model are briefly described in the following subsections. A description of the symbols used is given in Appendix A. This section makes a general reference to the work by Çengel et al.[6].

3.1.1. Heat transfer

Conduction, convection, and radiation are mechanisms of heat transfer relevant to the model. Conduction deals with thermal energy propagating through solid materials, convection is heat transfer between a solid surface and a fluid, and radiation describes thermal energy escaping a surface via electromagnetic waves. Conduction is expressed mathematically in Fourier's law of heat conduction as:

$$\dot{Q}_{cond} = -kA\frac{dT}{dx} \tag{1}$$

Convection is conduction coupled with fluid dynamics. The complexities introduced by fluid motion are compressed into a single coefficient, which will be dependent on system geometry, temperature difference, the type of fluid and whether the fluid is forced to move by an external force (such as a fan or pump). Mathematically, this is modelled with Newton's law of cooling:

$$\dot{Q}_{conv} = -hA\Delta T(t) \tag{2}$$

Chaotic changes in atoms' and molecules' configuration of charged particles give rise to the phenomenon of radiation. It can propagate without an intervening medium and suffers no attenuation in a perfect vacuum. All matter absorbs and emits radiation. Radiation is therefore modelled as the difference in absorbed and emitted radiation:

$$\dot{Q}_{rad} = \varepsilon\sigma A_s(T_s^4 - T_{surr}^4) \tag{3}$$

Note that Equation 3 is a special case, where the object is surrounded by a much larger surface (such as the walls in a room), separated by a gas that has negligible effect on the radiation (such as air).

3.1.2. Thermal resistance

Thermal resistance measures how much a material will resist heat transfer. In steady state conditions, the following equation holds:

$$\dot{Q} = \frac{\Delta T}{R} \tag{4}$$

3.1.3. Thermal capacity

Thermal heat capacity describes the relationship between thermal energy and temperature. It is a measure of the amount of energy needed to increase the temperature by a given amount. For example, a kilo of copper needs approximately 390 joules of thermal energy to increase the temperature by one kelvin.

3.2. Electromagnetism

The thermal energy released in the cable stems from phenomena described by electromagnetism, which makes the theory of electromagnetism relevant to the model. Relevant phenomena are briefly described in the following subsections. This section makes a general reference to the work by Young and Freedman[7].

3.2.1. Electric power

Electric power describes rate of work that stems from electric charge moving through a difference in electric potential. The following relationship describes electric power in a purely resistive electric circuit running on direct current:

$$P = VI \tag{5}$$

In the case of running a current through a conductive material, the work performed is released as thermal energy. In circuits running on alternating current, the electric power is also dependent on the cosine of the phase angle between the current and the voltage.

3.2.2. Electromagnetic induction

Moving electric charges are always associated with a magnetic field, and magnetic fields interact with the surrounding materials. Materials respond differently to the presence of magnetic fields; in the case of power cables the most notable materials that respond to magnetic fields are copper, aluminium, lead, and certain types of steel.

Electromagnetic induction is described by Faraday's law, which states that the induced electromotive force is proportional to the negative rate of change in magnetic flux:

$$\varepsilon = -\frac{d\Phi_B}{dt} \tag{6}$$

The negative sign in Faraday's law stems from Lenz's law, which gives the direction of the induced electromotive force. In general, an induced electromotive force will oppose a change in magnetic flux.

Electromagnetic induction gives rise to phenomena such as eddy currents (locally circulating currents), which cause transmission losses in power cables. Induction must therefore be considered when attempting to model thermal transients in power cables.

4. Modelling

Systems Engineering often use modelling as a tool. There are different kind of models. Muller[8] explains a set of these models as: (i) *first principle models* – a model based on the theory (laws of physics), that are converted into mathematical models to predict the outcome of the system, (ii) *empirical models* – a model based on observations and measurements, these models describe what we observe, (iii) *conceptual models* – these models bridge first principle and empirical models, and are simple enough to understand and to reason, realistic enough to make sense, (iv) *mental models* – models in our human brains, these models depend entirely on the individual and their background, and finally (v) *simulations* – an executable model based on first principle and empirical models, provides users with understanding when transforming outcome into insights.

