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Deriving an experimental and analytical relation between the core and fiber temperatures of a 3P XLPE cable

Manly Callewaert / Roel Vanthillo / Christian Fojtek (Marlinks)

Bart Mampaey (Elia)

manly.callewaert@marlinks.com

Every submarine power cable contains a fiber-optic assembly. Most windfarms have a distributed temperature sensing (DTS) device for continuous temperature monitoring. Using real-time thermal rating (RTTR) the performance of subsea cables can be increased or a less expensive cable can be installed.

The experiments aimed to establish the relation between the fiber and core (or conductor) temperatures in the cable. Fiber temperature was obtained using a DTS interrogator; thermocouples installed in the conductors yielded the core temperature data. The cable used in this test was a 20 meter-long 1800 mm², 1000 A export cable.

These experiments validated a new RTTR model proposed by Marlinks: a thermal RC-ladder model based on finite-element (FEM) calculations. Better suited to the complexity of the spacer geometry and existence of the fiber node, the Marlinks-developed model is considered to be more accurate than the industry standard.

1. Objectives

Reaching conductor temperatures of 90°C or higher will damage the XLPE layer which can render the whole cable useless. This is why some wind farms have RTTR modules to protect their assets. Most of these modules use the IEC industry standard to calculate the core temperature, however we find this method lacking as it does not take into account the increased geometrical complexity of modern cables due to the presence of spacers and a fiber node inside the cable (Figure 1).

This is why, in this paper, we propose and experimentally validate a new thermal RC-ladder RTTR model based on FEM calculations. The FEM calculations themselves have high predictive power, however, they are also too computationally demanding for real-time applications. The proposed new model tackles this issue. We will also argue why the IEC industry standard [1] is found imperfect for the purpose of RTTR.

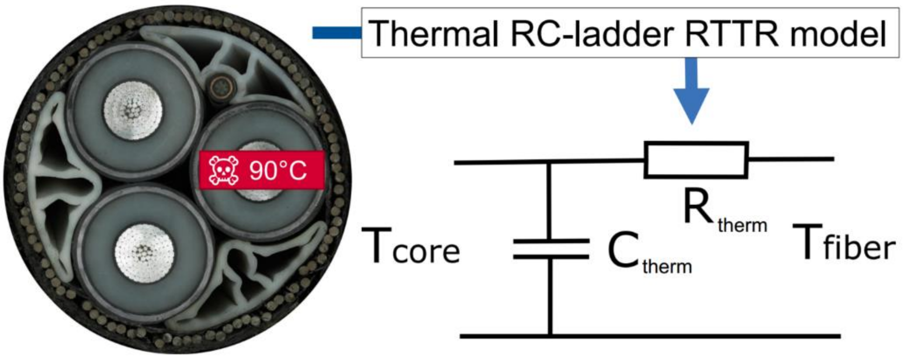

Figure 1 A method is proposed to translate a complex cable geometry into a simple model. Left: picture of a modern offshore high voltage export cable cross-section. Right: thermal RC-ladder model for RTTR modeling.

2. Methods

Prior to setting up the real-life experiment, the heat flows inside the cable and in the sand bed were described in the highest possible detail using an FEM model calculation. Next, an alternative and computationally less intensive method was proposed [2].

The new method uses a numerical iterative RC-ladder model (Figure 1) to calculate the core temperature from the measured fiber temperature obtained by a DTS interrogator. The thermal resistance *R* and capacitance *C* were established by fitting a dynamic FEM calculation [3-5]. To validate this approach, an experiment is set up with thermocouples measuring the actual conductor temperature.

2.1. FEM modeling

The cable as described in the datasheet [6] was FEM-modeled. A detailed CAD drawing of the cable was made. The cable datasheet also provided the materials used in the cable's construction. The thermal properties of the individual cable parts where found in a database [7]. The properties of the water-saturated sand were measured in the University of Ghent's geotechnics laboratory. The sand bed is simplified as an 80 cm-wide square. Figure 2 shows the effect of 1500 A applied for 24 hours. This explorative calculation was done prior to constructing the box. This calculation clearly shows that the dimensions of the box are chosen so that the heat does not reach the wall, and therefore that, for the purpose of the experiment, the cable can be considered buried in a semi-infinite body.

