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Published in:
2019 IEEE 13th International Conference on Compatibility, Power Electronics and Power Engineering (CPE-POWERENG)

DOI:
10.1109/CPE.2019.8862377

Publication date:
2019

Document version:
Accepted manuscript

Citation for pulished version (APA):
Nielsen, T. V. M., Jakobsen, S., & Savaghebi, M. (2019). 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)* [8862377] IEEE. https://doi.org/10.1109/CPE.2019.8862377

Dynamic Rating of Three-Core XLPE Submarine Cables Considering the Impact of Renewable Power Generation

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***Abstract*— This paper discusses how to determine the most suitable high voltage alternating current (HVAC) submarine cable in the design phase of new projects. A thermal ladder network method (LNM) is used to analyse the thermal behaviour in the centre of the conductor as the hottest spot of the cable. Based on an approved static cable rating method and thermal cable analysis of transient conditions, applied by a step function with transient time duration greater than one hour, this paper proposes a method for a dynamic rating of submarine cables. The dynamic rating accomplished through an iterative process. The method is tested with MATLAB simulation and validated in comparison to a finite element method (FEM) based approach with high accuracy.**

***Index Terms*— Dynamic Cable Rating, High Voltage Alternating Current Submarine Cables, Renewable Power Generation, Static Cable Rating, Thermal Cable Analysis of Transient Conditions.**

I. INTRODUCTION

It has not always been as challenging to fit energy generation with the consumers' power consumption patterns as it is now. Energy sources based on fossil fuels are replaced by renewable power generation, such as wind energy, in order to reach one of the global climate goals for at least 27% shares of renewable energy by 2030 [1]. Therefore, it is essential to investigate methods to reduce the cost associated with the transmission of renewable power generation. Multiply studies discuss implantation of Dynamic Line Rating (DLR) forecasting on already constructed lines, to optimise transmission capacity [2][3].

The market for renewable power generation is growing fast, and the number and size of offshore wind farms have increased rapidly in the past years. According to the Global Wind Energy Council, the annual installed global wind energy capacity has increased from 6.5 GW in 2001 to 52.4 GW in 2017 [4]. The disadvantage of such renewable power generation is the uncontrollability, as the power production varies with the speed of the wind.

In order to carry the massive amounts of power through a submarine cable (shown in Fig. 1) connecting a offshore renewable power generation source, such as a wind farm to a onshore station and at the same time minimise the levelised energy costs (LEC)[5], it is essential to select the most suitable cable for each specific case. A way to accommodate this is to change the design-phase and dynamically rate cables based on a worst case estimation of varying load profiles and surrounding conditions (shown in Fig. 1) of different cable environments, such as burial depth L, thermal soil resistivity ρ and ambient temperature θ_A.

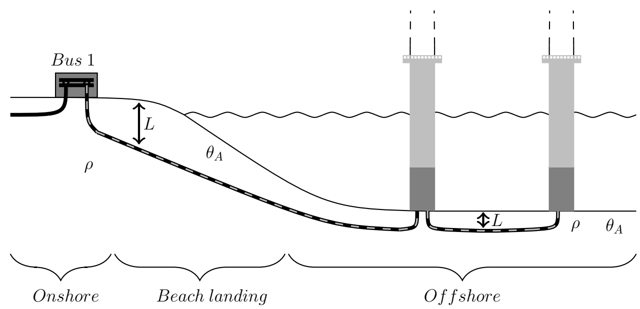

Fig. 1. Submarine cable power system from offshore wind farm and surrounding conditions

HVAC submarine cables are developed to carry a great amount of power across the water. The cable conductors consist of copper (Cu) or aluminium (Al) depending on size and price. Cross-linked polyethene (XLPE), with a maximum operational temperature of $90°C$, is the commonly used materials of insulation. A common construction of a three-core XLPE separate lead (SL), sheath type submarine cable, is shown in Fig. 2.