System models can be used for many purposes. Models can be used to support architecting system solutions, as well as break mission and system requirements down to system elements. Different models may be required to address different aspects of the system design and respond to the broad range of system requirements. This may include models that specify functional, interface, performance, and physical requirements, as well as other nonfunctional requirements such as reliability, maintainability, safety, and security[9].

4.1. Concept

For three-core cables, chasing analytical solutions for transient periods is unfeasible, due to factors such as the complicated geometry, the wide variety of materials, and the number of heat sources. The concept is based on the first principle model (from now on "the model") and therefore centered on dividing the system into a finite number of elements. Each element is associated with several thermal characteristics (resistance, capacity, temperature), as well as having interfaces to adjacent elements. Elements that are electrically relevant are equipped with an electrical overlay. The overlay feeds thermal energy into the system to simulate transmission losses.

Transient periods are divided into smaller increments, i.e. timesteps. The model assumes steady state conditions during each timestep. With that assumption, the energy exchange between elements is calculated in each timestep using steady state equations. That exchange of thermal energy translates into a change in temperature. Euler's method is used to numerically calculate the energy exchange in each timestep.

4.2. Euler's method

Euler's method is an explicit method to solve ordinary differential equations. It works well on so-called "well-behaved" problems, i.e. problems that have a steady rate of change. However, Euler's method will tend to diverge on problems that are not well-behaved. These are problems that experience bursts of rapid change, such as mechanical impacts or electrical short circuits[10].

The primary benefit with Euler's method is that it is computationally cheap to implement. It is direct (explicit); there are no intermediate steps needed in each iteration. In contrast, implicit methods (such as the backward Euler's method) require algebraic equations to be solved in each iteration. Those equations are often solved numerically, which means that the number of calculations needed can increase significantly.

4.3. Trade-offs

The most glaring trade-off is the one between the resolution of the simulation, and the computational resources needed. There are two main parameters that affect this: the duration of each timestep and the number of elements. Those two parameters are also interdependent, because increasing the number of elements will make the physical size of each element smaller. Smaller elements will have lower thermal resistance (increasing the heat flux) and a lower thermal capacity (energy exchanges will have a bigger impact on temperature change). Thus, increasing the number of elements will also increase the risk of divergent solutions, which puts a more stringent constraint on the timestep duration.

Another essential trade-off is the one between flexibility and usability. Commercial FEM software has near-infinite flexibility in the sense that it can simulate almost anything, if it has enough computational resources available. This flexibility comes at the expense of usability; the FEM software expects a nontrivial level of knowledge on the part of the user. Specialized software, such as a model that is designed specifically for cable systems, can achieve a higher level of usability by unburdening the user from building the system from scratch. However, a certain level of flexibility is still required, so that the model can be applied to a range of use cases.

4.4. Architecture

The model's architecture is separated into two distinct phases: building the system and acting upon the system. Building the system happens on behind the scenes at start-up and bases itself on the input parameters defined by the user. The building consists of declaring the necessary elements and interfaces, and then assembling those elements and interfaces into a coherent system. Acting upon the system can be done in real-time by the user, where the state of the system is updated accordingly. For example, the user can initiate a simulation and then export the results to a file.

The architecture is shown in Fig. 2, where the separation of the two phases is indicated by the dashed line. Note that the architecture is intended to show how the model is modularized and how the various modules interact.

