Implementation of finite element analysis and hybrid IEC-models in online ampacity tool

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ABSTRACT

Current tools for ampacity calculations are based on analytical expressions, and empirical expressions for complex laying geometries that in practice cannot be solved analytically, formulated in the IEC standards. Non-standard or highly complex laying geometries must be simplified and approximated, which often result in less accurate calculated ampacities. Norwegian utilities and industry have supported R&D to develop an online ampacity tool based on finite-element analysis (FEA). Some parts of IEC 60287 formulae have been included to reduce computation time. The result is an easy-to-use and accurate online tool for ampacity calculations.

KEYWORDS

Ampacity, software, cable, segmented, conductur, losses, IEC 60287, FEA.

INTRODUCTION

Optimal utilization of existing, and planning of new, electrical infrastructure is essential for the ongoing electrification where cables play an important role in the distribution of electric power.

Current tools for ampacity calculations are based on analytical expressions, and empirical expressions for complex laying geometries that in practice cannot be solved analytically, formulated in the IEC standards. Non-standard or highly complex laying geometries must then be simplified and approximated, which in many cases results in less accurate calculated ampacities. As a day-to-day tool, utilities often use a collection of ampacity tables for a limited set of cables and parameters, such as depth, distance, and number of cables, thus further limiting the full exploitation of true ampacity.

Since 2014 Norwegian utilities and industry have supported R&D to develop an ampacity tool that overcomes this lack of flexibility, but still is simple to use. The result of this research is an online ampacity tool based on finite-element analysis (FEA). The design tool is available through a web browser and FEA runs on a dedicated server, providing computation times from 30 seconds to a few minutes – depending on complexity. The FEA models are based on multi-physics models, but in some cases simplifications or inclusion of parts of IEC 60287 formulae have been included to reduce computation time.

In this work, challenges with implementing generic thermo-electric FEA models in such a way that non-experts can perform ampacity calculations for complex laying geometries are discussed. Further, the simplification of models is discussed with regards to decrease in both computation time and accuracy and how this compares to uncertainty due to changes in, or unknown, ambient conditions.

HEAT TRANSFER IN CABLE SYSTEMS

For determining the ampacity of a cable system, it is crucial to accurately determine heat transport in the cable system. The complexity and parameters involved vary between the three mechanisms conduction, radiation and convection [1], and should be addressed for an efficient implementation of ampacity calculations.

Conduction

Heat transfer by conduction q_{cond} is caused by exchange of random molecular motion in matter (diffusion) and is given by

$$q_{cond} = -k \cdot \nabla T, \qquad (1)$$

where q (W/m^2) is the heat flux, k (W/m.K) is the thermal conductivity of the material where heat by conduction happens, and T (K) is the temperature field. An analytical solution can be obatained for Eq. (1) for simple geometries and boundary conditions, e.g., by assuming isothermal surfaces of bodies investigated.

Radiation

All matter at non-zero temperature radiate thermal energy. The energy is transmitted by electromagnetic waves, and is not dependent on matter. Matter can also absorb thermal energy through radiation. Most relevant for cable systems is the case where an object (cable) is surrounded by a larger surface (pipe or duct). If the emission and absorption of heat is equal for the surface (grey body) and surrounding surface is assumed isothermal, heat exchange by radiation q_{rad} can be expressed as

$$q_{rad} = \varepsilon\sigma\left(T_{obj}^4 - T_{surr}^4\right), \qquad (2)$$

where ε is the emissivity, σ the Stefan Boltzman constant (5.67·10^{-8} W/m^2.K^4), T_{obj} the temperature of the object, and T_{surr} the temperature of the surrounding surface.

Convection

When diffusion is accompanied by a bulk movement of matter, the heat transport is termed convective. In natural convection, bouancy from temperature dependent density of matter in gas or liquid phase will provide a substantial contribution to heat transfer, and is one of the key challenges in accurate ampacity calculations. The general equation for heat transfer by convection q_{conv} is given by

$$q_{conv} = h\left(T_{obj} - T_{\infty}\right), \qquad (3)$$

where h is the convection heat transfer coefficient and T_{∞} is the gas/fluid temperature.

