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Correlation between calculated transmission capacity and actual one

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SUMMARY

During the design of high voltage circuits several assumptions are made. There is normally not enough information available to design the system properly. Further-on, during the laying, the route could be slightly varied and other parameters not known yet during the project could influence the transmission capacity of a cable. Therefore we evaluated the temperature after installation measured with a distributed temperature monitoring system (DTS). We obtained the regional temperature from meteorological data in order to get closer to the real case.
A 110 kV-cable circuit installed in a tunnel, conduits and trough has been taken as an example to confirm the calculations that have been done before the installation of the cable. This system is installed in the Czech capital, Prague, in 2009 using an aluminium conductor of two different sizes and a cross-bonding system. The fibre optic cable has been attached to the outer jacket, since the customer wanted to avoid any water increase into the accessories. A modern DTS was used to verify the actual cable temperature. The first approach showed that the calculated temperature was far off the real one. We therefore improved our model by taking more parameters into account and we used a finite elements method to calculate the temperature. We further modified the thermal resistivity of the material used by actual data obtained from the compound manufacturers. By using all these modifications, we could calculate the temperature with a variance of only 4 K to the real measured values. This difference might still have something to do by slight variations of the surrounding temperature and the actual temperature of the steam pipe.

KEYWORDS

Ampacity measurement, power transmission, DTS, thermal resistivity

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INTRODUCTION

During the design of a high voltage system several assumption are made to determine the transmission capacity of a high voltage cable system. The basis for this calculation is the IEC 60287. At voltage level around 110 kV the possibilities of doing a detailed survey before the design process is often limited. The conductor cross section of an extruded cable link is governed by the maximum allowable temperature of this conductor, which is 90 °C. If this temperature is exceeded, the lifetime and reliability of the cable circuit can be reduced, which may lead to unexpected premature breakdowns. In order to monitor the performance of their system it is quite common that utilities install distributed temperature monitoring system (DTS) to measure the temperature of their installed high voltage power cables.

During the design process the soil temperature including the thermal conductivity of the soil is mostly estimated; from time to time there is a chance that these values are known from earlier projects in same area. Additionally in the IEC 60287 the thermal resistivity of the material is taken as a constant however this property depends on the actual temperature in the cable and the surrounding earth and backfill material. Thus the result of temperature calculations have has a certain range of tolerance. Since the value of the thermal conductivity is taken very conservatively, the tendency of over designing a cable is high. Further-on, in other standards or recommendations like VDI or ISO the thermal conductivity of the materials have a different value.

In addition, during the actual installation some minor variation can be done resulting in a different thermal pattern of the cable system. Thus modelling the system leads to equations with many parameters where each small variation can result in a variation of the transport capacity, commonly called ampacity.

Moreover, economic factors drive utilities to use their high voltage cable circuits to achieve maximum allowable ampacity rating, thus using up previously designed safety margins.

If utilities have installed a distributed temperature monitoring system it becomes possible to exactly and accurately measure and monitor the cable temperature in real time service and to check the assumptions that have been made during the design of these cables and also taken into account the real temperatures in the cable including the environment.

The detection and analysis of hotspots helps to better understand the causes of overheating in certain cable sections. The most suitable methods are then used to rectify the hotspots and increase the cable ampacity. This could be done by improving the surrounding thermal conditions or cooling [8]. The DTS data also is in general logged by a computer network and analysed and dynamic rating (RTTR Real time temperature rating). The information is provided to the network operator for reliable operation of a cable network under dynamic and emergency loads.

PRINCIPLE OF THE MEASUREMENT

Fundamentals

The distributed temperature monitoring system DTS) systems utilizes a phenomenon that was discovered 90 years ago – the so called Raman scattering. In 1922, Indian physicist C. V. Raman published his work on the "Molecular Diffraction of Light," the first of a series of investigations with his collaborators which ultimately led to his discovery of the radiation effect named after him.[5] The Raman effect was first reported by him and in 1930 he received the Nobel Prize for the discovery that when light traverses a transparent material, some of the light that is deflected changes in wavelength. [6] There are two types of Raman scattering: Stokes and anti-Stokes scattering.[5]

If an optical laser pulse is launched into the fibre (incident light), light is scattered back, spread across a range of wavelengths. Raman Stokes and anti-Stokes wavelengths are affected by temperature changes while others are immune. The relation of the Raman Stokes and anti-Stokes is only temperature-dependent, allowing the calculation of the fibre temperature once the Raman Stokes and Raman anti-Stoke signals are accurately measured. [4]