The IEC standard, which was developed before the expansion of offshore wind and before the widespread adoption of fiber-optic cables and DTS equipment, does not allow calculating thermal R or C to a fiber node such as the one present in all modern submarine cables; it assumes the temperatures to be measured at the cable wall. To use the standard with DTS-based temperatures from the fiber node instead, the standard should be used to calculate cylindrical shell formulas up to the cable sheath. While the fiber is located close to the sheath in most cables, this method lacks the accuracy of the FEM calculation which is better able to deal with the highly complex spacer geometry inside the cable.

Based on a time-dependent simulation (Figure 3), these thermal RC-values can be fitted. The load profile used in this numerical calculation was equal to the ones used in the experiments (Figure 7, left panel). The resulting values are shown in Table 1.

R [K/W]	0.0817
C [J/K]	27373

Table 1 RC-values found by fitting a dynamic FEM calculation

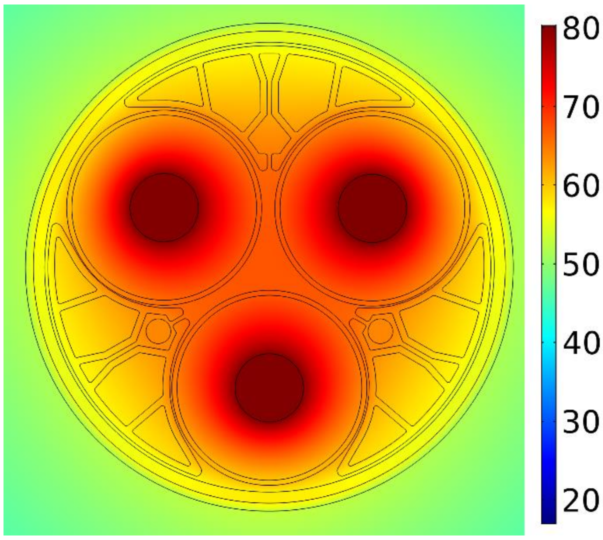

Figure 2 An FEM model is built using the material properties and cable geometry obtained from the cable datasheet. The figure shows the results of 24h constant load (1500 A) calculation, with core temperatures reaching 80°C (zoomed in).

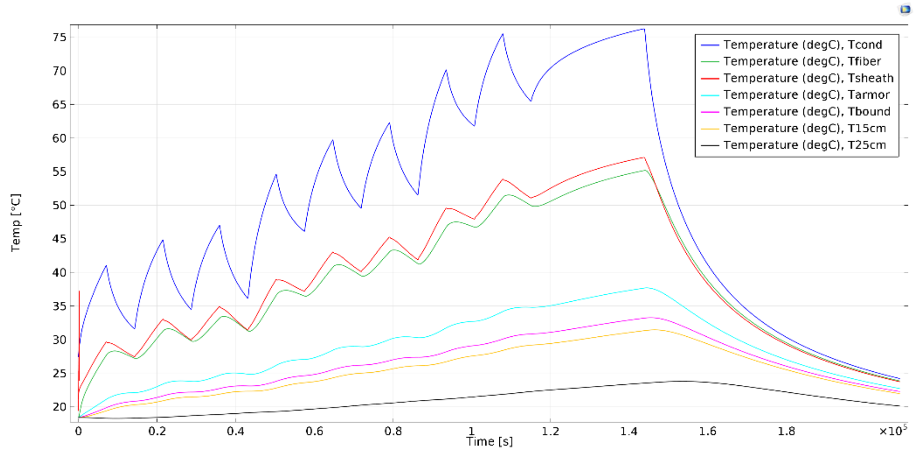

Figure 3 Result of a dynamic load profile FEM simulation prior to the experiment. Temperature versus time plots from important nodes inside the cable.

