MEASUREMENT, MODELLING AND REAL-TIME CALCULATION OF MEDIUM VOLTAGE CABLE TEMPERATURES

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ABSTRACT

The ever-increasing numbers of decentralized production units that are connected to the distribution networks cause a variety of challenges. When possible, the DSO tries to connect these units directly to existing distribution cables in order to have production and consumption close to each other. However, these networks were usually not designed to accommodate such high powers, which could result in over-voltages and/or overload of the cables. Often, the only option is to reinforce some of the feeders. In some cases, however, this would lead to very high social costs and other solutions should be considered. As the renewable energy sources such as wind turbines have a fluctuating power output, the high loading of the cables is only present for a very short period of time. A combination of automatic curtailment and flexible ampacity limits by applying dynamic line rating (DLR) could reduce the necessary investment costs. When applying DLR, a temperature measurement or calculation is needed. Therefore, in this paper, the measurement, modelling and real-time calculation of the cable temperature is discussed.

INTRODUCTION

In medium voltage (MV) network planning, load flow calculations are used to check possible violations of current and voltage limits. Often, the ampacity of the MV cables is a limiting factor. Decentralized generation units (e.g. wind turbines, PV panels), which are integrated in the MV network, usually have a fluctuating power production. This might result in high currents that only occur for limited periods in time, but that determine the rating of the cables. As the thermal behaviour (and not the short current spikes) is the limiting factor, the concept of dynamic line rating (DLR) is known as a possible solution to exploit the cables closer to their limits [1]. In this way, it is possible to shortly allow a higher current instead of over-dimensioning the network for these scarce periods of high cable loading.

In order to be able to use DLR in the distribution network or assist operators during emergency situations, it is necessary to have a notion of the cable temperature and the hot spot temperature in particular. Measuring the temperature of all MV cables is not feasible due to the large amount of cables in the distribution grid. Therefore, a real-time calculation of this hot spot temperature is needed.

In this paper, a real-time calculation method is developed which is programmed in the distribution management system (DMS). Firstly, measurements of the cable temperature are performed on a test site in the port of Antwerp. By analysing these measurements, hot spots could be identified. Secondly, based on the measurements of both current and temperature, an offline model for the hot spot temperature is developed, based on thermal calculations. Finally, the model is implemented in the distribution management system and compared with the real-time measurements of the hot spot temperature.

TEMPERATURE MEASUREMENTS

Test site

In the port of Antwerp, a test site with temperature measurements on an exploited MV cable is available. An overview of the test site is shown in Figure 1. Between the cabinets of wind turbine A and B, two MV cables are installed. The left cable is an XLPE-cable with a cross section of 50 mm² and a length of 230 m, whereas the right cable is an XLPE-cable with a cross section of 240 mm². A smaller cross section is used for the test cable, as this cable heats up faster for low currents.

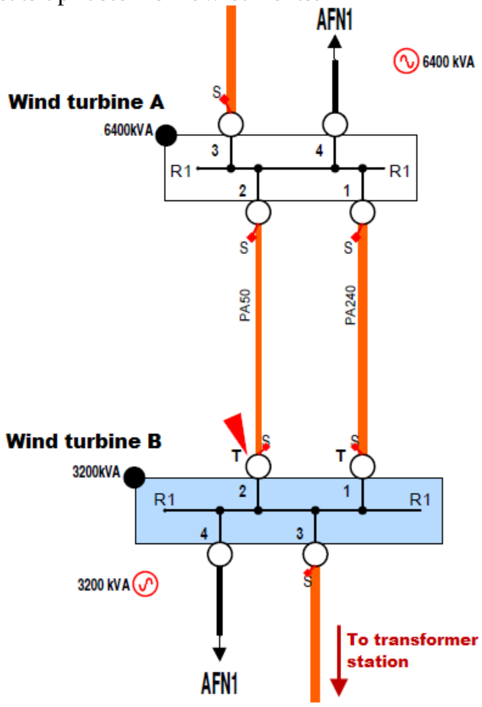

Figure 1: Overview of the test site

In normal operation, the XLPE-240mm²-cable is used as this cable has the highest capacity. The XLPE-50mm² cable is equipped with different temperature sensors and is only used during test periods. Firstly, a glass fibre is taped on the outer sheath on two of the three phases in order to measure the temperature variation along the trajectory of the cable between the two cabinets. Secondly, different PT100s are installed along the cable, in the cabinet of wind turbine B and in the soil close to the cable. Furthermore, current measurements are available on all the feeder cells. During tests, the network is reconfigured to make sure that only the power produced by wind turbine A flows through the XLPE-50mm²-cable. As the power output of the wind turbine can be curtailed, it is possible to control the current in the test cable. The nominal capacity of the XLPE-50mm² is 160 A, but during emergency situations, 230 A is allowed for a short period of time. As wind turbine A has a rating of 6 MW (two wind turbines of 3 MW) and is connected to a 15 kV network, this corresponds to the emergency current during periods of high wind speeds.