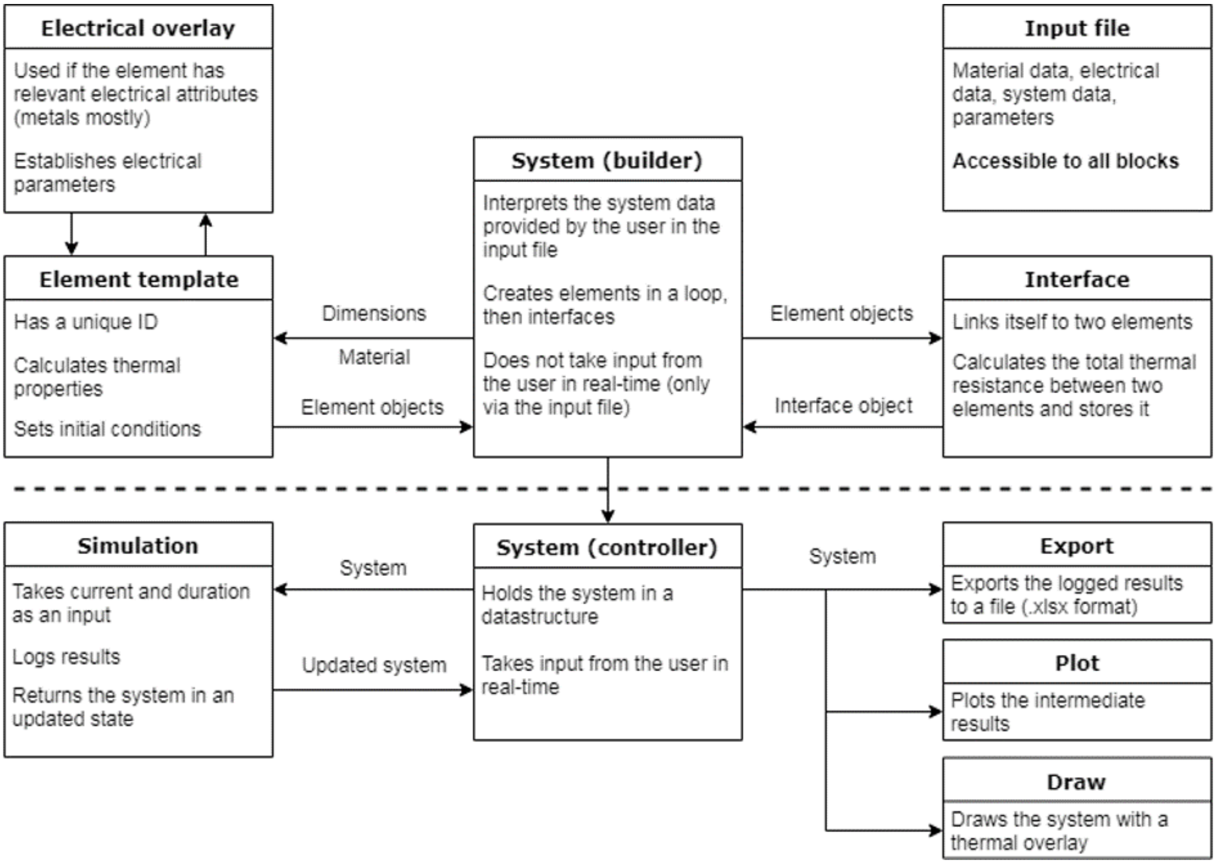

Fig. 2. System architecture showing how the model is modularized and how the modules interact.

4.5. Model development

The model development had two primary milestones: build and test a single-core model, then build and test a three-core model. The single-core model will serve as a steppingstone. It will be developed such that it can be transferred into the three-core model, by taking advantage of the similarities between the two cable variants.

The models (single-core and three-core) were developed in Python[11]. Python was chosen because it offers features relating to systems integration, compatibility, and usability that are key in this research, such as integration with Microsoft Excel (used often when designing cables at Nexans).

The final version of the single-core model ended up at approximately 1200 lines of code, while the final version of the three-core model ended up at approximately 1050 lines of code. Much of the single-core model code was reused in the three-core model, such as building the core and the element ID system. The single-core model was capable of modelling cables both in air and in soil, and it was also optimized for speed to make testing less cumbersome. These two factors are the cause of the single-core model having more lines of code.

5. Data collection

5.1. Cable heat cycling

This section will describe the setup and cable objects used to collect empirical data on thermal transients in single-core and three-core cables.

5.1.1. Test setup

In the case of collecting data on single-core cables, the setup consisted of a motorized autotransformer connected to a full-bridge rectifier (AC to DC converter). The rectifier was connected to the cable object in series with a temperature-independent shunt resistance. A computer program measured the voltage drop across the resistance via a voltmeter, which allows it to calculate and record the current in the cable object. A schematic is shown in Fig. 3. The single-core cables were equipped with temperature sensors on the conductor, on the lead sheath and on the surface. The cables were kept indoors and surrounded by air.

