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Evaluation of Thermal Network Modelling and Finite Element Analysis for Ampacity Rating Calculation of Wind Farm Export Cable

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SUMMARY

Load and temperature data collected from an onshore wind farm export cable during a nine-month period was used to test and evaluate models for transient calculations of cable temperatures. The temperature data was measured using a distributed temperature sensing (DTS) system. A single location along the cable, where the cable is directly buried in a trefoil formation, was chosen for analyses. The objective was to test models based on thermal equivalent circuits (TECs), which are simple and computationally effective models and promising candidates for affordable and efficient system-wide ampacity rating of cables. The TEC models were compared to finite-element analysis (FEA) models and tested on real data. The work was divided into three case studies with increasing complexity. Firstly, the steady state temperature of the cable was calculated for two different loads using both TEC and FEA. The results corresponded well, with a maximum deviation of 1.51 °C between the two model types. In the second case, the transient temperature response to a step increase of the load was calculated for two different loads. In this case, there was a larger deviation between TEC and FEA, especially for short times. Finally, the models were tested on real data from the cable installation. In this case, the FEA outperformed the TEC model with a mean error ($\pm$ standard deviation) of 1.17 $\pm$ 1.00 °C, while TEC had 2.44 $\pm$ 1.27 °C. The TEC showed systematic errors that followed the load and ambient temperatures, which indicates errors or room for improvements in the model itself. As for the FEA model there were no apparent systematic errors. It is hypothesized that the errors in this model arose due to the assumption that the thermophysical properties of the soil were constant in time. This is, in most cases, not a valid assumption because the weather, especially precipitation, has a large influence on the thermal properties of the soil. Further work should be done in terms of improving the TEC model, especially regarding modelling the soil.

KEYWORDS

Ampacity Rating Calculation, Distributed Temperature Sensing, Finite Element Analysis, Thermal Network Model.

1. Introduction

Integration of renewable energy sources and widespread electrification across several sectors changes the electrical load profiles that power cables are expected to carry. Unlike traditional load profiles, these new profiles display increased levels of dynamics and intermittency. For instance, on- and off-shore wind farms provide highly varying power output, see e.g., [1, 2]. This variability is also mirrored in the load patterns carried in the connecting export cable installations that transport this energy. To optimise planning and operation of cable installations connected to areas with high degree of intermittency and variation, one must have tools that are able to determine the current carrying capacity (ampacity) of cables under such conditions.

The ampacity of cables is typically assumed to be thermally limited and determined by setting a maximum allowed conductor temperature. For XLPE-insulated cables this temperature is usually 90 °C [3]. Traditionally, the ampacity is estimated using steady-state calculations following IEC 60287 [3]. For wind farms such calculations will give too conservative ampacity ratings because it does not consider the time it takes for a cable to reach steady state. Consequently, this will result in unnecessarily large cable cross-sections and high levelized cost of energy. By considering the thermal time constants of the cable and its surroundings, transient electrothermal calculations can provide more realistic ampacities.

There are several approaches to calculate ampacity, where all involve estimating the conductor temperature for a given load profile. One such method is finite element analysis (FEA), applicable to both steady state and transient calculations. While FEA can provide very precise results, it requires significant computational resources and specialised knowledge for anything beyond simple systems . For critical and expensive installations such efforts might be warranted, but most grid owners consider it too resource demanding for large-scale implementation.

Less resource demanding are the models provided by IEC, where the cable and its surroundings are described as a thermal equivalent circuit (TEC). Emergency rating, essentially step response, and cyclic ampacity calculations using this method are described in IEC 60853 [6]. Although future load profiles e.g., from wind power installations, are not cyclic, several studies have investigated how TEC-based models may be utilized for more general dynamic calculations. These investigations show promising results, with some models achieving an agreement within 1.5 °C compared to FEA models . Calculations implementing TEC-models have also been developed for cables connected to wind farm installations; both submarine cables [7] and onshore cables [8]. Nevertheless, for these models, the publications recommend using distributed temperature sensing (DTS) systems as input for the model to ensure sufficient accuracy. However, the supporting units required for DTS measurements are costly and therefore unrealistic to implement on a large scale in e.g., distribution grids.