Heat sources

Heat generated in the cable originates in either joule losses dependent on current, or dielectric losses dependent on voltage. The most important heat source in a cable system will be joule losses from the conductor

$$W_c = R_{ac} \cdot I^2, \quad (4)$$

where R_{ac} is the AC resistance of the conductor, taking into account skin effect, proximity effect to nearby cables and the temperature dependence of resistance, and I is the applied current. The current will induce circulating current in the sheat of the cable, and is proportional to W_c:

$$W_s = \lambda_s \cdot R_{ac} \cdot I^2, \quad (5)$$

where λ_s is the proportionality factor, often called sheat loss factor and is a number between 0 and 1. The third heat source is the dielectric losses which is dependent on electric field across the insulation

$$W_d = 2\pi f \cdot C_d \cdot U^2 \cdot \tan(\delta), \quad (6)$$

where f is the voltage frequency, C_d is the capacitance between conductor and screen, U voltage and tan(δ) the loss factor of the insulation.

Energy balance

From the first law of thermodynamics it is known that the total energy must be conserved in a closed system, hence the heat generated by a cable must be transported away from the cable under steady state conditions:

$$Q - W = \Delta W, \quad (7)$$

where W (W/m) is the heat generated by the cable, Q (W/m) is the net heat transport, and ΔW (W/m) is the change of stored energy. Under steady-state conditotions there is no net change of stored energy (ΔW = 0). Hence $W = Q$, and

$$W_c + W_s + W_d = q_{con} + q_{rad} + q_{conv}, \quad (8)$$

The challenge of accurate thermal rating of power cables can thus be reduced to 1) calculation of heat generated by losses in the cable (W), and 2) calculation of the heat transport away from the cable (Q).

CALCULATION METHODS

Several methods for calculation of the ampacity of buried cables exist. Rating of power cables has been addressed for over a century, and simplified analytical solutions have thus been preferred [2]. Today most solutions emerge from the Neher and McGrath paper published in 1957 [3].

IEC 60287

In the IEC 60287 [4], analytical expressions for temperature rise in buried cables are given. For the simplest case with a buried cable in a homogenous medium the admissible current is given by

$$I = \sqrt{\frac{\Delta\theta - W_d[0.5T_1 + n(T_2+T_3+T_4)]}{R_{ac}T_1 + nR(1+\lambda_1)T_2 + nR_{ac}(1+\lambda_1+\lambda_2)(T_3+T_4)}}, \quad (9)$$

where:

- $\Delta\theta$ is temperature increase above ambient.
- T_1-T_4 are the thermal resistivites of insulation, bedding between sheath an armor, serving and soil, respectively.
- n is the number of conductors in the cable.
- λ_1, λ_2 are the loss factors for screen and armoring, respectively.

For special laying geometries, such as cables in ducts and pipes, simplifying asssumptions are made for adjusting T_4 [5], e.g., isothermal surfaces and concenctric geometry for calculating heat transfer in the convective medium (air) between cable and inner pipe surface (T_4') [6]. These approximations thus have limited area of validity, such as a maximum equivalent cable diameter of 100 mm. Another example is rectangual duct banks, where the approximations in IEC 60287-2-1 is valid for a duct bank width-to-height ratios of 1/3 to 3. For larger width-to-height ratios, FEA have been applied to provide values for the geometric factor used in calculations [7]. Time dependent loads are treated in IEC 60853 [8], [9].

Finite Element Analysis

In cases where the assumptions in the analytical solutions implemented in IEC 60287 are too stringent, the heat transfer equations can be solved by appropriate numerical methods. FEA is usually chosen, as it is ideally suited for solving the heat transfer equations that are parabolic partial differential equations (PDE). The main advantage of using FEA is that it makes it straightforward to model complex configurations with many different materials in the soil with varying thermal properties. Non-isothermal surface conditions are also easily included. The element size, which determines the spatial resolution of the solution, can be varied to give high resolution in areas close to the cables parts while far away the resolution can be lower.

The cable losses could still be calculated using the methods described in IEC 60287, with an iterative procedure. However, a further refinement is to also use a numerical method to calculate the losses in the cable. This involves solving Maxwell's equation in a suitable form for the cable arrangements. A time-harmonic solution of Maxwell's equation is found which gives the electromagnetic losses in the cables.

The losses are inputs to the thermal modelling, while the temperatures from the thermal model are input to the electromagnetic model to modify the resistances of the cables.