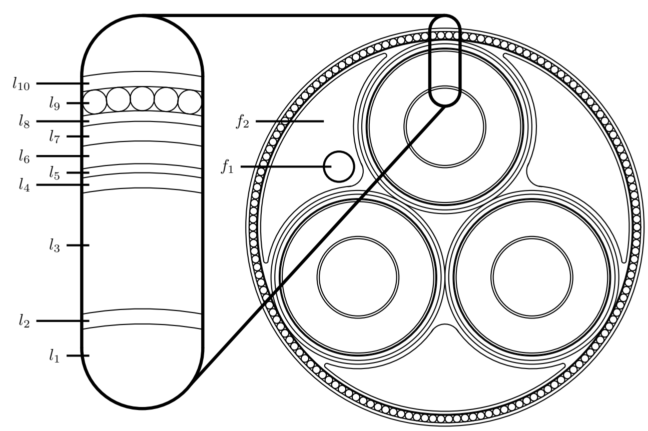

Fig. 2. Common construction of a three-core XLPE SL sheath type submarine cable

where, the internal part of the cable contains l_1: Conductor, l_2: Conductor screen, l_3: Insulation, l_4: Insulation screen, l_5: Swelling tape, l_6: Metallic sheath / screen, l_7: Anti-corrosion sheath and the common covering contain l_8: Bedding, l_9:

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Armour and l_{10}: Outer serving. The element f_1 is the optical fibre used for communication, and DTS [6] and f_2 represent the fillers and is usually filled with water in operation.

Static rating of HVAC cables in the voltage range 30kV to 275kV can be calculated based on a series of standards from the International Electrotechnical Commission (IEC) named IEC 60287 [4] and has historically been conservative as it is based on worst-case assumptions and does not take into account real-time changes of surrounding conditions [7].

Renewable power generation such as wind energy delivers an unpredictable production profile varying from no- to full-load several times within 24 hours. In Fig. 3 a typical current profile from wind generation in Denmark is shown. By considering the thermal behaviour caused by the production variation, the design of the cable parameters can be according to the actual load. Instead of using the steady-state rated current I_r, which is the peak value of the actually flowing current I_a. Rating cables to conduct the actual current I_a, evaluated through a thermal cable analysis of transient conditions, proposed in IEC 60853-2 [8]. This way, the selection of cable parameters can be improved, which can result in an economic advantage in the development phase [5].

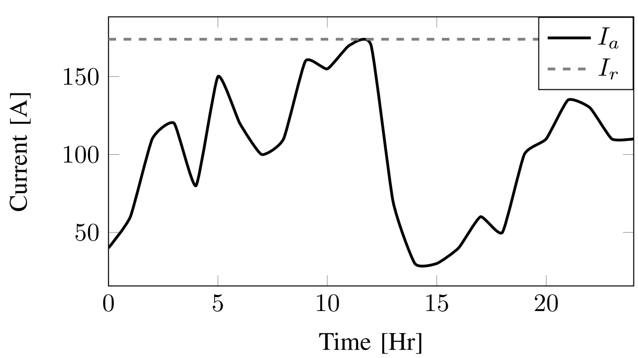

Fig. 3. Variable current profile illustrating the difference between the actual flowing current and the rated current

Thermal considerations of offshore submarine cables are worthy to investigate as the thermal soil conditions are better than onshore and thus there is an excellent opportunity for utilisation of the surrounding conditions in the cable current rating phase.

Previous work has shown, that based on a more dynamic approach, a significant improvement of cables transmission ability can be achieved using real-time monitoring systems on existing cables, such as distributed temperature sensing (DTS) [6]. This opens opportunities to investigate the possibilities to use a dynamic cable rating method in the design phase of new projects.

II. Dynamic Cable Rating Method

Dynamic rating of cables, as the main focus of this paper, involves rating cables due to variable cable loading. It is an iterative method containing static rating based on the IEC 60287 series [4] and a thermal cable analysis according to IEC 60853-2 [8]. In order to find an analytically solution of heat transfer from the center of the conductor to the surface of the cable and take into account the impact of the surroundings, a thermal ladder network is built up to represent the electrical parameters of the cable to evaluate the transient temperature response by forcing a step function shown in Fig. 4.