Comparison of temperature measurements

In Figure 2, the temperature measurement of the glass fibre is compared with the PT100-measurement at the same place, a spot close to the cabinet of wind turbine B.

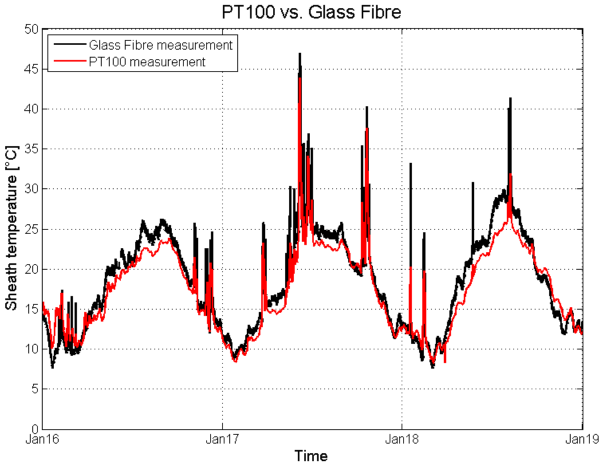

Figure 2: Comparison of differerent temperature measurements

It is immediately clear that both measurements give similar results. A measurement period of three years is consired. Two observations can be made:

1. Most of the time, no current flows through the test cable. Only the spikes with elevated temperatures indicate the test periods. Therefore, these temperature measurements represent the soil temperature for most of the time.
2. A clear seasonal effect of the soil temperature can be observed in the measurements.

Temperature profile along the cable

An important advantage of the glass fibre measurement is the fact that it can be used to determine the temperature profile along the cable. The temperature of the cable depends strongly on the construction method of the cable bed, as can be seen in Figure 3. In this figure, the temperature profile along the cable trajectory between wind turbine A and B is shown. The cable was heavily loaded (around 180 A at) to obtain these strongly elevated temperatures.

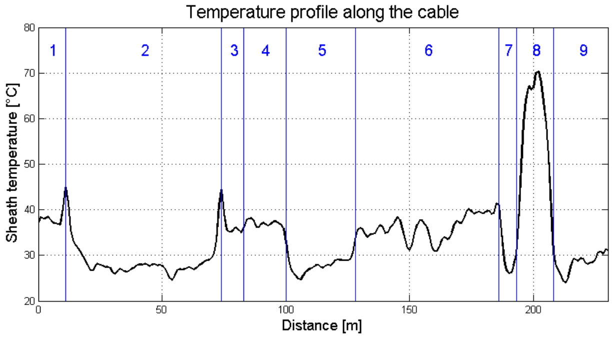

Figure 3: Temperature profile along the test cable

For the complete trajectory, trefoil formation is used for the three phases. In zone 1, the cable is placed in the ground on a depth of 80 cm. Zone 2 represents a horizontal directional drilling (HDD), which can be seen by the two temperature spikes at the beginning and end of the drilling. These elevated temperatures are caused by polyurethane props that are used to seal the drilling pipe and avoid soil subsidence [2]. Zone 3 is again normal construction at a depth of 80 cm. In zone 4, the cable is placed close to other loaded MV cables, which can be noted by a slightly elevated temperature. In zone 5, the cable is placed at a depth of 2.5 m, which can be seen by the lower temperature. Zone 6 is a mixed zone, at a depth of 80 cm, but with different soil types and soil density. The temperature is similar to the one measured in zone 1 and 4. Zone 7 and 9 are again at a depth of 2.5 m, with similar temperatures as in zone 5. The most interesting zone, however, is zone 8. Here, the cable is placed in a manual drilling under a street. As the PVC-tube is filled with air, a clear hot spot arises [3].

Conclusions

From the temperature measurements, some interesting conclusions can be drawn:

- There is a clear, repetitive and predictable seasonal soil temperature variation.
- Polyurethane props at the ends of HDDs should be avoided.
- For the most construction options, the temperature is well below the cable limits (90°C). However, an important hot spot was identified in the manual drilling.