Solving the heat transfer equation and Maxwell's equation in a coupled problem simultanously removes the need for an iterative solution procedure. In practice, solving these equations simultaneously might not be trivial, but modern software for FEA has progressed to a level where it is quite feasible.

Current practice

The practical task of determining the ampacity of a cable can be put in three categories, based on complexity of the cable circuit, available labor and economic resources, and criticality. The simplest "ampacity tool" are the tables provided by cable national committees, such as NEN 62.75 in Norway, or tables provided by cable manufacturers. These tables are based on IEC 60287 (in Europe), but have little flexibility with regard to e.g., number of cables, distance between cables, laying depth. For low and medium voltage distribution grids and simple industrial installations this is often adequate, and the effort used to determine ampacity is usually coherent with the cost of cable and criticality of failure.

The next level of ampacity calculations is by applying IEC formulae to directly calculate the temperature rise and this admissible current in the cable installation. The number of formulas involved and iterative dependencies, requires programming scripts or spreadsheets. The risk of miscalculation is not insignificant, and a publication have been provided with reference calculations to help engineers to understand and troubleshoot [10]. By utilities, most IEC calculations today are done using either commercial software solutions that have implemented IEC 60287/60853 with extensions for special cases published by e.g., CIGRE and IEEE.

For more complex laying geometries, and cases not well covered by tables and IEC standards, numerical multi-physics FEA are carried out, usually in a commercial software. This requires detailed skills regarding cable construction, electro-thermal calculations and defintion of geometries and physics in the software. As a consequence this is mainly done by specialists.

IMPLEMENTATION

As a part of joint effort between Norwegian DSOs and TSO, industry, research partners and co-funded the Norwegian Research Council, an FEA based on-line ampacity tool has been developed. The tool is based on COMSOL Multiphysics which runs on a server, and the user is presented with a web-based graphical user interface (GUI), where cable trenches can be defined and simulated. A focus group of engineers from utilities and industry have participated with input to layout and functionality. The tool is available to all Norwegian utilities and others, and for the last year the tool has had approximately 800 unique users running more than 36 000 simulations – on average 3000 per month.

Architecture

A first protopype was developed with the COMSOL Server and Application Builder functionality as described in [11]. The user was presented with a graphical user interface (GUI) on a webpage, but it turned out that using the built-in graphical tools did not provide the flexibility needed to build a generic ampacity tool. In the present version a GUI has been programmed in javascript. Based on the cable and trench geometry made in the GUI, a parameter file is defined and transferred to COMSOL where the FEA model is generated and simulation executed on a dedicated server. Based on complexity of the geometry and meshing the calculation time is from approximately 30 seconds to a few minutes.

Interface and functionality

Based on needs defined by the Norwegian utilities, it was decided the first version of the tool focused on buried cable installations. In Fig. 1 an example case is shown with a combination of directly buried cables and cables in pipes. The example also shows that the ground can be constructued with different zones with different thermal properties, including a top layer. In the top part the trench is defined with depths, angles and layers. The thermal properties of each layer is defined, and it can also be chosen if the surface is isothermal (as in IEC 60287) or convection from the surface should be taken into account.

