Design of a calorimetric measuring system for measuring loss in electrical power cables

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Introduction

High voltage underground power cables are used to supply electrical power to large cities. Cables with very large cross section conductors, up to 2500 mm², are used, Fig 1. Such large conductors are already at 50 Hz affected by skin effect so that the ac resistance is larger than the dc resistance. It can be more than 50% higher than the dc resistance but the conductors can be designed to have lower ac resistance, e.g. by segmentation. Lower ac resistance is important as the maximum working temperature 90°C of the power cables will set a limit for the maximum current in the cable and hence the maximum transferred electrical power.

Fig. 1. High voltage underground cables are used for the supply of electrical power to large cities.

The standardised method to determine the ac-resistance of a cable conductor from a measured dc-resistance value does not work for conductors with very large cross-section. Hence, CIGRÉ recommend in technical brochure 272 to measure the ac resistance of such conductors when the cable is type tested, either by electrical or calorimetric methods. Typically calorimetric methods are not as accurate as electrical methods.

However, very low loss power cables are made using lacquered wires in the conductor and it is not obvious that electrical methods are possible to use. Hence the development of this new calorimetric measuring method, which aims to be as accurate as electrical methods are for standard segmented cables.

Measuring system

The calorimetric measuring system is inspired by ac-dc transfer measurement. Two equal samples of a power cable are arranged in one ac and one dc current circuit, Fig 2. The ac and dc currents are adjusted until the self heating increase the temperature of the conductor of both samples to 90°C. The ratio of the ac resistance and the dc resistance of the conductor can then be determined as:

$$\frac{R_{AC}}{R_{DC}} = \frac{I_{DC}^2}{I_{AC}^2} \; when \; \Delta T_2 = 0 \; and \; T_{DC} = 90°C$$

To assure that the temperature rise at the centre of the two samples are due to self heating only both ends of the two samples are cooled and kept at equal temperature. The cable ends are cooled to <20°C and so that $\Delta T_1 = \Delta T_3 = 0$.

By having two samples the heat loss does not need to be measured, just made equal for both samples. So the cable samples need to be equally supported and have an equal environment so that losses due to convection and radiation are equal for both samples.

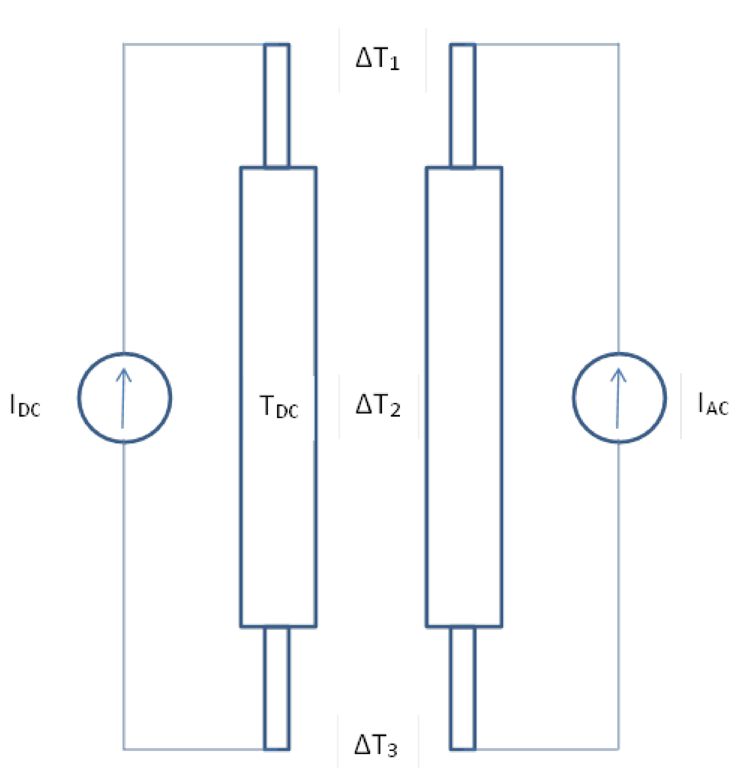

Fig. 2. Schematic drawing of the calorimetric measuring system.