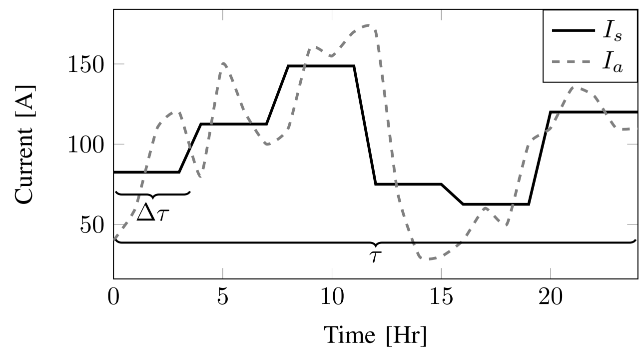

Fig. 4. Construction of a Step function, to minimise the evaluation time

Fig. 5 is a simplified overview of the iterative method. The first process is detailed in Section III, which describes the determination of cable loading, and electrical and thermal parameters. The second process, explained in Section IV, evaluates the transient temperature behaviour in the centre of the conductor, based on the electrical and thermal parameters determined in Section III. The first decision box represents the iterative process assessing the transient temperature response based on the applied step function. With the usage of XLPE as insulation, the upper boundary is at $90°C$. The third process represents the output of a suitable cable, base on dynamic cable rating.

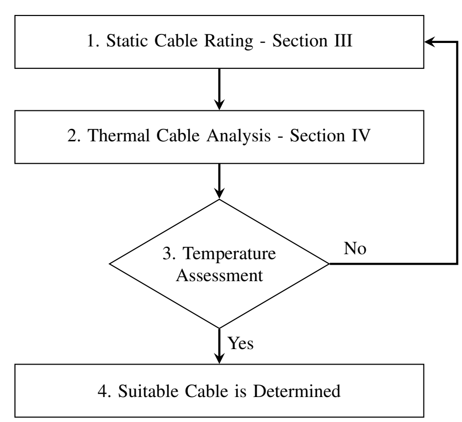

Fig. 5. Flowchart of the iterative dynamic cable rating method

III. Static Cable Rating

The dynamic cable rating method (shown in Fig. 5), is based on IEC 60287 series [9] to determine the cable parameters, in order to evaluate the thermal behaviour in Section IV.

A. Determination of Cable Loading

In order to determine the cable loading, the voltage level is fixed. The actual current I_a (shown in Fig. 3) is assumed to flow in the submarine cable (shown in Fig. 1).

B. Determination of Cable Losses and Loss Factors

IEC 60287-1-1 proposes a method to determine the conductor AC resistance R_{ac}, dielectric losses W_d, sheath loss factor λ_1 and armour loss factor λ_2. The references to IEC 60287-1-1 Sections, as given in Table I, are used to calculate the needed parameters of a three-core XLPE Submarine cable.

TABLE I
REFERENCE TO DETERMINATION OF IEC 60287 SERIES CABLE PARAMETERS

Cable parameter	Section in IEC 60287-1-1
AC resistance R_{ac}	2.1 AC resistance of conductor
Dielectric losses W_d	2.2 Dielectric losses
Sheath loss factor λ_1	2.3 Loss factor for sheath and screen 2.3.10 Cables with each core in a separate lead sheath (SL type) and armoured
Armour loss factor λ_2	2.4 Loss factor for armour, reinforcement and steel pipes 2.4.2.5 SL type cable

C. Determination of Thermal Resistances

To determine the cable rating, the thermal resistances are needed. IEC 60287-2-1 defines the thermal resistances T_1, T_2, T_3 and T_4, where T_1 is the resistivity between the conductor and metallic sheath/screen, T_2 is between metallic sheath and armour, T_3 is between armour and surroundings and T_4 is representing the surroundings. To simplify the calculation the following assumptions are made:

- Metallic layers are neglected, as the thermal resistance of them is negligible compared to poly-composite materials.
- The optical fibre inside the fillers is assumed not having any thermal impact.
- Swelling tape is assumed as a part of the insulation since its thickness is small and it is assumed to have the same thermal resistivity.
- The bedding material is assumed to be the same material as anti-corrosion sheath.