To accommodate system-wide and operational planning in a power grid with high penetration of renewable energy sources and electrification, computationally efficient and dynamic ampacity rating methods are needed. In a previous publication, static and dynamic FEA models of an onshore wind farm cable installation were developed and compared to DTS data from the same cable [2]. Building on this foundation, the current work involves evaluation and development of static and dynamic TEC models of the same cable installation. The TEC models are compared to FEA models and historical DTS measurements. Finally, the goal is to develop TEC models that can be used for efficient and affordable system-wide ampacity ratings.

2. Methodology

2.1 Thermal equivalent circuit

TEC is a method that can be used to describe energy transport and temperature distributions in physical systems, such as cables. TEC employs a coarse spatial discretisation of the system, where each layer of the cable is associated with one temperature node in the circuit. In steady state, the TEC can be described using a set of algebraic equations. To calculate the transient response, thermal masses must be included in the TEC as heat capacities, thus resulting in a set of coupled ordinary differential equations. To solve these, the "solve-ivp" method was used. To achieve numerical stability and computational efficiency an implicit solver[1] had to be used. The networks were set up according to IEC 60287 [3] and IEC 60853 [6] and solved directly.

When describing the transient response of a buried cable, it is challenging to model the soil. Firstly, one assumes cylindrical symmetry when mathematically describing the cable. This greatly simplifies the calculations, but the symmetry is broken when including the soil. Therefore, care must be taken to discretize the soil system in a way that models the correct behavior. Secondly, it is difficult to control, or characterize, the soil because its thermophysical properties vary greatly depending on moisture content, temperature, and composition. Several methods have been applied to model the soil in TEC-based models, such as dividing the soil in several (up to a 100) concentric layers [5], and dividing the soil in fewer but non-concentric layers [9]. There is however a computational cost to adding more layers, and this is especially true when using implicit numerical methods.

In this work a model similar to that in [5] with *one* layer is used, and IEC 60287 is used to calculate the thermal resistance of the soil, commonly denoted T_4. The issue with having one layer is overestimation of the thermal capacity of the soil. Having one layer assumes that to increase the temperature at the cable surface the temperature must increase in the entire soil layer, at the same time. This does not happen because the heat flux from the cable will contribute more to increasing the temperature close to the cable surface than into the bulk soil. This can be solved by spatially resolving the soil, but with this comes added computational cost. In this work, a different approach was tested. First, the thermal capacity of the soil layer, $C_{\text{soil}}^{\text{total}}$, was calculated using the thermophysical properties of the soil and an area corresponding to a cylinder with area $\pi\left(d_{burial}^2 - r_{cable}^2\right)$, where d_{burial} is the burial depth of the cable and r_{cable} is the radius of the cable. As this is an overestimation of the effective thermal capacitance, an effective heat capacity is defined:

$$C_{\text{soil}}^{\text{eff}} = k \cdot C_{\text{soil}}^{\text{naiive}} \quad (1)$$

where k is a dimensionless parameter, presumably between 0 and 1. To determine k a grid search over different k was performed. The k that gave the highest similarity between FEA and TEC as evaluated using a step response was used to estimate the optimal k. This k was then used to test the TEC on real data.

2.2 Finite Element Analysis

FEA is a numerical method for solving differential equations in mathematical modelling of physical systems. The method consists of the system into smaller parts called finite elements, and then solving the associated equations for each element, giving an approximation of the solution for the whole physical system. FEA simulations are widely used for electromagnetic and thermal modelling of cable installations, both in steady-state (assumed constant load) and time-dependent scenarios. One advantage of using FEA compared to IEC 60287 calculations, is that it can solve for any installation geometry and operational scenario. However, FEA often requires detailed information about the installation conditions and physical parameters of the ground, which can be difficult to estimate without in-situ measurements. Furthermore, the application of FEA models may require dedicated software and expert domain knowledge to gain benefit. To overcome this, web-based tools based on simplified and verified FEA models have been developed [10].