As the hot spot of the cable determines the ampacity, from now on only the hot spot temperature will be considered. This is the point at 202 m from cabinet A.

MODELLING OF THE TEMPERATURE

Steady-state temperature simulation

As the hot spot determines the ampacity of the cable, the hot spot situation is simulated in thermal simulation software (according to IEC 60287 and IEC 60853) [4-6].

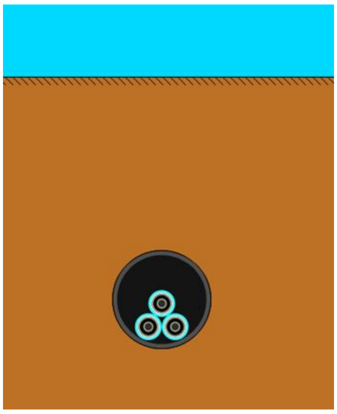

Figure 4: Simulation of hot spot temperature

An XLPE-50mm² is simulated in a PVC-tube on a depth of 80 cm. For steady state temperatures, the resemblance between the measurements and the calculations is very good. However, for dynamic simulations, the time constant in the simulation is about 2.5 times higher than in the measurements [7].

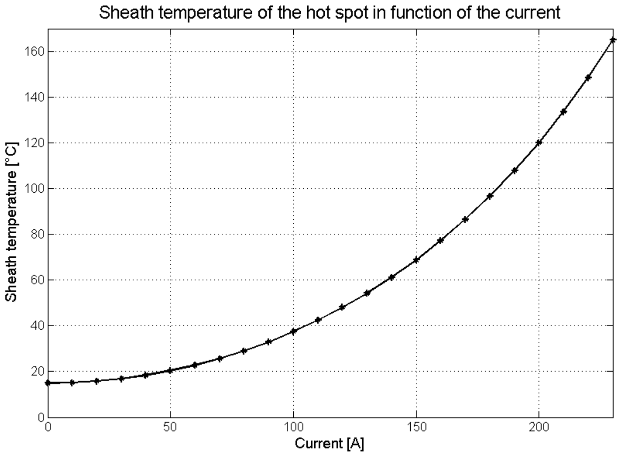

Figure 5: Simulated sheath temperature

In Figure 5, the results of different steady-state temperature calculations are summarised. It is possible to fit a curve that gives the relationship between the current and the steady-state temperature:

$$T_{steady-state} = a|I|^2 + b|I| + T_{offset} \qquad (1)$$

Where $T_{steady-state}$ is the steady state temperature, a and b are factors determined by the temperature simulations for the hot spot, I is the current through the cable and T_{offset} is the temperature of the soil. The quadratic term of (1) is dominant, as it represents the heat production in the cable by Joule losses. In the simulations, a constant soil temperature of 15°C was assumed, whereas Figure 2 suggested a seasonal variation. Therefore, in the next paragraph, an approximation of T_{offset} is introduced.

Seasonal variation of T_{offset}

In order to obtain a useful calculation model, it is important to take the seasonal variation of the soil temperature into account. In Figure 6, the suggested approximation is visualized. The offset temperature can be approximated as a sinusoidal function of time:

$$T_{offset} = 17 - 9\cos\left(\frac{t \cdot 2\pi}{N} - \frac{\pi}{5}\right) \qquad (2)$$

Where t is the considered day of the year and N is the number of days in a year (366, or 365 for a leap year). As Figure 6 shows, (2) is a good approximation for the seasonal variation for most of the time.

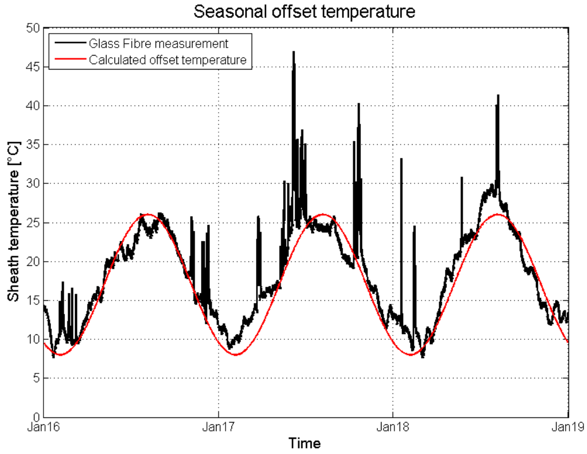

Figure 6: Seasonal variation of the offset temperature

Dynamic calculation of the temperature

With (1) and (2), it would be possible to calculate the steady-state temperature of the cable sheath for a given current. However, this is not very useful as a steady current is rarely observed in a cable in the distribution network.