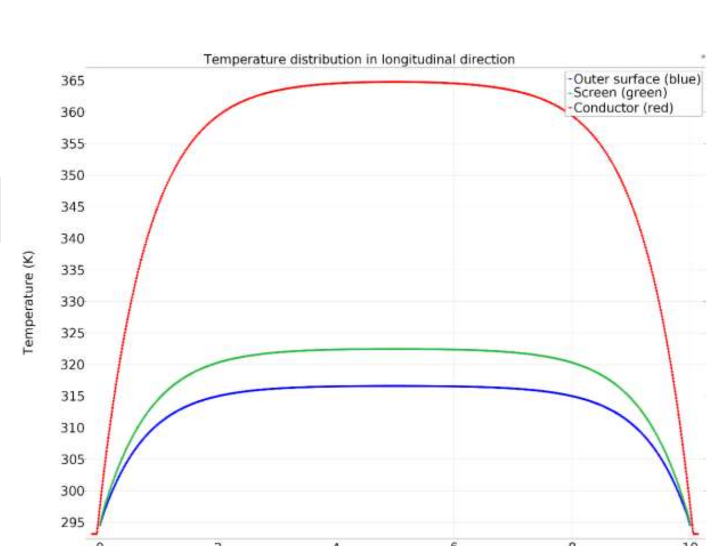

Fig. 3. The temperature distribution along the cable conductor (red), screen (green) and outer surface (blue) in the ac circuit.

Dimensioning

For selection of suitable length of the high voltage power cable to be measured and the equipment needed to generate and measure the ac and dc currents a simulation was made for a cable with 2000 mm² copper conductor. The temperature distribution in the ac and dc cables were determined by FEM simulation in COMSOL. Some simplifications were made in the simulation: the conductor was assumed to be homogeneous and the temperature dependence of some parameters were not included if their influence on the temperature distribution was negligible. E.g. the thermal conductivity of copper is so high that the temperature distribution in a cross section of the conductor will be homogeneous even if the thermal conductivity varies.

Also the self inductance of the ac current circuit and the mutual inductance between the two current circuits need to be investigated.

Temperature distribution

After a warm up period the temperature distribution in the cables varies along the length as in Fig. 3. The temperature distribution is not exactly equal in the ac cable and the dc cable, as the temperature coefficient of ac and dc resistance differ due to the skin effect. The temperature coefficient of the ac resistance also depends on the cross section due to the skin effect. If the length of the cables are chosen to 10 m the temperature will be within 1 K from the maximum temperature within a symmetrical interval of 3,6 m for the ac cable and 3,4 m for the dc cable.

Thermoelectric effects can distort the symmetry of the temperature distribution in the dc-cable. If necessary a current reversal switch can be used. The self heating gives a constant change in temperature of the cables. Hence a change in the ambient temperature will influence the maximum value (at steady state) equally. A larger part of the power loss is by radiation from the surface of the cables. As this is a non linear process a variable ambient temperature will cause an error. For a sine variation with amplitude 2 K and a period of 2 h the temperature error in a conductor was <10 mK. But, as mentioned, changes in ambient temperature will influence both cables.

Time constant

A transient solution shows the time dependence of the temperature in the cables, Fig 4. Of the same reason as above there is a difference between the time constant of the ac and dc cable. The time constant of the conductor of the ac cable is approx. 3,6 h and for the outer surface approx. 5,0 h. For the dc cable the time constant of the conductor is approx. 4,1 h and for the outer surface approx. 5,3 h. The warm up time need to be >6 time constants until the temperature is within 0,2 K of the steady state temperature.