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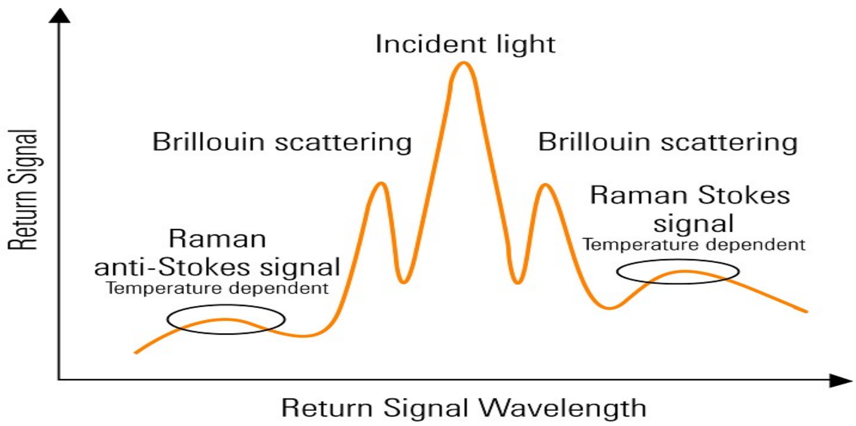

Figure 1 Incident light, Raman and Brillouin scattering over the frequency band

Stokes and anti-Stokes

Measurement of a sensing fibre exposed to various temperature environments shows that the anti-Stokes signal is lower in intensity, but shows more dominant changes in intensity, which allows the calculation of the temperature from the relation of both signals.

Positioning

The propagation speed of the light in a multi-mode fibre is known and it even varies a bit between individual manufacturing lots of fibre. It is a parameter typically provided by the cable manufacturer as part of the production record – the so called Refractive Index. By clocking the delay between pulses sent out and the reflections returning to the DTS device an exact positioning of temperatures along the fibre is possible.

Temperature profile

Figure 2 Display of Data Visualisation of DTS measurement

Based on this principle, the DTS instrument and the optical fibre as the sensor can generate thousands of individual discrete temperature measurements, equally spaced along the cable route [7]. The DTS

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instrument used for this project utilizes an optical time domain reflectometry (OTDR) principle where the laser pulses are sent at different times into the sensor fibre, which is representing the sensing element in this set-up. Distribute Temperature Sensing instruments represent a major trend in cable temperature monitoring nowadays primarily due to their ability to identify the critical hot spot locations along several kilometre of cable route. [7]

CASE STUDY

System Design parameters

For several cable projects in the Czech capital, Prague, the local utility decided to upgrade their high voltage transmission net and to install several lines of high voltage 110 kV cables. The cable should have a current rating of 800 A and the thermal conductivity of the ground was given with 1 Km/W. The ground temperature was given at 25 °C during the summer and 15 °C during the winter. The temperature in the tunnel was assumed with 15 °C in a humid environment [1].
Figure 1 outlines the cable route in the city of Prague.
The 110 kV cable had to pass several thermally difficult conditions:

- Crossing of another 110 kV cable
- Crossing of a steam pipe with a surface temperature of around 50 °C
- Crossing under two roads as well as railway tracks, where the three phases of the circuit were laid into a steel pipe with diameter of 500 mm² gladded with PVC