In order to simulate the thermal inertia, a low-pass filter is used:

$$T_{sheath} = \frac{1}{1 + \tau s} T_{steady-state} \qquad (3)$$

Where s is the Laplace operator and τ is the time constant. This time constant is determined by applying a current step and observing the settling time of the resulting cable temperature. The current step could be realized by curtailing wind turbine A to a predefined setpoint, while using the XLPE-240mm²-cable. Then, the network is reconfigured to use the XLPE-50mm²-cable. Another way to determine the time constant τ is by analyzing the delay between a fluctuating current and the resulting cable temperature. For the hot spot temperature on the test site, a time constant of 75 min is obtained.

Real-time temperature calculation

By combining (1), (2) and (3), the hot spot sheath temperature can be calculated as a function of the measured current and time:

$$T_{sheath} = f\big(t, I(t)\big) \qquad (4)$$

As (4) is a continuous function of current and time, it should be discretized before it can be programmed in the distribution management system. The bilinear transform could be used to convert (3) from the Laplace domain to the Z-domain:

$$s = \frac{2}{t_{sample}}\left(\frac{1-z^{-1}}{1+z^{-1}}\right)$$

In the DMS, a sampling time t_{sample} of 60 s is used to obtain sufficient accuracy. In the next section, the results of the calculation are compared to the measured temperatures.

REAL-TIME CALCULATION RESULTS

Long-term results

In Figure 7, the measured hot spot temperature and the calculated temperature based on the measurement of the current in DMS are plotted for a period from October 2017 until December 2018.

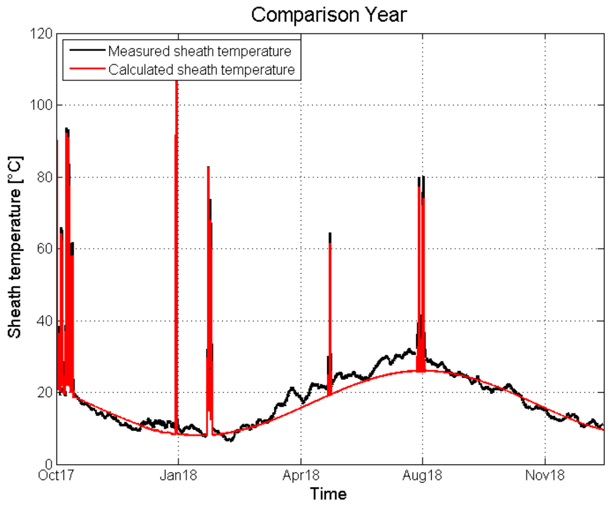

Figure 7: Long-term results

As expected, the seasonal variation is modelled correctly. Also, five distinct test periods are visible. The results for these test periods are shown in the next figures.