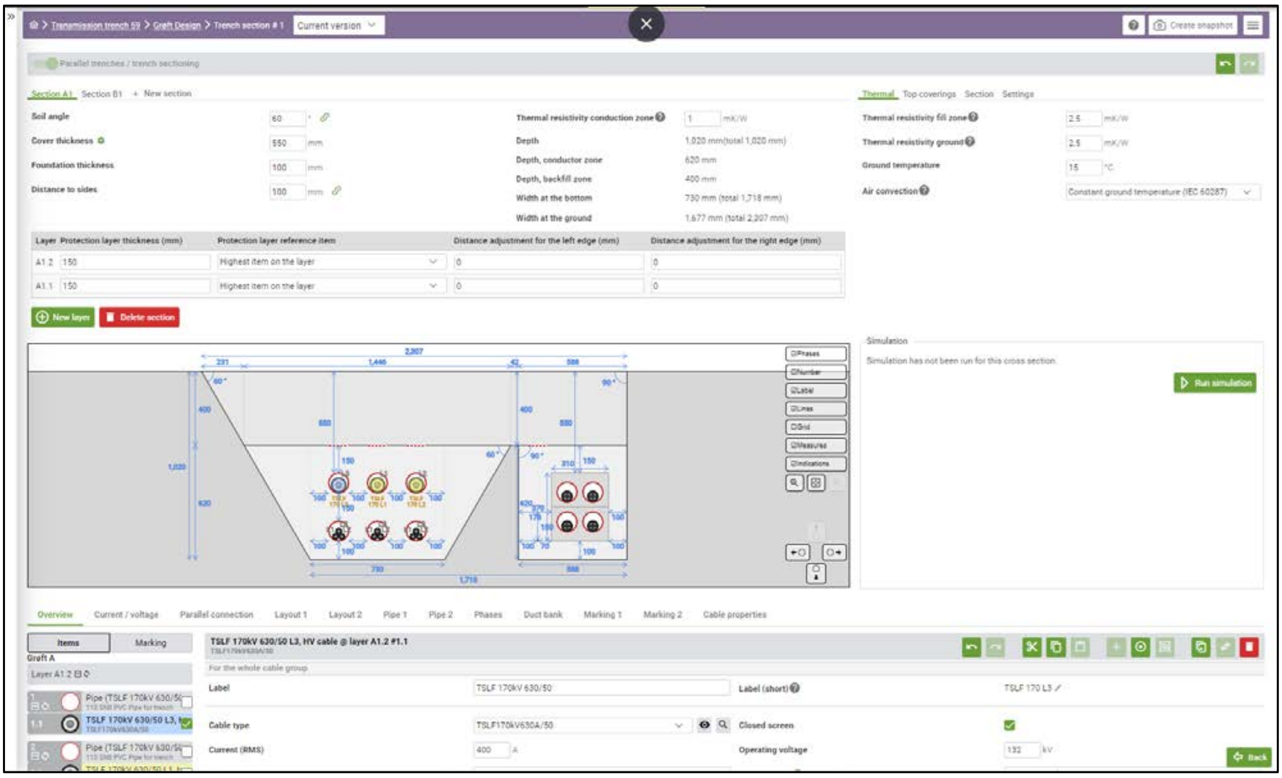


Fig. 1: Web interface of ampacity tool. The example shows two different types of cable groups in pipes and two setes of buried cables.

In the middle part the trench geometry is drawn, and cables and other infrastructure is shown. In the bottom part the cables and infrastructure is defined by choosing either from a drop-down menu or by defining own cable designs using the cable generator function. The current is set and phase configuration for each cable group is also defined here. After running the simulation, results are presented as a heat map and relevant temperatures, magnetic induction, impedance and induced screen currents are given in tabular form. Results are also exported in a standardized pdf report for documentation. The main functionality can be summarized as:

- Buried cables
- Cables in pipes and ducts
- District heating and water pipes
- Zones with different thermal resistivity
- Cable generator tool
- Segmented conductors

VERIFICATION

Conduction

Published FEA models for ampacity calculations show in general good agreement with IEC 60287, see e.g., [12], [13]. The implemented FEA models in the tool have been benchmarked against IEC 60287 for a number of cross-sections and insulation thicknesses with standard deviation of 3% [11]. Further verification have been provided by comparison to an example case in Cigre TB 880 [10], which provides a number of detailed calculations for various cases using IEC 60287. In Table 1 the calculated values for Case 0 (Cu 630 mm^2 XLPE insulation cable buried at 1 m in trefoil formation) are compared.The same conditions were applied for both methods and current set to 803 A in the FEA computations.

Table 1: Comparison between IEC and FEA for Case 0 in CIGRE TB 880 [10].

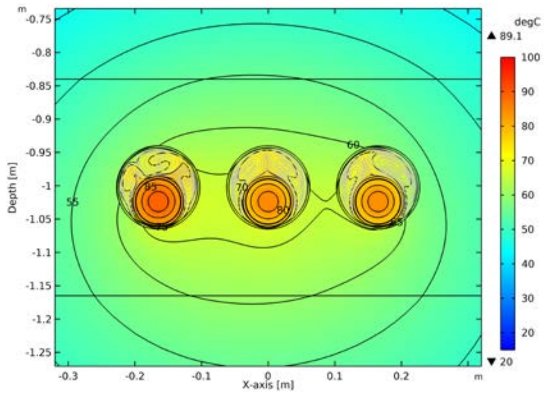
Param	IEC value	FEA value	Deviation
θ_c	90.0 °C	91.0 °C	1.0 °C (1.1 %)
θ_s	79.2 °C	81.0 °C	1.8 °C (2.2 %)
W_c	25.49 W/m	25.43 W/m	-0.06 W/m (0.2 %)
W_s	9.34 W/m	9.11 W/m	-0.23 W/m (2.4 %)