Fig. 6 show a static thermal representation of a three-core cable, based on the cable construction in Fig. 2, where the electrical resistances are equivalent to the thermal resistances listed in Table II and define the ability of the materials to impede heat flow, and the losses W_n is located in the original position. In Fig. 6, θ_c is the conductor temperature, θ_{os} is the outer covering (cable surface) temperature and θ_A is the ambient temperature of the surroundings. As the cable is a three-core cable and T_1 represent the resistance of the inner cables, the circuit is represented with T_1 as three resistances in parallel.

The thermal resistances shown in Fig. 6 are determined in (1), (2), (3) and (4) [10] Where, thermal resistivity ρ

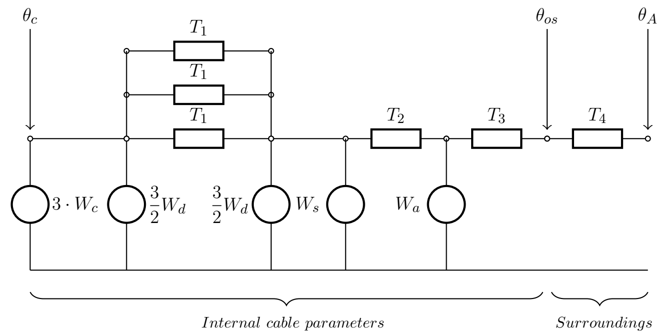

Fig. 6. Static representation of thermal resistances T_n in a three-core XLPE SL sheath type submarine cable, including power losses W_n located in the respective layers and temperature denotation θ_n

TABLE II
THERMAL-ELECTRICAL ANALOGY PARAMETER COMPARISON

Electrical	unit	Thermal	unit
Resistance R	Ω	Thermal resistance T	$k \cdot m/W$
Capacitance C	F	Thermal capacitance Q	$J/k \cdot m$
Voltage U	V	Temperature θ	^oC
Current I	A	Heat flow w	W/m

for commonly used cable materials and surrounding seabed conditions is defined in Table III.

TABLE III
COMMONLY USED THERMAL RESISTIVITY FOR CABLE MATERIALS AND SURROUNDINGS, AND SPECIFIC HEAT CAPACITY OF CABLE MATERIALS

Material (abbreviation)	**Thermal resistivity [9][11]** ρ $[K \cdot m/W]$	**Heat capacity [12][13]** c $[J/K \cdot m^3]$
Copper (Cu)	-	$3.46 \cdot 10^6$
Aluminium (Al)	-	$2.46 \cdot 10^6$
Lead & lead-alloy (Pb)	-	$1.47 \cdot 10^6$
Polyethylene (PE)	3.5	$2.4 \cdot 10^6$
Cross-linked polyethylene (XLPE)	3.5	$2.4 \cdot 10^6$
Polypropylene (PP)	10	$1.8 \cdot 10^6$
Seabed sand/gravel	0.6-0.9	-

where, t is the thickness of the respective cable layers, D_c is the conductor diameter, D_a is the outer diameter of the armour, D_{os} is the outer cable diameter and $G(X_s)$ is a geometric factor as a function of thickness of material between sheaths and armour X_s expressed as a fraction of the outer diameter of the sheath: $X_s = t_2/D_s$.

$$T_1 = \frac{\rho}{2\pi} \cdot \ln\left(1 + \frac{2 \cdot t_1}{D_c}\right) \quad (1)$$

$$T_2 = \frac{\rho}{6\pi} \cdot G(X_s) \quad (2)$$

$$T_3 = \frac{\rho}{2\pi} \cdot \ln\left(1 + \frac{2 \cdot t_3}{D_a}\right) \quad (3)$$

$$T_4 = \frac{\rho}{2\pi} \cdot \ln\left(\frac{2 \cdot L}{D_{os}} + \sqrt{\left(\frac{2 \cdot L}{D_{os}}\right)^2 - 1}\right) \quad (4)$$

$G(X_s)$ is determined in (5)[10].