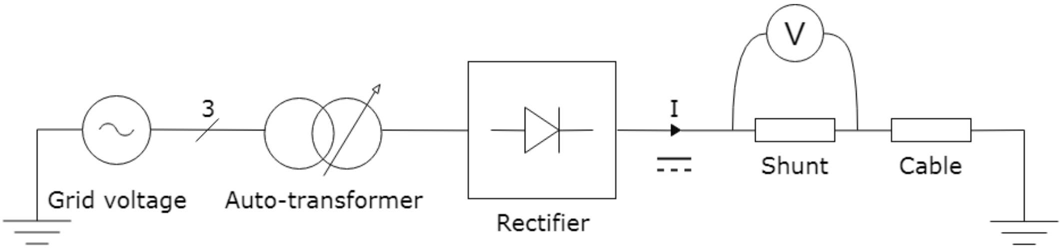

Fig. 3. Schematic of single-core setup.

The three-core setup was similar to the single-core setup, but there was no rectifier involved since it ran on alternating current. The transformer outputs were connected directly to the cable cores. One core (of the three) was equipped with a shunt resistance to monitor the current continuously. The current in the two remaining cores, as well as the three lead sheaths, could be measured manually using an ampere meter clamp. This was used to verify that the current was balanced between the cores and sheaths (equal current in the cores and equal current in the sheaths).

The three-core cable was buried in soil inside a container, which eliminated the challenges related to convection and radiation (elaborated in the Results and Discussion section). Additionally, the temperature transients observed in soil are more realistic since the cables are buried in the seabed.

5.1.2. Cable objects

There were four cable objects: three single-core objects and one three-core object. Table 1 shows basic information about each design; they were selected such that the data yields information about a wide range of designs. Fig. 4 shows cross-section drawings of the second (left) and fourth (right) designs from Table 1.

Table 1. Basic information about the cable designs.

Conductor cross-section	Conductor material	Conductor type	Nominal voltage level	Cores	Armored
400 mm^2	Copper	Round wire	52 kV	1	No
1200 mm^2	Copper	Round wire	245 kV	1	No
2000 mm^2	Aluminium	Flat wire	420 kV	1	No
1200 mm^2	Aluminium	Round wire	245 kV	3	Yes

Fig. 4. Cross-section drawings of (a) single-core cable and (b) three-core cable.

5.2. Thermal properties of swellable tape and filling compound

This section describes the setup for measuring thermal resistance and thermal capacity in swellable tape and filling compound. Note that the thermal resistance in filling compound was deemed to be negligible, because the conductor has metallic (low resistance) contact throughout. Even if the filling compound has a high resistance, the thermal energy can pass through the low resistance metal.

Thermal resistance was measured by placing a layer of the swellable tape between two square copper plates (highly thermally conductive). One of the copper plates had an integrated heating element, and both copper plates had thermocouples to measure the temperature. The sides are thermally insulated. See Fig. 5 for a sketch of the test setup.

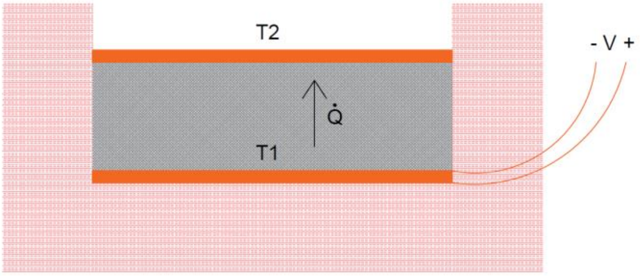

Fig. 5. Principle sketch of thermal resistivity test setup.

The heating setup was left with the heating element turned on for approximately two days, which allowed the system to reach steady state conditions. At steady state, the temperature gradient across the material is linear. With a known power, temperature difference, height and area, the thermal resistivity can be calculated using Equation 1 and Equation 4.

Thermal capacity was measured by heating up the material in question to a known temperature, and then placing it in an isolated chamber filled with water at a known temperature. When this system reached its equilibrium temperature, the increase in temperature in the water gave information about the energy transfer (the thermal capacity of water is known). By energy conservation, the same amount of energy must have been lost by the material in question, and the decrease in temperature is known. The difference in temperature and the difference in energy are enough to calculate the thermal capacity of the material. Note that the mass of the water and the material in question must be known as well. The two materials (swellable tape and filling compound) were heated to 70 °C with a laboratory heating cabinet.

6. Results and discussion

6.1. Single-core cable systems

The three single-core cable systems were subjected to a heating period followed by a cooling period, with temperature sensors mounted on the conductor, the lead sheath, and the outer sheath. Ambient temperature was also recorded during the heating and cooling periods.