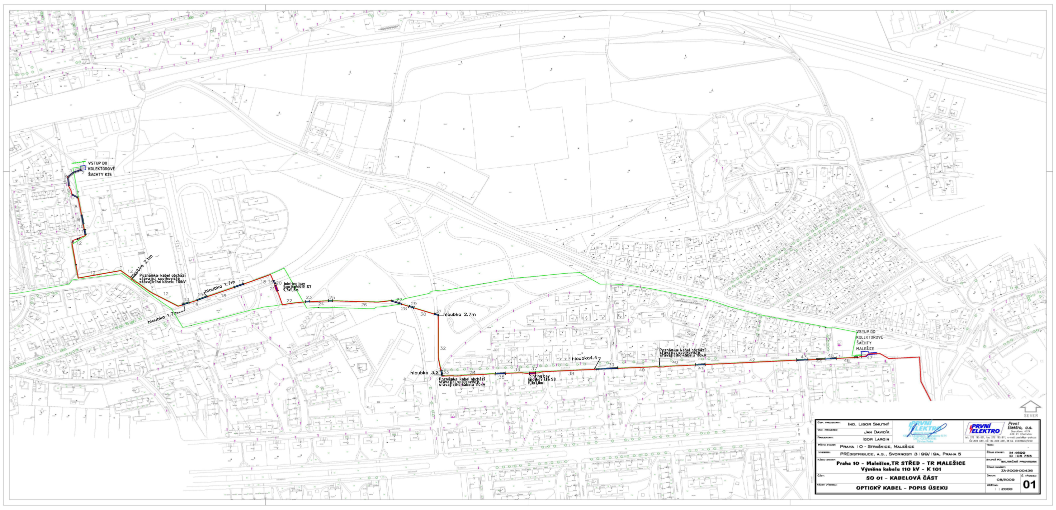

Figure 3 Route of the cable in the city of Prague

Cable design

Different conductor sizes were evaluated, with aluminium given as the preferred conductor material by the utility due to material cost. In the first section of 4303 m the cable system has been installed in an accessible tunnel. The second section of 1819 m is directly buried. The total length of the cables is 7739 m. For the section in the tunnel, the size of aluminium conductor is 1200 mm² was sufficient, while for the buried section a size is 1600 mm² was necessary. The type of jacket used in the tunnel is a halogen free low smoke flame retardant jacket, whereas the jacket in the other sections is of high density polyethylene with a higher shore hardness avoiding damage during installation in directly buried situation. The temperature monitoring system is based on a fibre optic cable which was attached on the outer cable jacket of the top cable (Trefoil formation) over the whole length of the cable circuit. This way of fixation and thermally contacting the sensor cable with the high voltage cable circuit avoids additional interfacing (in- and out-) at accessories and has been chosen in order to

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avoid any water increase into the accessories. This was preferred compared to the other option which uses a fibre optic sensor cable in the wire screen of the cable.

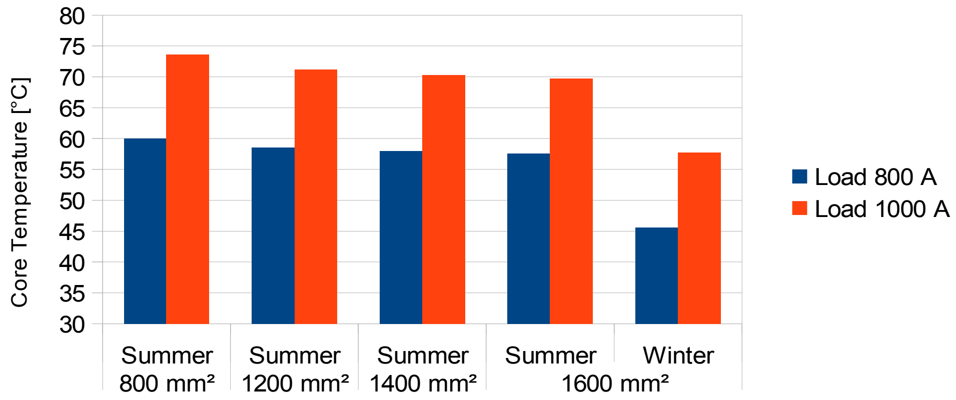

Figure 4 Simulated core temperature of the cable considered for installation according to IEC 60287

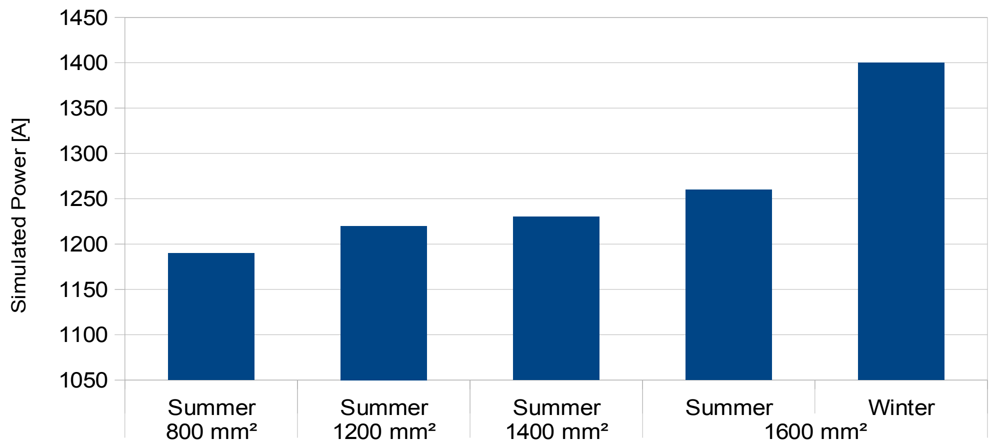

Figure 5 Simulated power transmission of cable laid in earth taking the heat pipeline influence into account