$$G(X_s) = \begin{cases} 2\pi \cdot (0.000202380+ & \text{if } 0 < X_s \\ \quad 2.03214 \cdot X_s - 21.6667 \cdot X_s^2) & \quad \le 0.03 \\ 2\pi \cdot (0.0126529 + 1.101 \cdot X_s - & \text{if } 0.03 < X_s \\ \quad 4.59737 \cdot X_s^2 + 11.5093 \cdot X_s^3) & \quad \le 0.15 \end{cases} \quad (5)$$

D. Static Temperature Calculation

IEC 60287-1-1 describes the calculation of current rating and losses at 100% load. However, with the method proposed in this paper, more accurate results, can be achieved. For the proposed method it is assumed that the cable loading is known. IEC assumes a maximum conductor temperature of 90^oC, which for the proposed method is calculated as an iterative process with the steady-state reached temperature given by (6), derived from Fig. 6 [9].

$$\theta_c = \left(I_r^2 \cdot R_{ac} + \frac{W_d}{2}\right) \cdot T_1 + \left[I_r^2 \cdot R_{ac}(1+\lambda_1) + W_d\right] \cdot 3 \cdot T_2 + \left[I_r^2 \cdot R_{ac} \cdot (1+\lambda_1+\lambda_2) + W_d\right] \cdot 3 \cdot (T_3+T_4) + \theta_A \quad [^\circ C] \quad (6)$$

IV. THERMAL CABLE ANALYSIS OF TRANSIENT CONDITIONS

A three-core XLPE submarine cable contains multiple non-conductive layers. An equivalent electric circuit can describe the thermal properties of the cable layers according to the thermal-electrical analogy parameters listed in Table II [14], where thermal capacitances represent the layers ability to store heat.

By constructing a thermal analogy ladder network, it is possible to study the thermal behaviour in the centre of the conductor. Equation (7) is used to calculate the thermal capacitance for the layers. Where, S is the cross-section area and c_m is the specific heat capacity of the material (typical values can be found in Table III).

$$Q = S \cdot c_m \quad (7)$$

A. Thermal Ladder Network Construction

In order to analyse the transient temperature response in the centre of the conductor, it is essential to thermally model the cable with high accuracy. The cable is transformed from the three-core cable into a single-core equivalent cable, with same thermal properties to simplify the equivalent thermal circuit. According to IEC 60853-2 [8], transients greater than one hour are assumed to be of long duration transients which usually is the case for cable loading from wind farms. Therefore this method is based on long transients and is intended for the use of long duration temperature transients only.

Fig. 7 shows a quarter of the cross-section of the equivalent single-core cable, with thermal resistances represented on the x-axis under the respective layer and thermal capacitances represented on the y-axis beside the respective layer.

Fig. 8 show the thermal representation of the dielectric layers, where Van Wormer's coefficient as equation (8) is applied to describe the allocation of the thermal capacitance Q_i[14] more accurately.