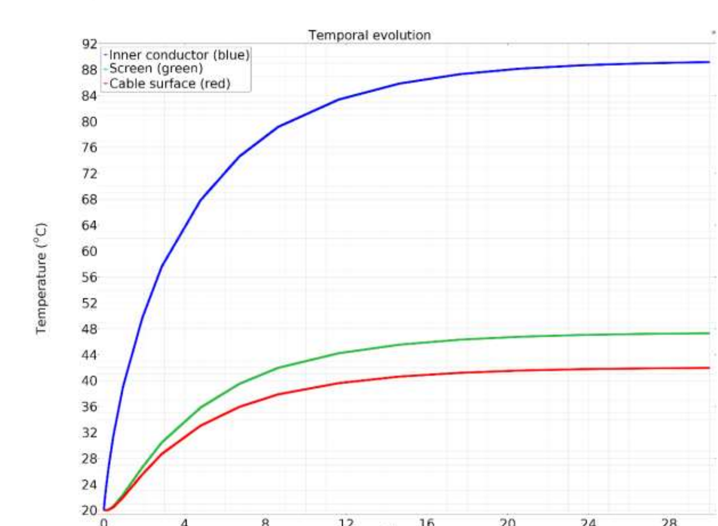

Fig. 4. The temperature of the conductor (red), screen (green) and outer surface (blue) of the cable in dc circuit during warm up.

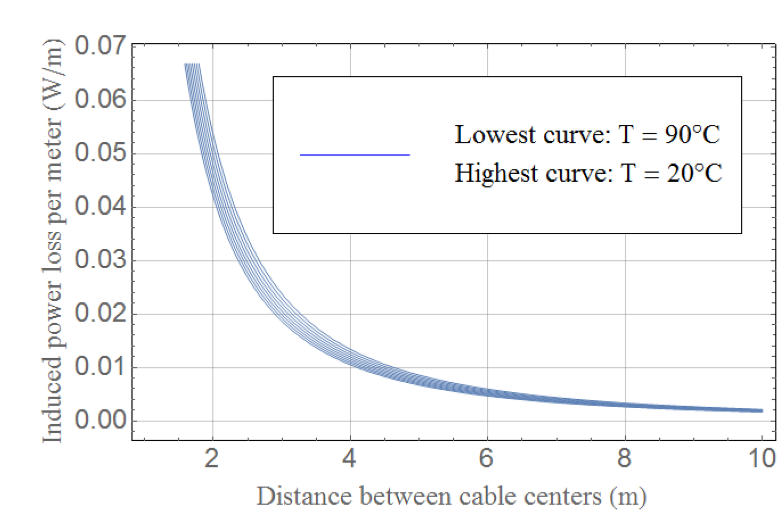

Fig. 5. The power loss in the dc circuit due to the induced ac current can be neglected compared to the self heating, which is approximately 90 W/m, if the distance between the cables are >2 m.

Self and mutual inductance

The self inductance of the ac current circuit is needed for the rating of the current generator needed, as it will determine the compliance voltage. An equation for the self inductance of a rectangular loop is developed for the case where the diameter (d_1) of the conductor on one of the long sides is larger than the diameter (d_2) on the three other sides and which also consider the internal inductance. For a rectangular loop with the sides 10 m and 2 m long it was found that the difference in self inductance compared to an equation for the self inductance of a rectangular loop with conductor of equal diameter and no internal inductance is within ±5% for ratios d_2 / d_1 in the range 0,2 to 1. For rating of the current generator this is not critical.

The mutual inductance between the two circuits will cause an ac current to be induced in the dc circuit and this induced current will induce an ac current in the ac circuit and so on. An approximate equation for the mutual inductance between two rectangular circuits placed side by side was determined. The power loss in the dc circuit due to the induced ac current can be neglected if the distance between the cables are 2 m, Fig 5. The induced current in the ac-current circuit is negligible.

Equipment

With the chosen parameters and conditions an ac current of approx. 2400 A and a dc-current of 2900 A is needed to heat the cables to 90°C. The compliance voltage of the ac current generator is mainly determined by the self inductance and need to be >23 V, Fig 6. Our dc current source is based on two 3 kA generators in parallel that can supply up to 6 kA and 5 V compliance.

Fig. 6. SPs new ac current generators can supply up to 10 kA and 15 V compliance each.

Conclusion

A calorimetric measuring system for measuring the ratio between ac and dc resistance of the conductor of high voltage cables has been designed. Based on a simulation the length of the cable samples is chosen to 10 m and the distance between the ac and dc circuit is chosen to 2 m. The warm up time of the cables need to be >24 h. The dc current source and new ac current source of SP can supply the currents needed.