2.2. *Experimental set-up*

The cable used for this test is a 20 m-long, 1800 mm², 1000 A export cable. We buried it in the center of a 80 cm-wide square duct (Figure 4). The experiment (Figure 5) consists of 3 current transformers and a star point. There were 9 thermocouples installed inside the cores, i.e. 3 in each phase. Thermocouples were installed at various distances on 3 wooden frames to monitor the heat propagating inside the box.

The cable's nominal load was 1000 A, however in order to reach sufficiently high temperatures in the experimental window of a few days, much higher currents of 1500-1800 A were induced into each of the three conductors with current injection transformers (Figure 7). The three phases were connected in star with aluminum cable terminations (Figure 6). The soil and armor were grounded together. Power capacitators were used to increase the cos phi and to avoid power supply failures.

The dimensions of the duct were chosen so that the heat would not reach the boundaries within a 24-hour period of constant heating. To remove the heat and prepare the setup for another experiment, a drainage system was installed underneath the sand bed consisting of drain pipes and lava stone.

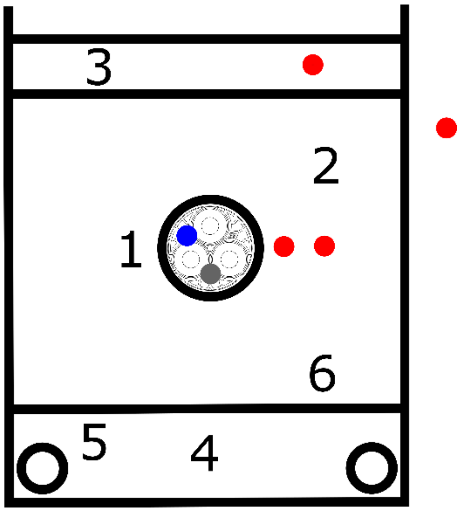

Figure 4 Cross-sectional drawing of the box. Red dots: thermocouples outside the cable

1) cable 2) sand 3) water level 4) lava stone layer 5) drainpipe 6) canvas

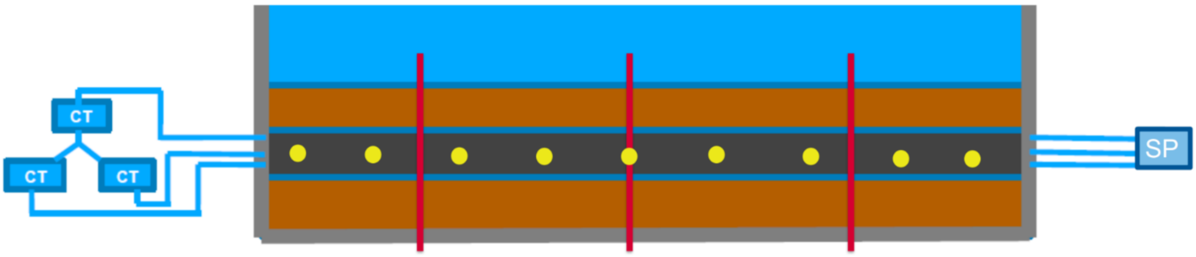

Figure 5 Schematic diagram of the experiment. Yellow dots: thermocouple inside the conductor, Red lines: positions of wooden frames with thermocouples, CT: current transformer, SP: star point.

3. Results

3.1. Construction

The offshore high-voltage cable was installed when the box was constructed and half filled with sand (Figure 6, top left). Three wooden frames (Figure 4) with thermocouples were installed to monitor the heat propagation inside the box. Based on the lay length of the cable, nine equidistant spaced holes were drilled in the cores to install thermocouples (Figure 6, bottom left and Figure 5, yellow dots). The star point was made by short circuiting the three phases with thick aluminum plates.

Figure 6 Overview pictures of the set-up

3.2. Experiments

We performed a first experiment with 24 hours of constant load, and a second with a dynamic load profile. It is important to note that much more current was applied than the nominal 1000 A. In the first experiment, the load was constantly 1500 A; in the dynamic-load case the maximum load briefly climbed to 1800 A.

In the first phase of the experiment, a constant current of 1500 A was applied for 24 hours. Thereafter, the current was switched off for 18 hours. In the second phase, a dynamic-load profile was applied to the cable for 36 hours after which the cable was allowed to cool for 18 hours (Figure 7). Ultimately, we removed the heat in preparation for a new experiment by opening the drain taps and flushing with fresh water.