CABLE ROUTE

The cable route is shown in figure 3. The cable had an insulation thickness in total of 17.2 mm including semi-conductive shields. The wire screen was of 209 mm² Copper and over semi-conductive swelling tape the aluminium foil composite sheath with. The jacket thickness was 4.5 mm.
An optical cable with 12 fibres multi-mode 50/125 sensor cable is fixed on the top of trefoil formation of HV cable. Cable measure temperature in two parts of HV cable line.
Optical cable goes through five jointing bays and is fixed to each joint so we are able to measure temperature of each HV joint.
Two installations are shown in figure 7 and 8. Figure 7 shows one installation below the rail road and figure 8 shows the installation in the tunnel. As noticed the temperature of the conductor is significant below the 90 °C limit (Figure 9, narrow dotted blue line).

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Figure 6 Diagram of temperature measured on the 17.02.2010. load about 800 A, ambient temperature around 0°C

The temperature changes along the cable laid in the tunnel are caused by air inlets. The air is forced throughout the tunnel. The temperature increase of the cable surface is caused by external heat source as explained earlier on.

When we make a first approach (figure 9, dark red long dotted line) we see that the temperature does not correlate in the way how it was calculated. The calculation was made using the material values out of IEC 60287 and using a standard ampacity calculation program.

The new calculations were made using the above formulas and calculations given in [2,3]. Additionally we took - unlike in the IEC and the Electra 143 model - the AC resistance of the conductor as a function of the temperature. For the insulation material we took values out of measurements available by the material suppliers of the thermal resistance which showed different values of the insulation and semi-conductive materials. The modelling of tunnels is very complex and different models are proposed in the literature. We have followed the model outlined in [3]. We took into consideration that the cable is connected to the tunnel wall via the metal gallery and by a thermal resistance given by the heat transfer by radiation. The convection heat transfer also has to be taken into account. These values are a function of the particular installation and ventilation parameters, whereas here the ventilation parameters are limited. The axial heat transfer is permitted between the air nodes due to movement through the tunnel system. However here the complication of the fact that there are additional air inlets has been neglected for this calculation. Additionally in [3] it was mentioned that in a humid environment the thermal resistance might be corrected by the model of Philip and DeVries [10] where

$$R_f = \frac{1}{c_{pf} V A_f} \quad \text{Equation (1)}$$

The tunnel had the following dimensions:

Diameter	3100 mm
Depth of the tunnel below ground	49 m to 45 m
Thermal conductivity of the ground	1 Km/W
Air inlet temperature	- 3 °C
Soil temperature	5 °C
Prandtl Number of air	0.7071
Tunnel wall convective heat transfer coefficient	8.75 W/m² K

Table 1: Dimension of the tunnel

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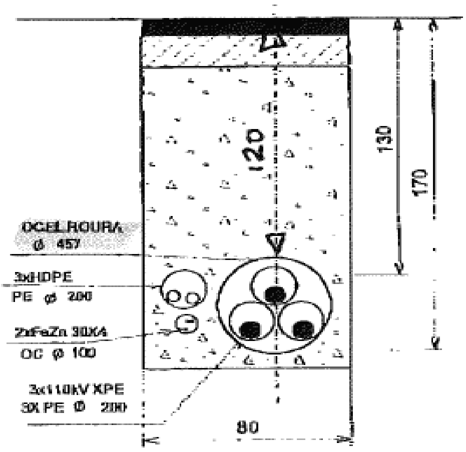