In the case of the cable with a 400 mm^2 copper round wire conductor, the model showed a good fit throughout. However, the model deviated from the measured values on the cable with a 1200 mm^2 copper round wire conductor (see Fig. 6) and the cable with a 2000 mm^2 aluminium flat wire conductor. In both cases, the model predicted a temperature at the end of the transient that was almost 10 % higher than the measured value.

These results sparked an investigation to find the root cause or causes. The primary suspect initially was the effect of radiation, because radiation is affected by the temperature of the surrounding surfaces, which is not necessarily the same as ambient temperature. With the walls and roof leading outdoors (which was the case here), radiation can be affected by factors such as time of day and cloud cover, even when the cable is located indoors.

However, radiation does not account for why the model's predictions of the 400 mm^2 conductor cable were a good fit. Also, the deviation started early in the simulation, and the error accumulated at a steady rate. This, combined with the prediction trajectory, suggests that the problem is a constant error in thermal resistance. This led the investigation towards the input parameters relating to cable dimensions, which had been assumed to be at nominal values in the model.

Samples are taken repeatedly during cable manufacturing, which are used for routine testing. Part of the routine test regime is to measure the dimensions of the cable core, which means that the measured values can be found in the records. Table 2 shows a comparison between nominal values and measured values for the cable with a 1200 mm^2 copper conductor.

Table 2. Comparison between nominal values and measured values.

Layer	Nominal diameter	Measured diameter	Nominal thickness	Measured thickness
Conductor	43.7 mm	44.1 mm	-	-
Insulation	-	-	22.0 mm	21.2 mm
Outer semiconductive layer	93.7 mm	94.2 mm	-	-
Lead sheath	99.8 mm	101.6 mm	2.20 mm	2.11 mm

The model's input parameters were updated to reflect the measured values, which significantly improved the model's predictions in terms of accuracy. The comparisons are shown in Fig. 6. When using measured cable dimensions (as opposed to nominal), the single-core model is accurate enough to be regarded as completed.

6.2. Three-core cable systems

The three-core cable system was subjected to a heating period of approximately nine days. Several tons of wet sand make the system's response slower, and thus the time it takes to reach equilibrium increases. Even at nine days, the temperature measurements suggested a slight trend upwards, as seen in Fig. 7.

A sample of the sand used was sent to a laboratory to measure thermal resistance, because the thermal resistance of sand is known to vary significantly depending on factors such as water content, compression, and how fine the grains are. Measurements were made on dry sand, fully saturated sand, and sand with approximately 5.7 % water content, as well as no compression and tight compression (pressed). The measured values ranged from 0.40 to 0.99 Km/W (increased compression and water content reduced resistance). Measuring the thermal resistance of the sand was not in itself part of the research, but it was considered necessary because it was vital input for the model. The nine days of heating were simulated in the three-core model and superimposed on the measured values, see Fig. 7.

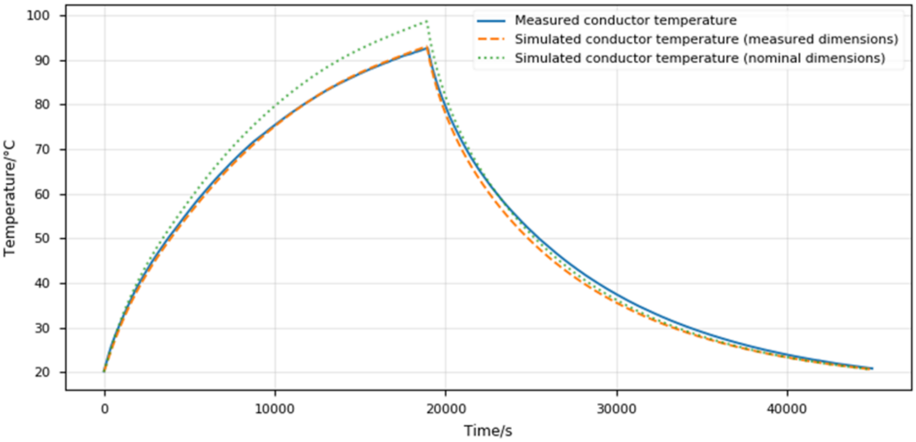

Fig. 6. Conductor temperature: Measured and predicted (modelled) for single-core cable.