The conductor temperature (θ_c) deviation is 1.0 °C. The surface temperature (θ_s) for the FEA calculation is 1.8 °C, but it should be noted that IEC assumes isothermal surface while the FEA value is the maximum surface temperature. Losses in conductor are very close to the IEC value, while the sheat losses are 2 % lower.

Convection and radiation

The radiation heat transfer contribution is calculated directly in FEA, without any simplification and with the correct geometry. The convection heat transfer contribution is given by the approach described in [14], where the additional heat transfer by convection is deducted from the cable and added to the pipe wall (for better accuracy the added heat on the pipe wall is non-uniform). This approach to consider the convective heat transfer has been shown to be accurate, as verified by comparison with full computational fluid dynamic (CFD) calculations for trefoil and cradle formation and both laboratory and full scale experiments for single cable formations [14], [15]. Further verification has been undertaken using reference case 0-3 in Cigre TB 880, where the same cable previsoly described in the "Conduction" section is put in pipes. In Fig. 2 temperature field (color) and streamlines in air (black lines) are shown for full CFD and the simplified method in (a) and (b), respectively. In Table 2 the calculated values from IEC 60287, full CFD and the implemented simplified method are given. The full CFD values are generally slightly lower than IEC values while simplied FEA values are slightly higher than IEC values. Using the IEC values as benchmark, all deviations of the simplified method are within 1.4 %.

(a)



(b)

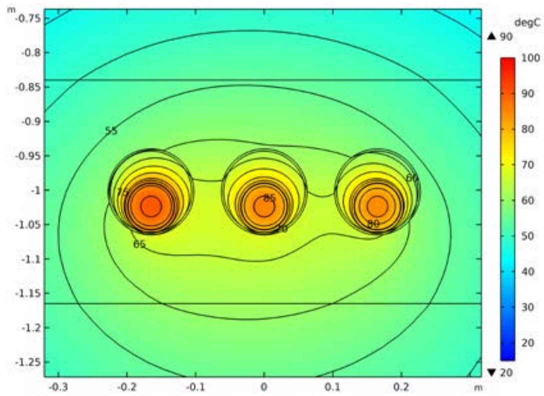


Fig. 2: (a) Full CFD calculation for three cables in buried pipes, with black lines for temperature contour and gray lines for streamlines in the air volume. (b) Simplified calculation for three cables in buried pipes, with black lines for temperature contour.

Table 2: Comparison between IEC and FEA for Case 0-3 in CIGRE TB 880 [10], I_{load}=634 A for the hottest cable.

Para-meter	IEC	FEA Full CFD	FEA Simplified	Deviation
θ_c	90.0 °C	89.1 °C	90.6 °C	0.6 °C (0.7 %)
θ_s	83.4 °C	82.5 °C	84.6 °C	-1.2 °C (-1.4%)
W_c	15.49 W/m	15.46 W/m	15.67 W/m	0.18 W/m (1.1 %)
W_s	26.34 W/m	26.895 W/m	26.18 W/m	-0.16 W/m (-0.6 %)

Segmented conductors

The ampacity tool also includes functionality for calculations of segmented conductor designs. Due to the stranding and twisting of wires and segments in such conductors, as well as the difference in wire size and twisting pitch, modelling losses in these conductors using FEA becomes a complex three-dimensional problem requiring great amounts of computational power. The implemented solution is based on a hybrid method in which a simplified 2D FEA model is combined with the empirical formulae in IEC for R_{ac} and skin and proximity effect factors y_s and y_p for segmented conductors.

The approach has been verified against standard IEC calculations [16], for a typical cable with segmented Cu conductor and XLPE insulation, with parameters and laying configuration given in Table 3. The cable was modelled in both flat and trefoil formation, with both single-ended (1-point) and solid (2-point) bonding.