In this work, a commercial FEA software was used to create FEA models of the cable installation. The time-dependent model was added to the model by solving a frequency-transient study where the electromagnetic equations are solved in the frequency domain, and the heat transfer equations are solved in the time domain. These two solutions are linked, so that the electromagnetic losses from the frequency domain study are heat sources in the transient time domain study, and the temperature field from the transient time domain study is used to update the electrical conductivities in the electromagnetic frequency domain model. The transient time domain study is solved using an implicit

[1] In this work, the so-called Radau solver

backward differentiation formula with free time steeping, and a maximum time step set to ½ hours (for load data with 1 hour resolution this ensures that all load steps are visited), and a relative tolerance of 10^{-4} on the error of the solution is used to achieve required accuracy. The spatial temperature distribution in the ground was initially set by using an equation from [11] that, based on measured temperature data, can provide the soil temperature as a function of time and soil depth. Details on how this was calculated for the specific case used in this work can be found in [2].

3. Case description

3.1 Cable installation

The onshore wind farm cable installation investigated in this work, has previously been described in [2]. The installation comprises a 145 kV 3x1x1600 mm^2 cable with an aluminium segmented conductor, XLPE insulation, combined copper wires and aluminium laminate screen.
The cable is 4.8 km long, connecting a wind farm to a substation. The installation conditions vary along the cable; the types and presence of backfill masses vary, and burial depths range from 0.5 m to 5.5 m. Furthermore, in a few sections the cable is installed in pipes and duct constructions. Further details may be found in [2]. When positions were selected for modelling in this paper, the directly buried trefoil formation was selected, as this is the better documented case by IEC standard. The burial depth of the selected installation was 0.8 m, with a 10 cm thick layer of thermal backfill around the trefoil, directly buried in the native soil. The thermal resistivity of the surrounding soils used in the modelling was 1.0 K.m/W. The directly buried trefoil formation occurs at several locations along the cable route, for instance between 1100 and 1500 m. The average and maximum measured temperature in this section of the cable route can be seen in Figure 1.

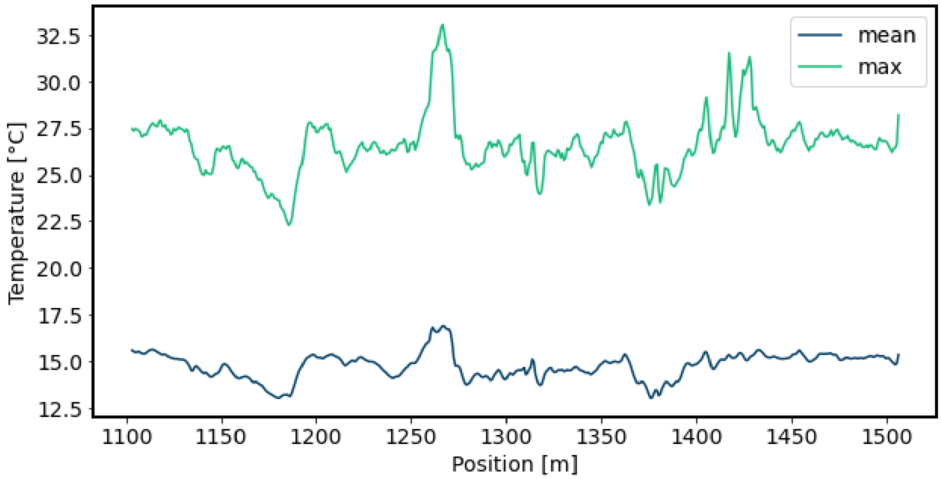


Figure 1: Average and maximum measured temperature in directly buried trefoil, between 1100 and 1500 meters.

3.2 DTS measurement system

The cable was equipped with a DTS measurement system. The DTS has a fiber optic sensor twisted around the central axis of the cable together with the screen wires, giving a total 5 700 data points along the cable, recording the screen temperature of the cable. Measurements were performed every ten minutes during a period of nine months. The DTS was installed by the local grid company as part of an R&D project. Variations in temperature as a function of the position and time of year can be seen in Figure 2.