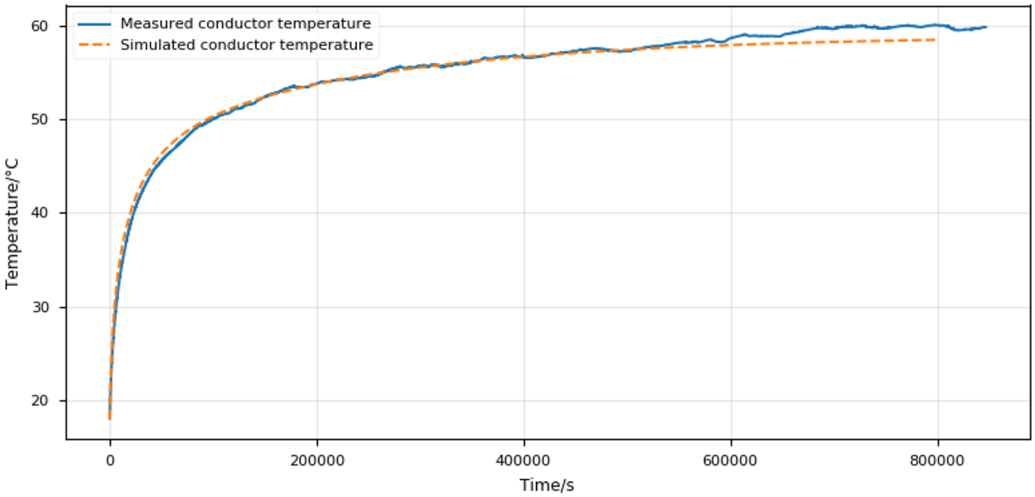

Fig. 7. Conductor temperature: Measured and predicted (modelled) for three-core cable.

The results displayed in Fig. 7 are encouraging, though the model appears to deviate towards the end of the nine-day period. However, the model is tending towards equilibrium, which is the expected behavior of a thermal system with stable conditions, while the measured values are still increasing. The likely explanation for these observations is that the sand is drying out due to the heat, particularly around the cable. If this is the case, it would mean that the thermal resistance of the system increases with time (at a rate that is related to temperature), and equilibrium would not be reached until the sand was completely dried out.

Relating this back to the first research question, how the first principle model's predictions compare to empirical measurements, the research shows that the developed model accurately predicts the thermal transient in the three-core cable systems. Though in future testing, the thermal resistivity of the sand should be measured before and after a transient, to investigate whether the sand is getting dryer and quantify the difference if it is.

6.3. Predictions by prevailing standards

The IEC model makes a few assumptions that do not hold in this case, such as water being above the soil, rather than air. The IEC model also assumes that the soil extends to infinity in all other directions, but in this case the soil extends to the container walls. Consequently, the IEC model is well-suited to handle the cable design itself, but the environment around the cable in the test setup is too novel to be properly modelled. Despite this, the IEC model can give valuable insight into the temperature distribution in the cable.

The IEC model was tuned with the same input parameters, such as cable design, electric currents, and soil conditions. Then, the cable burial depth was adjusted such that the predicted conductor temperature was the same in both models (IEC and Python). Steady state temperature increases with burial depth in the IEC model.

IEC does not give a complete image of the temperature distribution, but it calculates the temperature of the conductor, lead sheath, armor, and cable surface. It only gives a single value for each, while the developed model provides a complete thermal profile, as shown in Fig. 8. The temperature predictions by the IEC model and the first principle model are shown in Table 3.

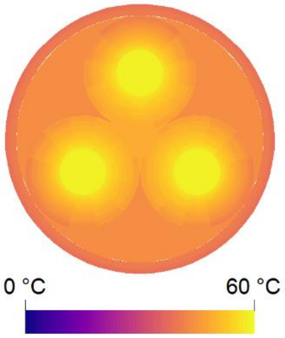

Fig. 8. Thermal profile of three-core cable.

Table 3. Comparison between IEC model and first principle model.