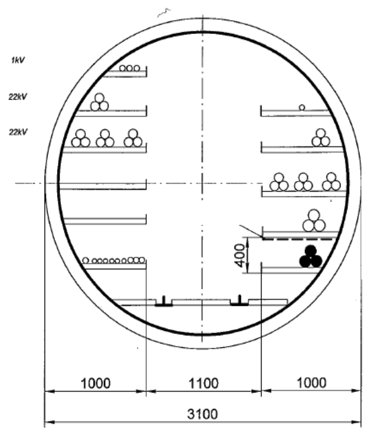

Figure 7 Laying below the rail road

Figure 8 Tunnel Dimensions

We now further calculate the temperatures using the model outlined in [2,3]. where the thermal resistance R can be calculated as follows:

$$R = 1 \div \left(c_{cf} . A_f V \right) \qquad \text{Equation (2)}$$

$$Q_{5,y} = \pi D_c \Delta\chi \varepsilon_{cab} \sigma \sum_{c=1}^{N} F_{cc(y,c)} \left[\Theta^4{}_{5,A(y)} - \Theta^4{}_{5,A(c)} \right] \qquad \text{Equation (3)}$$

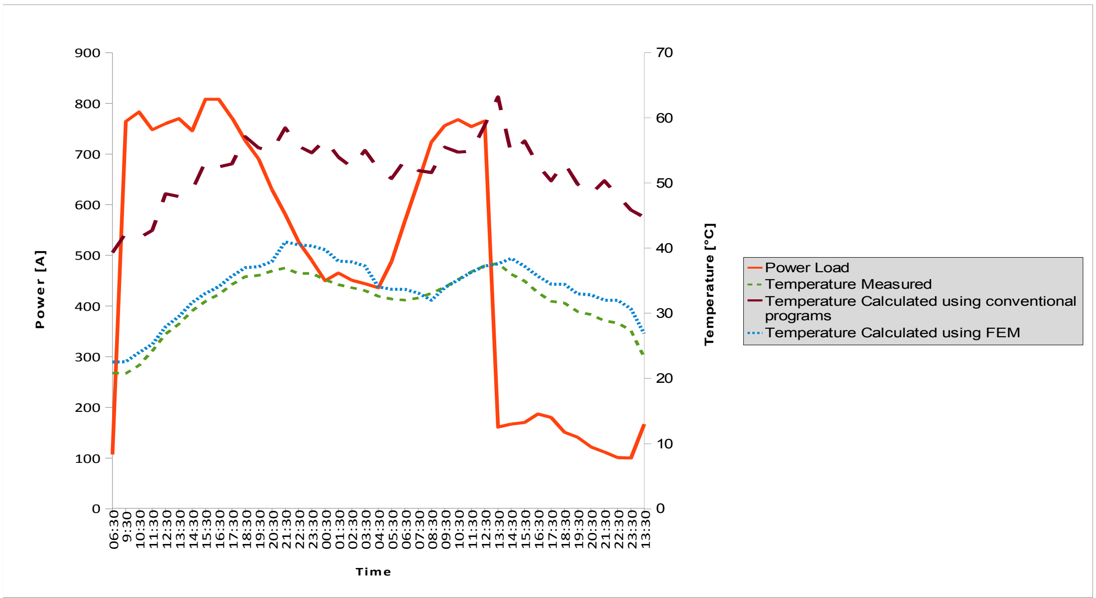

Figure 9 Load carrying over one day. Outside Temperature around 0 °C

Actually in different specification around the world different values for the thermal resistance of polyethylene is given and we therefore relied on the measurements given by the material supplier. By updating the values during the iteration we could obtain a closer match to the actual measured value could be reached. Now the temperature difference between calculated value and measured value is only 4 K down from 25 K. This could be due to some convection value errors from the steam pipe. (Figure 9, green line, small space line).

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CONCLUSION

The above mentioned sample demonstrates that a more detailed evaluation of a high voltage line is necessary before designing the cable layout. It also highlights that the calculations according to IEC 60287 gives a conservative result for conductor size. This is good in a certain way that the cable will not be overheated. However taking today's metal prices into account this might result in a more expensive cable design.

As the utility is planning to install additional lines in this tunnel, the temperature monitoring can be used to monitor all lines carefully. Hotspots are monitored precisely and actions for improving the thermal situation (e.g. near steam pipe) in order to keep the cable temperature within the limits even at high load.

An approach using actual measured material data and a finite element analyses based on new proposal simulated the temperature of this cable line quite well.

NOMENCLATURE

A_f	Tunnel cross section	m²
C_j	Thermal capacitance	J/K
D_c	Outer diameter of the cable	m
Pr	Prandtl number	
Q_j	Heat source	W
R_j	Thermal resistance at point j	K/W
ε_{cab}	Cable surface emission	
Θ_A	Temperature at point A	K
σ	Stefan-Boltzmann constant	

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