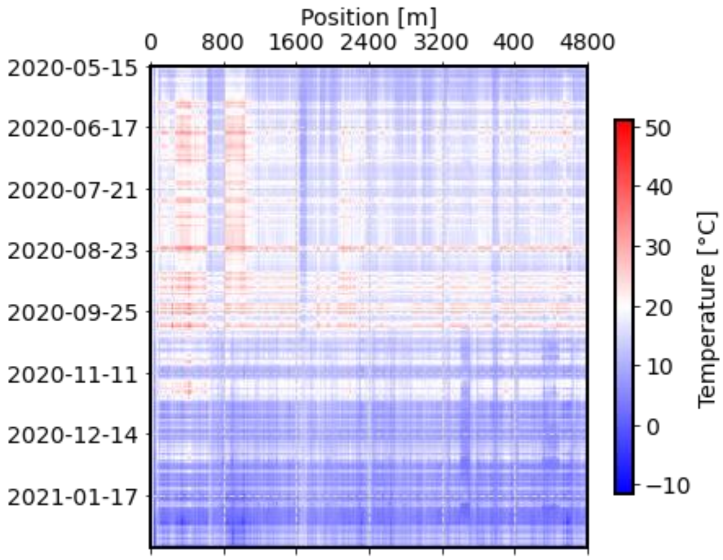
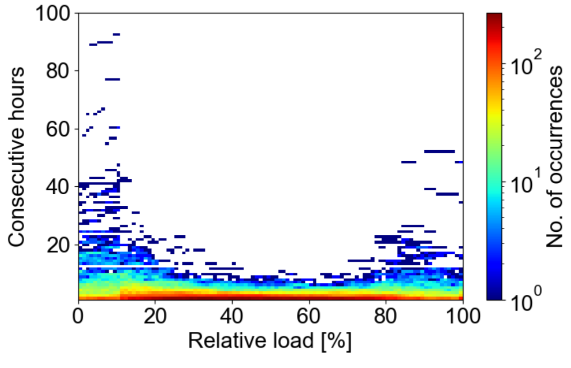


Figure 2: Variations in cable temperature as a function of position and date.

3.3 Load data

Load data was collected hourly from May to February. As this is a wind farm export cable, delivered power varies with wind speeds, giving an intermittent load pattern with frequent starts and stops. A statistical analysis of the load data is shown in Figure 3 (a). The load data is split into 100 bins and plotted in a 2D histogram, with each bin representing the number of consecutive hours that a load value ± 10% is applied. The color bar indicates the number of occurrences of a specific load duration. The load is highly intermittent with typical load durations of less than five hours. There are some occurrences of low load durations of around 90 hours and some occurrences of high load durations of around 50 consecutive hours. An example of the latter case occurred between 21 and 23 November, as can be seen in Figure 3 (b).



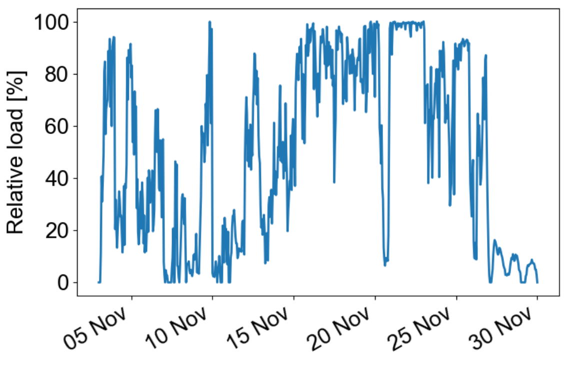


Figure 3 (a): Statistical treatment of load data. (b): Load data from November. Figures were initially published in [2].

4. Results and discussions

To evaluate and compare the methodologies of TEC and FEA, three cases with increasing complexity were chosen, ranging from steady state to real load temperature measurements from a wind farm export cable. The cases are summarized in Table 1.

Table 1: Overview of case studies.

Case	Description
A – Steady State	Comparison between the steady state solutions for a given current. For TEC, this method uses only IEC 60287.
B – Step Response	The current is switched on to a constant value at t=0 and the transient temperature response is calculated.
C – Real Data	The transient temperature response to real load data from a wind farm export cable is calculated. The calculated screen temperature is compared to that measured by DTS.

The results from the cases are presented and discussed in the following sub sections.

4.1 Case A – Steady State

For this case, the ambient temperature was set to 15 °C and the current was set to a constant level at 60 % and 100 % of the maximum rated load specified by the manufacturer, respectively. The resulting temperatures are shown in Table 2.