Component	IEC model	First principle model		
		Average	Min	Max
Conductor	58.7 °C	58.70 °C	58.69 °C	58.71 °C
Lead sheath	45.2 °C	45.54 °C	42.34 °C	48.29 °C
Armor	40.5 °C	40.35 °C	40.13 °C	40.58 °C
Surface	36.4 °C	38.21 °C	38.06 °C	38.36 °C

As shown in Table 3, the lead sheath has a measurable temperature gradient across, while IEC assumes the lead sheath is isothermal. Though the average temperature in the lead sheath (according to the developed model) is strikingly close to the value calculated by the IEC model. The same goes for the armor, though the two models appear to deviate slightly at the cable surface. One factor that contributes to this is that IEC assumes a thermal resistance of zero in the armor, while the model calculates a thermal resistance based on the characteristics of the steel.

Relating this back to the second research question, how the first principle model’s predictions compare to predictions made by the prevailing standards, the research shows that the two models (IEC and first priniple) make similar predictions of how thermal energy propagates through the cable. These two models use entirely different methods but arrive at nearly identical answers. However, since it is not possible to recreate the environmental parameters in the IEC model, the conductor temperatures were not possible to compare.

6.4. Thermal properties of swellable tape and filling compound

The results from measuring the thermal properties of swellable tape and filling compound are provided in Table 4.

Table 4. Results from measuring thermal resistivity and capacity on swellable tape and filling compound.

Material	Thermal resistivity	Volumetric heat capacity
Swellable tape	$R = (12.2 \pm 2.4)\frac{Km}{W}$	$C = (460 \pm 50)\frac{kJ}{m^3K}$
Filling compound	N/A	$C = (1680 \pm 220)\frac{kJ}{m^3K}$

It is interesting to compare the measured values to those used in the current standards. For swellable tape, the measured thermal resistivity is twice as high as the value defined in the standards, and the measured thermal capacity is one-fourth of the value given in the standards. There are no values available for filling compound.

The filling compound's thermal capacity was measured to determine its influence on the conductor's total thermal capacity. If the filling compound has a significant effect, it should be implemented in models attempting to predict thermal transients in cables (thermal capacity does not affect steady state temperatures).

As an example, the diameter of the 1200 mm^2 aluminium conductor shown in Fig. 4 has a nominal value of 42.9 mm, which equals a cross-sectional area of approximately 1445 mm^2. That leaves 245 mm^2 of occupied space that is not aluminium. It is safe to assume that this space is filled with filling compound, considering that the conductor has been tested and is deemed waterproof at 10 bar water pressure as part of the qualification process[12]. Below is a comparison of thermal capacity in the conductor with and without filling compound:

$$C_{without} = 2.5 \cdot 10^6 \frac{J}{m^3K} \cdot 1200\,mm^2 = 3000\frac{J}{mK}$$

$$C_{with} = 2.5 \cdot 10^6 \frac{J}{m^3K} \cdot 1200\,mm^2 + 1.68 \cdot 10^6 \frac{J}{m^3K} \cdot 245\,mm^2 = 3412\frac{J}{mK}$$

The filling compound increases the thermal capacity of the conductor by nearly 14 %. Since the conductor is the primary heat source, and thus the first component to respond to an increase in temperature, this finding is a significant factor that must be incorporated in the developed model.

Relating this back to the third research question, how the swellable tapes and the filling compound influence system performance thermally, the research shows that both components will affect the thermal response (during transients) of the system, and the swellable tapes will also affect the ultimate steady state temperature.

Higher thermal capacity makes the system respond slower. More thermal energy must be released in the conductor for it to heat up, and more energy must be siphoned out of the conductor for it to cool down. In terms of system performance, the result is that the cable can be subjected to an overload with either longer duration or higher current, but it will also take longer for it to cool.

Higher thermal resistance around the conductor (via swellable tapes) will throttle the amount of energy released to the environment. With all other parameters being equal, higher resistance in the swellable tapes will make the conductor warmer. From a system design perspective, these findings can be used to argue for minimizing the use of swellable tape.

6.5. Developed model's role in cable systems design

The developed model does the same job as the currently used IEC model, except that it provides detailed information about the transient periods, the thermal profile in the cable, and it can handle an arbitrary load profile.

This makes the model more suited for designing cables that are intended for offshore wind power, because it can handle the sporadic nature of the load profile (due to changing wind speeds).