Figure 8 shows graphs of the experiments. The red line indicates the measured DTS temperature, the black line shows the measured core temperature, and the dashed line is the prediction made using our RC-ladder RTTR model based on the FEM calculation. It should be abundantly clear that this is a very good fit.

A nominal load of 1000 A proved to be very conservative as the cable sustained a continuous load of 1500 A without reaching the critical temperature of 90°C. The underpinning IEC norm is considered to be equally conservative and inadequate. The FEM-based method is demonstrably the better approach in terms of RMS prediction errors. This also means that the end-user needs not build in any additional safety factors when evaluating core temperatures as these are already incorporated in the IEC norm.

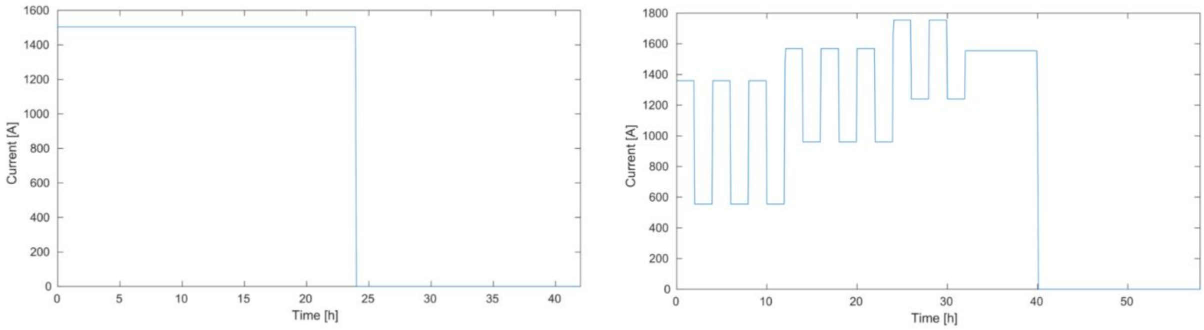

Figure 7 Current profiles applied during the experiment: Left: 24h constant current, Right: synthetic dynamic load.

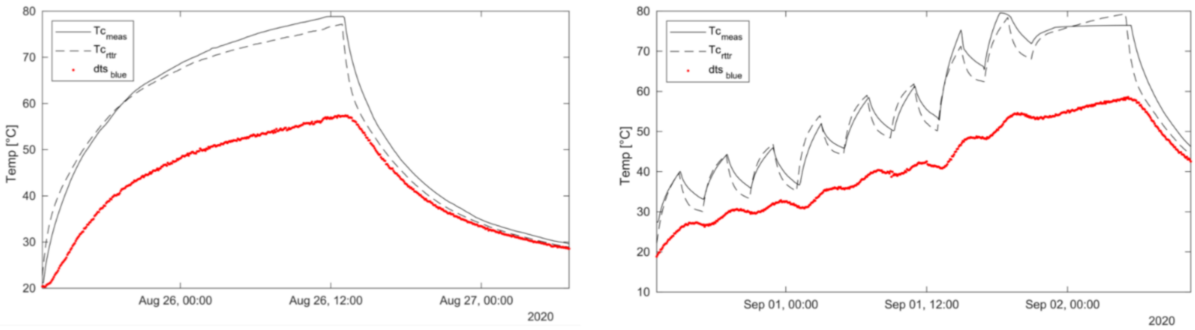

Figure 8 Comparison of the measured core temperatures and those predicted by our RTTR model based on the measured DTS temperature.

4. Conclusion

Having accurate and real-time insights in core temperature allows end users to maximize power output and rapidly react to rising core temperatures without risking cable failure.

The experiments laid out in this paper validate the proposed new approach's predictive power for providing such accurate and real-time insights. The RC-ladder values derived from the FEM calculation's results are found to be very accurate, and they far less computationally intensive than the FEM calculation itself.

It was also shown that the proposed RTTR model enables cables to transport much higher currents than the maximums dictated by the in our view outdated industry standard.

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