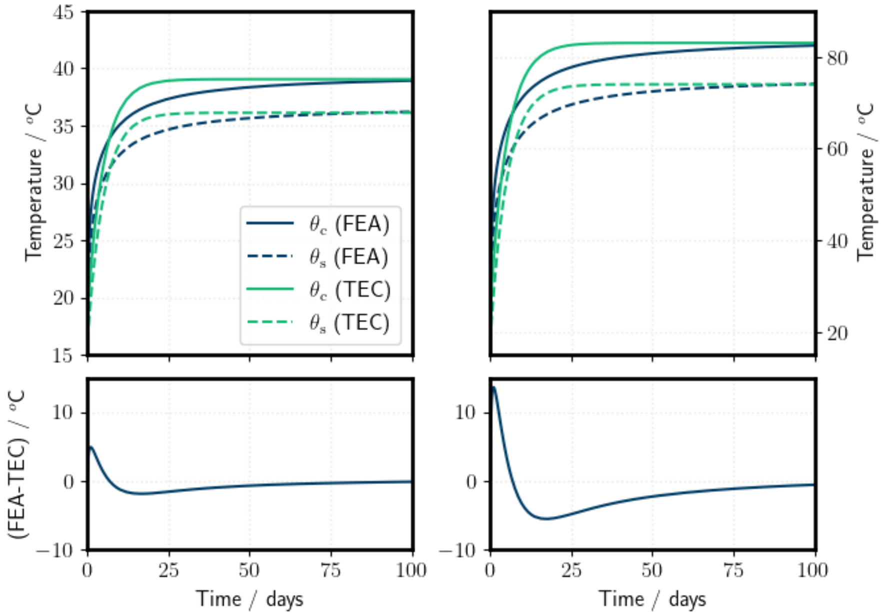
Table 2: Resulting temperatures at conductor and screen at 60% and 100% of manufacturers rated current.

Current	Method	Conductor temperature	Screen temperature	Temperature rise (conductor – screen)
Max operational (60% of rated)	FEA	39.56 °C	36.83 °C	2.74 °C
	TEC	38.08 °C	35.31 °C	2.77 °C
	Deviation (FEA – TEC)	1.48 °C (4%)	1.51 °C (4%)	-0.03 °C (1%)
Rated	FEA	84.16 °C	75.72 °C	8.44 °C
	TEC	83.05 °C	74.44 °C	8.61 °C
	Deviation (FEA – TEC)	1.11 °C (1%)	1.28 °C (2%)	-0.17 °C (2%)

For the screen temperature there is a difference of 1.51 °C and 1.28 °C at maximum operational and rated load, respectively, between the FEA and TEC calculations. The deviations between calculated conductor temperatures are comparable, but slightly smaller. The calculated temperature rise (from screen to conductor) is even more similar between the two modelling approaches, with -0.03 °C and -0.17 °C deviations. Overall, the difference between the models is small for the steady state calculations. The small deviations are to be expected, as different simplifications and assumptions are made in the two approaches. Note also that the differences are within the order of accuracy typical of a DTS system.

4.2 Case B – Step response

For the step response case, the initial temperature in all parts (cable, soil and ambient) were set to 15 °C. The transient temperature response to a constant load was calculated using FEA and TEC. Since the heat capacity for use with TEC was calculated using the FEA results, the transient behavior is necessarily also similar. The smallest deviation between FEA and TEC was found for $k = 0.065$. The resulting transient responses for FEA and TEC, and corresponding deviation as function of time, is shown in Figure 4. From initial time t = 0 and until t < 180 h the TEC model underestimates the temperature, while for t > 180 h the TEC model overestimates the temperature. For load transients lasting less than a week, this will provide a conservative temperature estimate using the TEC model.



(a) (b)

Figure 4: (a) shows the transient response at maximum operational current, while (b) shows transient response for rated current. The lower panels show the deviation between the two models.

4.3 Case C – Real Data

Both models, FEA and TEC, were given data from the same 45-day period from the beginning of November to the middle of December. The k found in case B was used to calibrate the heat capacity in the TEC model. The results from the models are shown in Figure 5 a), deviation between models and measured values in b), while in c) the temperature and precipitation for the region is shown. The latter was collected from the meteorological station located closest to the cable location [12].