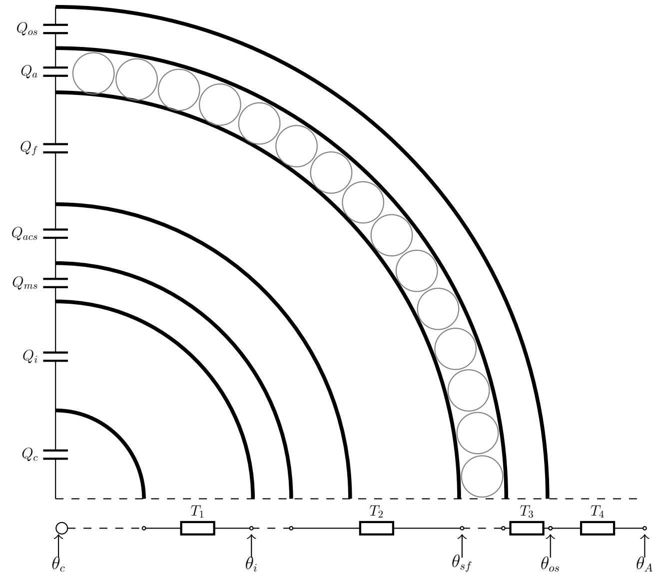

Fig. 7. Single-core XLPE SL sheath type submarine cable equivalent

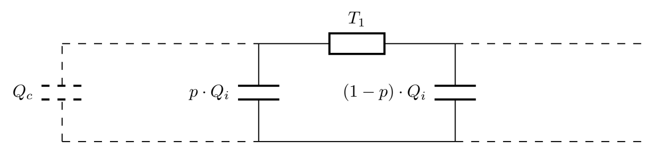

Fig. 8. Thermal representation of dielectric

$$p = \frac{1}{2 \cdot ln\left(\frac{D_i}{D_c^*}\right)} - \frac{1}{\left(\frac{D_i}{D_c^*}\right)^2 - 1} \quad (8)$$

As mentioned before, due to the asymmetry of the internal parts of the three-core cable shown in Fig. 6, the allocation of thermal resistance T_1 has to be defined as an equivalent single-core conductor diameter D_c^* dissipating same losses as determined in (9).

$$\frac{T_1}{3} = \frac{\rho}{2 \cdot \pi} \cdot ln\left(\frac{D_i}{D_c^*}\right) \quad \rightarrow \quad D_c^* = D_i \cdot e^{\frac{-2\pi \cdot T_1}{\rho \cdot 3}} \quad (9)$$

Repeating this procedure for each layer contained in the cable, it is possible to construct a thermal analogy of the cable based on electrical equivalent parameters.

By developing lumped parameters shown in Fig. 7 for each part of the cable, a three-core XLPE submarine cable is thermally represented as Fig. 9.

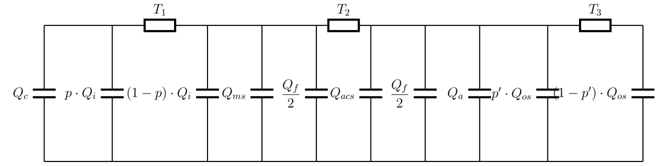

Fig. 9. Thermal three-core XLPE submarine cable ladder network

The thermal ladder network includes the conductor loss W_c, dielectric loss W_d, sheath loss W_s and armour loss W_a in their physical position, to represent the cable in operation.

Using the Cigre two-loop method [8] to reduce the mathematical complexity of the circuit analysis, the final thermal ladder network including power losses can be derived as shown in Fig. 10, where θ_c is the conductor temperature and θ_{os} is the temperature at the outer serving.

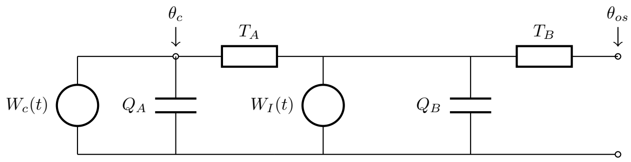

Fig. 10. Final thermal ladder network

According to IEC 60853-2 [8], the apparent thermal resistances in the ladder network are defined in (10) and (11). The apparent thermal capacitances are defined in (12) and (13) [8]. Cable conductor loss W_c is determined in (14) and the total internal cable losses W_I, including dielectric, sheath and armour losses, are determined in (15).

$$T_A = T_1/3 \qquad [K \cdot m/W] \tag{10}$$

$$T_B = T_2 + T_3 \qquad [K \cdot m/W] \tag{11}$$

$$Q_A = Q_c + p \cdot Q_i \qquad [J/m \cdot K] \tag{12}$$

$$Q_B = (1-p) \cdot Q_i + \left(\frac{T_2+T_3}{T_2+T_3}\right)^2 \cdot Q_{ms} + \left(\frac{T_2+T_3}{T_2+T_3}\right)^2 \cdot \frac{Q_f}{2} + \left(\frac{T_3}{T_2+T_3}\right)^2 \cdot Q_{acs} + \left(\frac{T_3}{T_2+T_3}\right)^2 \cdot \frac{Q_f}{2} + \left(\frac{T_3}{T_2+T_3}\right)^2 \cdot Q_a + \left(\frac{T_3}{T_2+T_3}\right)^2 \cdot p' \cdot Q_{os} \qquad [J/m \cdot K] \tag{13}$$

$$W_c(t) = 3 \cdot \Big[I_a(t)^2 \cdot R_{ac}\Big] \qquad [W/m] \tag{14}$$

$$W_I(t) = W_c(t) \cdot [1 + \lambda_1 + \lambda_2] + 3 \cdot W_d \qquad [W/m] \tag{15}$$