The results are summarized in Fig. 3. In (a) it can be seen that there is a temperature deviation of up to 4.6 %. These issues are likely related to screen configuration, which was not the same as implemented in the ampacity tool and used in other verifications, as it can be seen in (b) and (c) that deviation in both AC resistance and average conductor losses are all within 1 %. Also, for 1-point bonded system simulations the maximum temperature was approximately 35 °C. Hence, an absolute temperature deviation of 1.2 °C gives relative temperature deviation of 3.35 %. Overall, the results of the proposed method match up well with the IEC standard

Table 3: Cable and laying paramters [16].

Cable	
Cross-section	2000 mm^2
Conductor diameter	56 mm
DC resistance at 20 °C	0.0090 Ω/km
Insulation thickness	13.1 mm
Screen design	Cu wires + Al foil
Cross-section	205 + 60 mm^2
Screen diameter	95 mm
Overall cable diameter	105
Installation	
Soil thermal resistivity	1 K*m/W
Depth of laying	1 m
Ground temperature	20 °C
Load	600 A
Voltage	132 kV

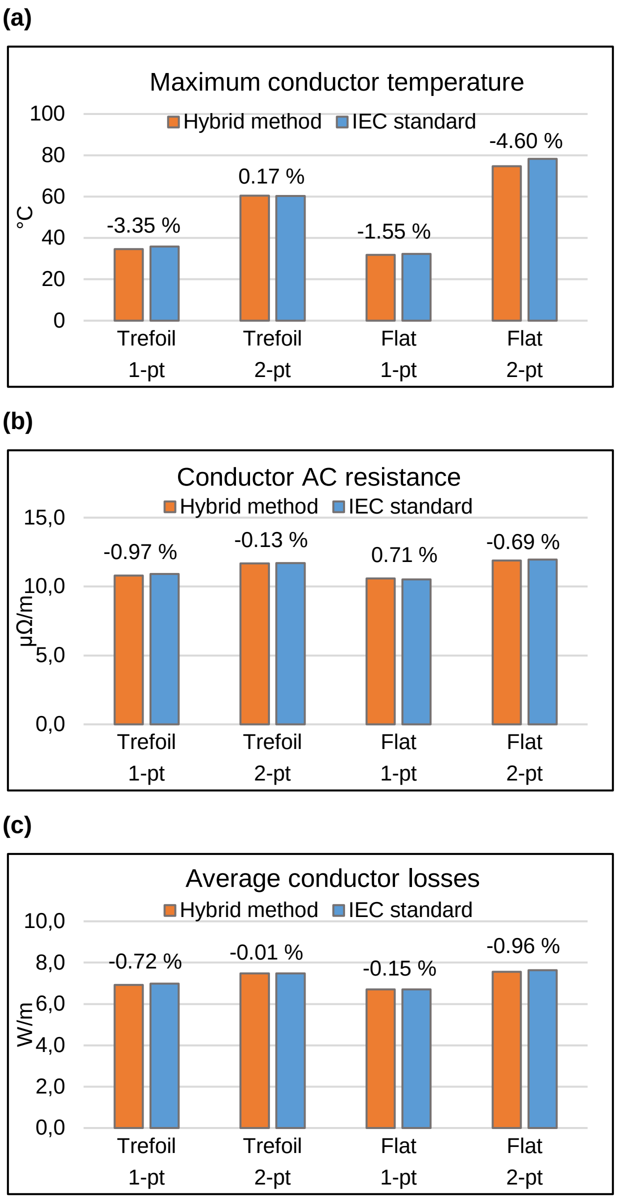


Fig. 3: (a) Maximum conductor temperature, (b) conductor AC resistance at operating temperature, hybrid method vs. IEC, and (c) average conductor losses, hybrid method vs. IEC. Deviation in % for each modelled configuration. In flat formation, the middle cable is considered.

SUMMARY

An online ampacity tool has been created that is based on FEA models and hybrid IEC models for segmented conductors. The accuracy, i.e., deviation in conductor temperature, of the simplified FEA models are within 1% For segmented conductors, a full FEA model is not feasible, and a hybrid where R_{ac} is modified according to IEC 60287 have been implemented.