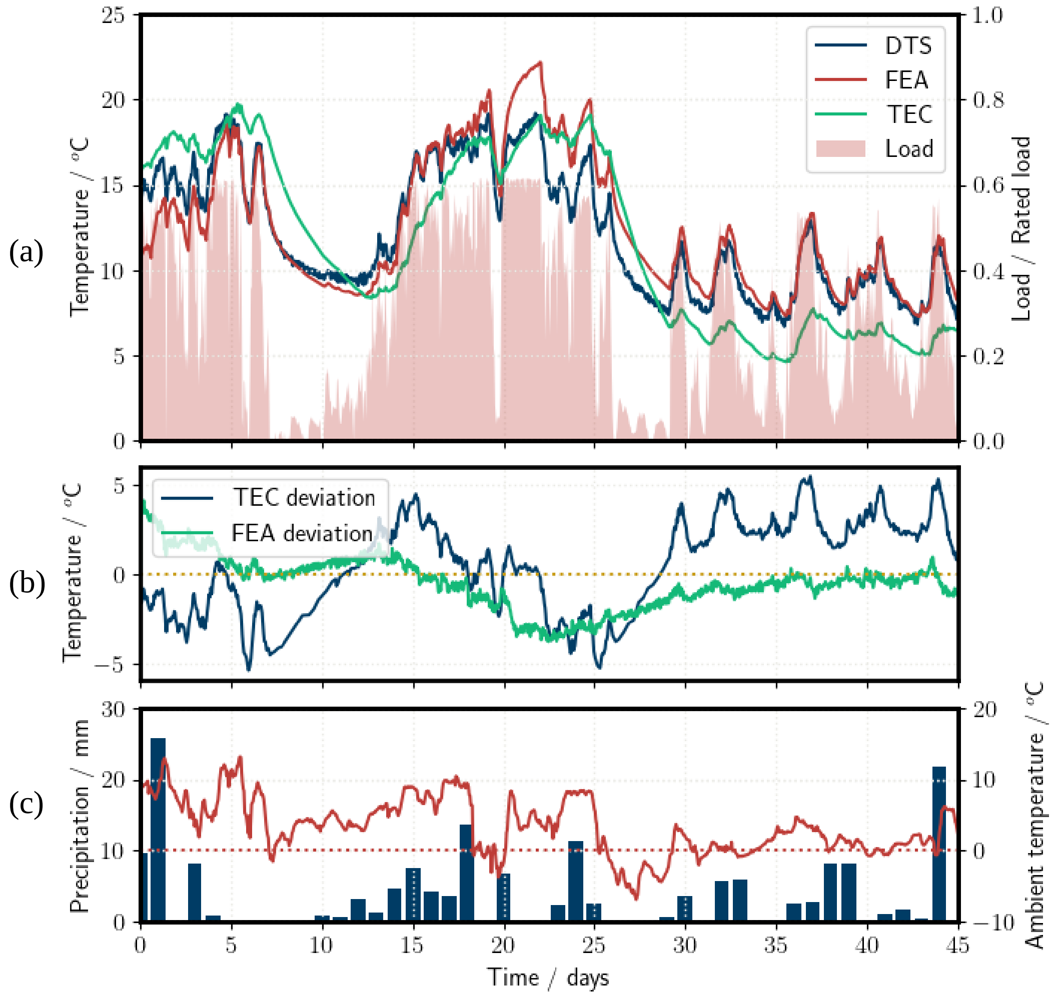


Figure 5: Three plots showing. (a) the calculated screen temperature done by FEA and TEC, as well as the actual temperature measured by DTS. In addition, the load is plotted for reference. In (b) the deviation of the FEA and TEC models as compared to the DTS over time is plotted. In (c) the precipitation and state of ground is plotted.

The maximum deviation between measured and calculated sheath temperature are approximately 4.2 °C and 5.5 °C for FEA and TEC, respectively, while the mean $\pm$ standard deviation of the errors are 1.17 $\pm$ 1.00 °C and 2.44 $\pm$ 1.27 °C respectively. As the maximum permissible load was not reached during the measurement period, the maximum measured temperature is far from the thermal limit.