Test periods

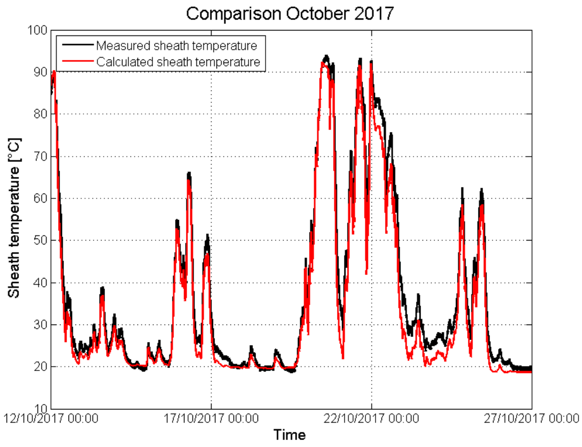

Figure 8: Test period in October 2017

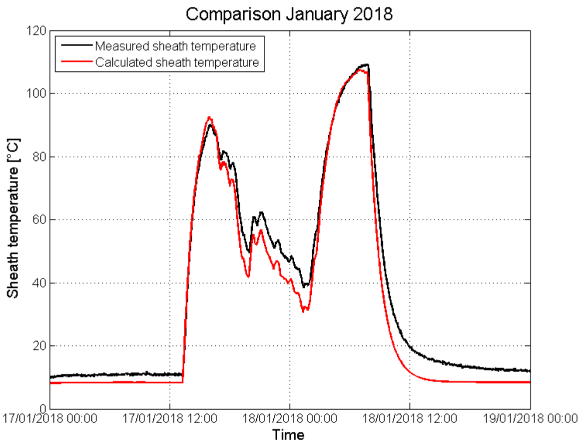

Figure 9: Test period in January 2018

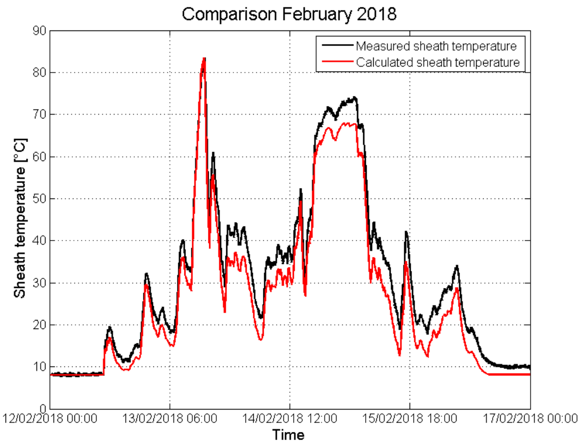

Figure 10: Test period in February 2018

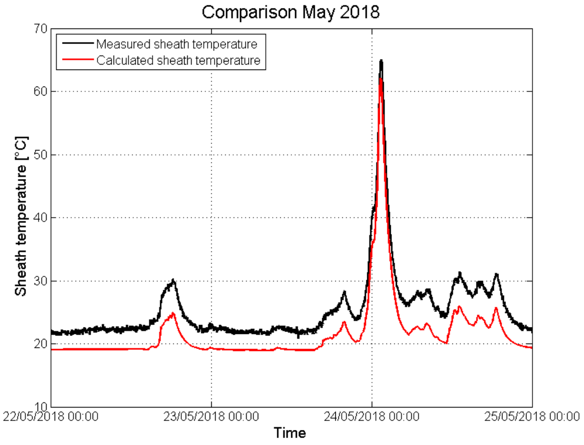

Figure 11: Test period in May 2018

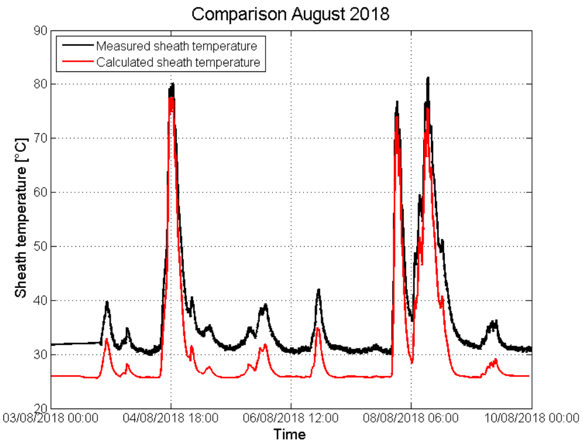

Figure 12: Test period in August 2018

In order to assess the performance of the calculation model under different conditions, tests were performed throughout the year. It is immediately clear that the developed model is able to calculate the sheath temperature with a sufficient accuracy. For the first three test periods, the results are very good, as there is almost no difference between the calculated and the measured temperature. For the two last test periods, the resemblance is less good, especially during periods of low currents. The main reason is the offset temperature, which is close to the real soil temperature for the first three tests. For the last two tests, the approximation gives an underestimation of the soil temperature, as can be seen in Figure 7.

For all the test periods, it is clear that the model is able to accurately calculate the cable temperature, particularly during the heating of the cable. The temperature calculation is a bit worse during the cooling process of the cable, but this has very limited impact on the overall performance during fluctuating loadings of the cable.

Nevertheless, for all the test periods, the difference between the measured and the calculated temperature is well below 10°C, which makes it applicable for DLR-applications.

CONCLUSIONS AND FUTURE WORK

In this paper, the measurement, modelling and real-time calculation of cable temperatures was discussed. From the glass fibre measurements, it was concluded that different hot spots can occur due to the construction of the cable bed. The two hot spots at the end of a HDD are caused by the use of polyurethane foam to seal the drilling. As a result of this observation, new drillings are treated differently and no polyurethane props are used anymore.

Then, a calculation model was developed to calculate the hot spot temperature in real-time in the distribution management system, only by measuring the current. The results of different test periods showed that it is possible to calculate the cable temperature with a good accuracy.

In the near future, it is planned to use the results of the calculated temperature to perform DLR on a wind turbine feeder. By using the temperature of the cable instead of fixed ampacity ratings, some additional decentralized production might be connected to the existing infrastructure.

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