B. Transient Temperature Response to a Step Function

In order to evaluate the transient temperature behaviour in the centre of the conductor due to an applied step function, it is needed to model the thermal temperature response mathematically.

A step function is made to reduce the number of calculations needed. Fig. 4 illustrates a current step function I_s with i numbers of 4 hours constant load steps $\Delta\tau$. I_s is as the average of the actually flowing current I_a for each step during the current profile segment illustrated in Fig. 3.

To determine an appropriate length for the constant time-steps $\Delta\tau$, an emperical calculation is proposed by Georg J. Anders [14] as given by (16).

$$\Delta\tau = \frac{\sum T \cdot \sum Q \cdot \left(\frac{\tau}{\sum T \cdot \sum Q}\right)^{\frac{1}{3}}}{10^{1.25}} \tag{16}$$

The LNM is only applicable in cases where the thermal parameters do not change as a function of temperature variations, as it uses superposition principle to solve heat flow equations, which is used exclusively for linear systems.

The transient temperature rise above ambient due to the i^{th} step of the step function is given in (17) and describes the temperature drop from the centre of the conductor to the surface of the cable with surrounding temperature dissipation taken into account.

$$\theta_{j,i}(t) = \theta_{c,i}(t) + \alpha_i(t) \cdot \theta_{e,i}(t) \tag{17}$$

Using Kirchoff's current law, on the circuit shown in Fig. 10, the temperature drop from the conductor centre to cable surface is determined in (18). Evaluating the differential function as a transfer function solving for roots and zeros, the thermal behaviour parameters T_a, T_b, a and b used in (18) are determined using IEC 60853-2 [8] Section 4.2.3.

$$\theta_{c,i}(t) = W_{c,i} \cdot \Big[T_a \cdot (1 - e^{-a \cdot t}) + T_b \cdot (1 - e^{-b \cdot t})\Big] \tag{18}$$

The transient temperature response from surroundings is given as an exponential integral [15] in (19).

$$\theta_{e,i}(t) = \frac{p_T \cdot W_{I,i}}{4\pi} \cdot \left[\left[-Ei\left(\frac{-D_e^2}{16 \cdot t \cdot \delta}\right) - \left[-Ei\left(\frac{-L^2}{t \cdot \delta}\right)\right]\right] + \sum_{k=1}^{k=N-1}\left[-Ei\left(\frac{-(d_{pk})^2}{4 \cdot t \cdot \delta}\right) - \left[-Ei\left(\frac{-(d'_{pk})^2}{4 \cdot t\delta}\right)\right]\right]\right] \tag{19}$$

The attainment factor from the conductor centre to cable surface is a correction factor used for modelling the temperature absorption from the surroundings and is given in (20).

$$\alpha_i(t) = \frac{\theta_{c,i}(t)}{W_{c,i} \cdot (T_A + T_B)} \tag{20}$$

Common values for axial depth of burial L and ambient temperatures θ_A used for common submarine cable locations are shown in Table IV, while thermal soil resistivity ρ can be found in Table III.

TABLE IV
COMMONLY USED SURROUNDING CONDITIONS

Cable location	Burial depth L $[m]$	Ambient temperature θ_A $[C^o]$
Beach landing	2.50	15.0
Surf zone	5.00	12.0
Offshore	2.00	10.0

The sum of all partial temperatures transient above ambient $\Delta\Theta_c$ is the sum of each partial transient given by (21).

$$\Delta\Theta_c(t) = \theta_{j,1}(t) + \theta_{j,2}(t) + ... + \theta_{j,i}(t) + ... + \theta_{j,t}(t) \tag{21}$$

To determine the total temperature response Θ due to an applied step function, the ambient temperature θ_A is included and given in (22).

$$\Theta(t) = \Delta\Theta_c(t) + \theta_A \tag{22}$$

V. Method Validation

This Section compares the thermal LNM calculations presented in this paper with a COMSOL Multiphysics based simulation using a FEM to solve heat transfer problems.