Although the model must be thoroughly tested with different use cases before it can be implemented as the de facto current rating model, it can potentially become a key component in the design phase of the systems engineering lifecycle at Nexans. Either as a complementary model or a replacement model, depending on the needs of each specific project. An added benefit, if compared to finite element analyses, is that it does not impose increased complexity on the user, even though it provides a more detailed analysis of the modelled system. Ultimately, the benefit of modeling and simulation is proportional to the stakeholders' perception of the timelines, trustworthiness, and ease of use and maintenance of the model or simulation[9].

7. Conclusions

The purpose of this research has been to develop and test a fit-for-purpose model based on the first principles that can give detailed information about thermal transients in three-core cable systems used for offshore wind power. The developed model could potentially be used to optimize three-core cable designs by describing the thermal transient in any given wind scenario. This could allow clients to take full advantage of short-term bursts in wind speed when they normally would have had to throttle the current in the transmission system.

The developed model is currently a proof of concept. The model has been verified by empirical data and aligned with the model given by the International Electrotechnical Commission, relating back to the first and second research questions, respectively. The model leverages some of the ideas behind finite element analyses, which gives it some of the same predictive power. It lacks the flexibility of finite element analyses, but it achieves a higher level of usability by being specialized and tuned specifically for three-core cables. From a user perspective, the model unburdens the user from designing the system from scratch, because it has a hardcoded blueprint of a three-core power system.

To address the third research question, the thermal characteristics of the swellable tapes and the conductor filling compound were measured. The thermal resistivity of swellable tape was twice as high as the value given by the prevailing standards, and the thermal capacity of the filling compound (an unknown) was shown to increase the thermal capacity of the conductor by almost 14 % in the three-core cable used in this research. Both observations are significant for thermal transients and must be incorporated in any model that hopes to make accurate predictions.

In summary, the concept has been shown to work as expected and the model as a prototype works well, based on comparisons with empirical measurements. Although there is more work to be done, it could eventually become an intrinsic part of the designing of three-core power cable systems.

8. Future work

The model requires rigorous testing before it can be the litmus test when designing cables in delivery projects. This includes testing the model on several different three-core designs, with varying conditions and load profiles.

Currently, the model is limited to the most common use case: three-core cable buried in soil. However, there are other use cases that must be included in the model. For example, offshore wind farms typically have an offshore platform where the three-core cable is terminated. The cable transitions from the seabed to the platform deck via a J-tube (steel pipe shaped like the letter J). Designing cables for offshore wind farms include thermal considerations in the J-tube, which means that this use case must be included in the model. The model will need a proper graphical user interface. This is key for usability.

Finally, the model should be optimized for speed in the same manner that the single-core model was. The single-core model is (roughly estimated) a thousand times faster than the three-core model. Optimizing can be quite time consuming, because changing how the model performs calculations calls for the output to be reverified.

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Appendix A. List of symbols and descriptions

Symbol	Phenomenon	Unit	Description
$\dot{Q}$	Heat flux	W	Rate of change in thermal energy
k	Thermal conductivity	$\frac{W}{Km}$	A measure of how well the material conducts thermal energy
ρ	Thermal resistivity	$\frac{Km}{W}$	A measure of how well the material insulates thermal energy (inverse of thermal conductivity)
R	Thermal resistance	$\frac{K}{W}$	How well a particular component or object resists the flow of thermal energy
A	Area	m^2	Physical size of a surface
T	Temperature	K	Average kinetic energy of atoms and molecules (macroscopic interpretation)
h	Convection coefficient	$\frac{W}{Km^2}$	Empirical proportionality value used to calculate the heat flux between a surface and a fluid
ε	Emissivity	$-$	Ratio of heat energy radiated by the surface and by a black body at the same temperature
σ	Stefan-Boltzmann constant	$\frac{J}{m^2K^4s}$	Proportionality constant that describes the relationship between radiated energy of a black body per unit area per second and the absolute temperature to the fourth power
P	Power	W	A measure of energy per unit time
V	Voltage	V	A measure of electric potential between two points
I	Current	A	Rate of flow of electric charge
E	Electromotive force	V	Electrical work performed by a non-electrical (often magnetic) source
Φ_B	Magnetic flux	T	Defined as the surface integral of the normal component of the magnetic field passing through the surface

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