As can be seen in Figure 5, there is a systematic deviation in the TEC model that follows the load and temperature. The calculated temperature is lagging the measured values, and for short peak loads, the calculated temperature is lower. This is consistent with the underestimation of temperature for $T < 180$ h as shown for the step response in case B. For the FEA model, no systematic deviation between measured and calculated values can be seen. For the modelling in this work, including FEA, static values for thermal resistivity and capacity were used. The thermal resistivity is very sensitive to moisture content since the soil is partially saturated [13] and precipitation will have great impact on the thermal resistivity already within an hour after rainfall. Thermal capacity also depends on moisture content but is not as sensitive as thermal resistivity. It is thus hypothesized that precipitation changes the thermal properties dynamically over time, by decreasing resistivity and increasing capacity of the soil. This will affect FEA models that use static thermophysical properties incorrectly unless the weather is very stable. This is a challenge for predicting cable temperatures. Earlier experiences in validation of FEA models show good correspondence between measured and calculated values when the thermal properties of the cable surroundings are known and controlled [14].

An important shortcoming of this case study, and many others, is that the thermal properties of the soil have not been characterized in-situ. The backfill closest to the cable is specified to follow Norwegian guidelines [15] and has a thermal resistivity close to 1 m.K/W. That is, if it is compacted properly and the moisture content is around 5 %. Our experience is that this is most often the case, with a variation of around 10 % in thermal resistivity from case to case. The natural soil further away from the cable will have less impact on the heat transport, but the variation can be even larger. This is reflected in Figure 1, where the installation geometry is supposed to be uniform but there is a large temperature variation as along the cable installation.

To succeed with dynamic ampacity rating and temperature prediction it is not sufficient to solely install a DTS. The thermal environment of the cable must be carefully characterized, and the effect of weather must be considered. An example of taking precipitation into account was shown in [16]. Secondly, there are discrepancies both between the TEC and FEA models, which should be resolved to provide accurate temperature prediction. Our experience is that FEA can provide very accurate results, both for scaled laboratory setups and full-scale cable trenches [14], but because of the computational power and expertise needed to properly use FEA, it is not likely to be a viable option for system-wide implementation dynamic cable rating and TEC models should be further developed. As stated earlier, the challenge for transient TECs is mostly related to representing the thermal equivalent of the soil, and computationally effective methods to do this should be explored further. The thermal resistance T_4 can be calculated by using FEA [17], while other research literature demonstrate that sectioning the soil in layers [18] and using Kalman filters to adapt the soil thermal properties with historical data [19] can provide more accurate representations. The challenge in validating soil models is that small-scale setups in controlled environments can accurately be represented by a single layer, while large-scale such as the one described in [20] require massive efforts to provide results. In [20], a similar deviation in short-time response that was seen in this work is found for the TEC models, while the deviation is negligible for FEA.

5. Conclusion

A dataset containing load and screen temperature for nine months was acquired from an export cable for an onshore windfarm in Norway. A section where the cable is directly buried in trefoil formation was chosen for further studies of electrothermal models using TEC and FEA. Prior to testing on the real load profile, the TEC and FEA methodology were compared for steady-state load and step response. It was found that:

- The TEC model has time delay in step response, underestimating temperatures in the initial phase of temperature increase when compared to FEA.
- The same time delay appeared when evaluating TEC on real load and temperature data, showing a systematic deviation during rapid changes in measured temperatures.
- Comparison of the FEA models with real load and temperature data showed no systematic deviation; hence it is hypothesized that this is caused by lack of correct thermal parameters in the soil, and that they are likely to vary in time due to e.g., precipitation.

Further work should focus on:

- Developing a more detailed model of soil in TEC methodology, likely by dividing the soil in concentric layers away from the cable.
- Include temporal variations in thermal properties of soil and predict these from weather forecasts and/or use predictive methods for parameter estimation.
- Include several cable sections with different installation conditions and geometries.