In order compare the methods, same cable parameters, dimensions and material are used. Cable data of an estimated 66kV $3x800mm^2$ XLPE SL sheath type Submarine cable are given in Table V and surrounding cable condition parameters used in the validation are given in Table VI.

TABLE V

Cable Data - layers are numbered according to Fig. 2

Cable layer	**Thickness** t $[mm]$	**Material**
l_1	16.9	Al
l_2	1.40	XLPE
l_3	9.00	XLPE
l_4	1.40	XLPE
l_5	0.60	PE
l_6	2.30	Pb
l_7	2.50	PE
l_8	3.00	PE
l_9	5.00	St
l_{10}	4.00	PP

TABLE VI

Surrounding condition parameters

Parameter	L [m]	θ_A $[^oC]$	ρ_T [K·m/W]	δ_s $[m^2$/s]
Value	1.5	10	0.7	$0.5 \cdot 10^{-6}$

By applying different load profiles to the ladder network, it is possible to analyse the thermal temperature behaviour of the cable. First, a constant load with a period of 400 hours is applied (shown in Fig. 11). The constant load-step represents a pre-loading phase and shows the behaviour for a long lasting transient duration, which should approach a steady-state temperature, as given in (6), to be valid.

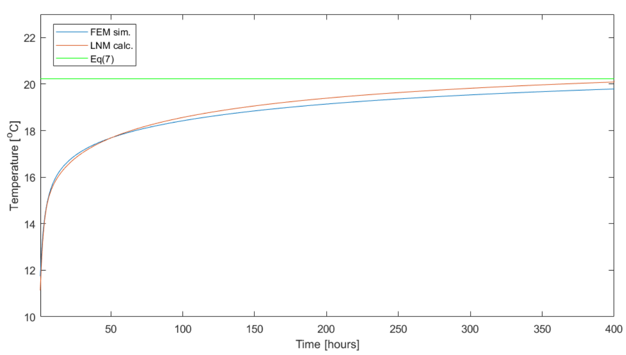

Fig. 11. Long transient response to a constant load step

To analyse the thermal temperature rises and falls for transients between 1 and 50 hours, a varying load profile is applied to the cable and the results are shown in Fig. 12.

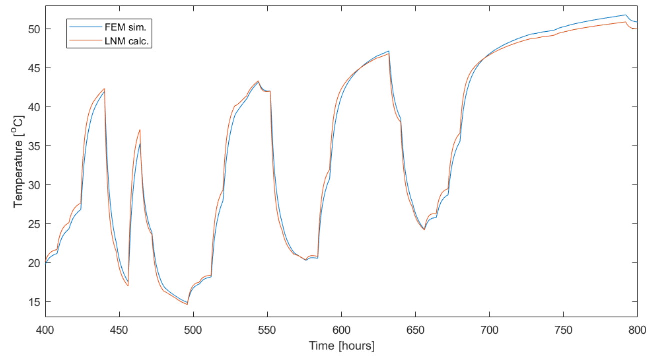

Fig. 12. Wind-based short transient response to a varying load profile

VI. Conclusions

This paper proposes an iterative method combining two approved standards to make a dynamic rating of three-core XLPE submarine cables by an evaluation of the transient temperature behaviour in the centre of the conductor. The method is validated with a FEM-based simulation and shows in the specific case a maximum deviation of $0.89°C$. In comparison with a FEM-based approach, the method presented in this paper is remarkably faster evaluating the temperature progress and will in most cases be a good first-shoot in the cable rating phase of a project.

Acknowledgment

This study was carried out as a bachelor project, thanks to the collaborating companies: Energinet Eltransmission A/S and Vattenfall Vindkraft A/S.

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