By taking a pragmatic approach, an online tool that is flexible, but yet simple to use, have been developed. Complex cable trench geometries can be defined, and both predefined and custom cables can be simulated. Other heat sources/infrastructure such as water pipes and district heating can also be simulated

The project partners have taken an active role in the development of the tool by providing feedback and relevant use cases. This collaboration between research and industry have thus yielded project results which can directly can be operationalized. The tool is now used by most Norwegian DSOs, and several major consulting companies. This can potentially provide cost savings and increased security of supply by taking a large leap in how cables are rated, by replacing ampacity tables with accurate software in everyday use.

The tool is in continuous development, and future work will consist of implementing simplified three dimensional configurations and time varying currents, magnetic materials (armoring of subsea cables), and cables laid in air and water.

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REFERENCES

[1] F. P. Incropera and F. P. Incropera, Eds., *Fundamentals of heat and mass transfer*, 6th ed. Hoboken, NJ: John Wiley, 2007.

[2] J. A. Pilgrim, ‘Circuit Rating Methods for High Temperature Cables’.

[3] J. H. Neher and M. H. McGrath, ‘The calculation of the temperature rise and load capability of cable systems’, *Transactions of the American Institute of Electrical Engineers. Part III: Power Apparatus and Systems*, vol. 76, no. 3, pp. 752–764, Apr. 1957, doi: 10.1109/AIEEPAS.1957.4499653.

[4] International Electrotechnical Commision, ‘IEC 60287 Electric cables - Calculation of the current rating - Part 1-1: Current rating equations (100 % load factor) and calculation of losses - General’, 2006.

[5] IEC Standard 60287-2-1, ‘IEC Standard-Electric Cables—Calculation of the Current Rating—Part 2: Thermal Resistance—Section 1: Calculation of the Thermal Resistance’, 2015.

[6] G. J. Anders, *Rating of Electric Power Cables: Ampacity Computations for Transmission, Distribution, and Industrial Applications.* 1997.

[7] M. A. El-Kady and D. J. Horrocks, ‘Extended Values for Geometric Factor of External Thermal Resistance of Cables in Duct Banks’, *IEEE Transactions on Power Apparatus and Systems*, vol. PAS-104, no. 8, pp. 1958–1962, Aug. 1985, doi: 10.1109/TPAS.1985.318767.

[8] International Electrotechnical Commision, ‘IEC 60853-1 - 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.

[9] International Electrotechnical Commision, ‘IEC 60853-2- 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.

[10] CIGRE WG B1.56, ‘Power cable rating examples for calculation tool verification’, TB 880, 2022.

[11] E. Eberg, K. Espeland, S. M. Hellesø, S. Hvidsten, and K. T. Solheim, ‘Development of a web-based user-friendly cable ampacity calculation tool’, in *CIRED Conference Proceedings*, Jun. 2019. doi: 10.34890/964.

[12] D. J. Swaffield, P. L. Lewin, and S. J. Sutton, ‘Methods for rating directly buried high voltage cable circuits’, *IET Generation, Transmission & Distribution*, vol. 2, no. 3, pp. 393–401, May 2008, doi: 10.1049/iet-gtd:20070142.

[13] F. de Leon and G. J. Anders, ‘Effects of Backfilling on Cable Ampacity Analyzed With the Finite Element Method’, *IEEE Trans. Power Delivery*, vol. 23, no. 2, pp. 537–543, Apr. 2008, doi: 10.1109/TPWRD.2008.917648.

[14] S. M. Hellesø and E. Eberg, ‘Simplified Model for Heat Transport for Cables in Pipes’, *IEEE Transactions on Power Delivery*, vol. 37, no. 5, pp. 3813–3822, Oct. 2022, doi: 10.1109/TPWRD.2021.3137876.

[15] E. Eberg, K. Espeland, S. M. Hellesø, and S. Hvidsten, ‘Full-scale case study of a road crossing thermal bottleneck in a buried medium-voltage cable installation’, *CIRED - Open Access Proceedings Journal*, vol. 2017, no. 1, pp. 194–197, Oct. 2017, doi: 10.1049/oap-cired.2017.0820.

[16] H. Strand, E. Eberg, and G. J. Anders, ‘Hybrid Method for Numerical Implementation of Segmented Power Cable Conductors in Finite-element Based Ampacity Calculation’, *Proceedings of the Nordic Insulation Symposium*, vol. 27, no. 1, Art. no. 1, Jul. 2022, doi: 10.5324/nordis.v27i1.4709.