BIBLIOGRAPHY

[1] Working Group WG B1.40 CIGRE, ‘Offshore Generation Cable Connections’. (CIGRE TB 610, Feb. 2015).
[2] H. Strand, E. Eberg, K. O. Asklund, N. M. Thomsen, and K. S. Thinn, 'Experiences with ampacity rating calculations for wind farm export cable’. (27th International Conference on Electricity Distribution (CIRED 2023), Rome, Italy: Institution of Engineering and Technology, 2023, pp. 2180–2184).
[3] International Electrotechnical Commission, ‘IEC 60287 Electric Cables - Calculation of the current rating’. (2023).
[4] J. A. Rosendo-Macías et al., ‘The Spanish Experience: Squeezing Line Ampacities Through Dynamic Line Rating’. (IEEE Power and Energy Mag, vol. 21, no. 1, pp. 73–82, Jan. 2023).
[5] R. S. Olsen and U. S. Gudmundsdottir, ‘Dynamic temperature estimation and real time emergency rating of transmission cables’. (2012 IEEE Power and Energy Society General Meeting, San Diego, CA: IEEE, Jul. 2012, pp. 1–8).
[6] International Electrotechnical Commission, ‘IEC 60853 Calculation of the Cyclic and Emergency Current Rating of Cables’. (2008).
[7] G. Callender, D. Ellis, K. F. Goddard, J. K. Dix, J. A. Pilgrim, and M. Erdmann, ‘Low Computational Cost Model for Convective Heat Transfer From Submarine Cables’. (IEEE Trans. Power Delivery, vol. 36, no. 2, pp. 760–768, Apr. 2021).
[8] S. Catmull, R. D. Chippendale, J. A. Pilgrim, G. Hutton, and P. Cangy, ‘Cyclic Load Profiles for Offshore Wind Farm Cable Rating’. (IEEE Trans. Power Delivery, vol. 31, no. 3, pp. 1242–1250, Jun. 2016).
[9] J. Lux, T. Czerniuk, M. Olschewski, and W. Hill, ‘Non-Concentric Ladder Soil Model for Dynamic Rating of Buried Power Cables’. (IEEE Trans. Power Delivery, vol. 36, no. 1, pp. 235–243, Feb. 2021).
[10] E. Eberg, S. M. Hellesø, H. Strand, M. Engebrethsen, and D. Østerberg, ‘Implementation of Finite Element Analysis and Hybrid IEC-Models in Online Ampacity Tool’. (Jicable’23, Lyon, Jun. 2023).
[11] G. P. Williams and L. W. Gold, ‘Ground temperatures’. (Canadian Building Digest, p. 6 p., Jul. 1976).
[12] ‘Norwegian Centre for Climate Services’. (https://seklima.met.no/, Jan 17, 2024).
[13] K. Rieksts and E. Eberg, ‘Experimental Study on the Effect of Soil Moisture Content on Critical Temperature Rise for Typical Cable Backfill Materials’. (IEEE Trans. Power Delivery, vol. 38, no. 3, pp. 1636–1648, Jun. 2023).
[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).
[15] REN AS, ‘RENblad 9200 Kabelanlegg prosjektering’, (2022).
[16] R. Olsen, G. J. Anders, J. Holboell, and U. S. Gudmundsdottir, ‘Modelling of Dynamic Transmission Cable Temperature Considering Soil-Specific Heat, Thermal Resistivity, and Precipitation’. (IEEE Trans. Power Delivery, vol. 28, no. 3, pp. 1909–1917, Jul. 2013).
[17] 'Soil Temperature Calculator', Cableizer, (April 20. 2015, Available: https://www.cableizer.com/blog/post/soil-temperature-calculator/, Accessed: Jan 17, 2024).
[18] R. S. Olsen, J. Holboll, and U. S. Gudmundsdóttir, ‘Dynamic temperature estimation and real time emergency rating of transmission cables’. (2012 IEEE Power and Energy Society General Meeting, Jul. 2012, pp. 1–8).
[19] D. Aegerter and S. Meier, ‘Model-based predictive control for use in RTTR temperature sensing systems of high voltage cables’. (10th International Conference on Insulated Power Cable, Jicable'19, Versailles, Jun. 2019).
[20] E. Olsen, F. Brynem, and M. Hatlo, ‘Dynamic Current Rating – Thermal Transient Response’. (Cigre Science and Engineering no.23, Dec. 2021).