SOME CONSIDERATIONS REGARDING THE INSTALLED ENVIRONMENT OF UNDERGROUND POWER CABLES

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INTRODUCTION

Cable ampacity issues have been dealt with for a long time and our own involvement, in large part to provide information of local relevance to the cable industry and power companies in Finland, is quite recent. Nevertheless, in investigating the local environmental conditions of underground HV and MV cables, a number of practical issues worth stressing have come up. Further, in acknowledgement of the difficulty in knowing the actual thermal conditions of a cable at any given point in time, a simple temperature monitoring system has been devised, based on on-line current and cable surface temperature measurements. This monitoring system involves a simple transient algorithm that enables quite accurate prediction of the conductor temperature. The conductor temperature corresponds to the maximum temperature of the insulation, and is therefore the critical parameter in determining the current rating of a power cable.

This paper therefore follows two main themes. In order to highlight an area that is easily overlooked in practical cable installation, the effect of the native soil environment of a typical HV cable installation is investigated. The other aim is to provide some practical advice on the installation of the temperature monitoring system, which may be based on surface temperature measurements or distributed optical fibre temperature sensing located inside the cable sheath. Finite element method modelling was used in the simulations that provide the material for this paper.

CABLE INSTALLATION PARAMETERS – A REMINDER NOT TO NEGLECT THE 'NATIVE' SOIL.

Generally, the thermal environment of an installed cable consists of the cable itself, specially selected backfill material in the region immediately around the cables, and the surrounding native soil area. In fact, the 'native soil' may not be native at all, as central city excavation of cable trenches often involves the removed material being taken away, and then later replaced with some form of groundfill. There are many variations on this general theme. For instance, in order to provide mechanical protection and to aid installation, cables may be located in tubes, cable duct banks, or in backfilled concrete trenches. There may exist other heat sources in the native soil area. This paper will assume that sufficient attention has been paid to the immediate environment of the cable, but will examine the effect of the so-called native soil area that surrounds the back-filled trench.

To provide a consistent approach, a particular but typical type of high voltage cable will be modelled, but the conclusions to be drawn are general in nature. The motive is to prompt power companies to verify the thermal conditions of their important cable installations.

The model cable layout, shown in Figure 1, consists of three HV cables installed in trefoil in the centre of a 400x300 mm backfilled trench, with a burial depth to the centre of the trefoil of 1.1 m. The cables themselves are 110 kV XLPE cables, each consisting of an 800 mm^2 stranded aluminium conductor (diameter 33.4 mm) surrounded by an insulation layer (including the semiconducting conductor shield and insulation screen) with outer diameter 70 mm, a lead alloy sheath with outer diameter 74.6 mm and a polyethylene jacket with outer diameter 83 mm. Because the focus is on the native soil environment, the backfill around the cable will be idealised, that is, it will be assumed homogeneous and thermally stable.

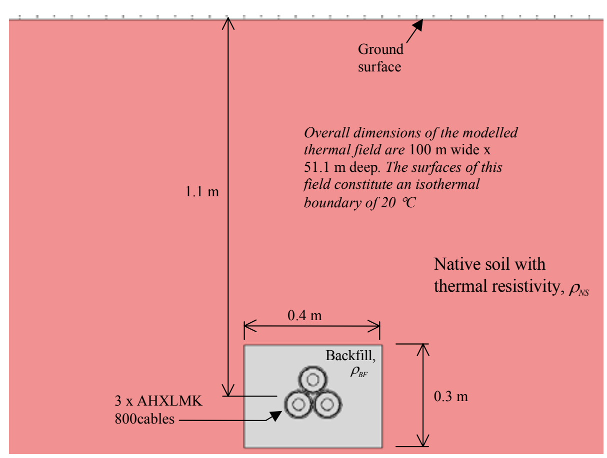

Figure 1 Installation layout used for thermal modelling

The thermal resistivity of the native soil does indeed have a significant impact on the true rating of a cable. The first set of simulations using FEMLAB®, summarised in Figure 2, shows the effect the thermal resistivity of the native soil has on the steady-state rating of the cables. The thermal resistivity of the backfill ρ_{BF} is held constant at 0.5, 1.0 and 2.0 K·m /W respectively, and the conductor temperature is limited to 65 °C.

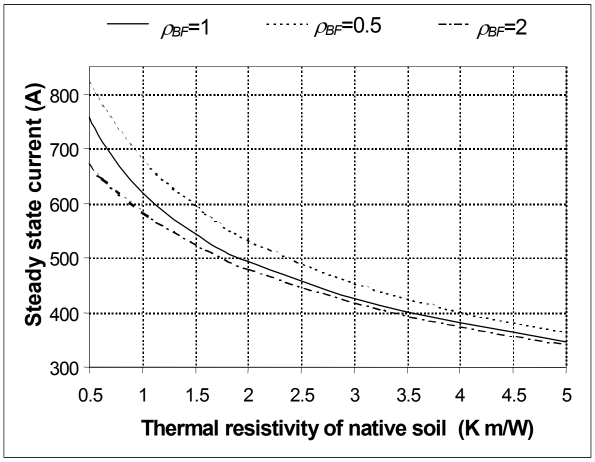

Figure 2 Steady-state ampacity versus native soil thermal resistivity

The other point to make is that if considerable effort is made to ensure that the backfill is of high quality, neglecting the quality of the native soil will have a relatively greater impact. As can be seen in Figure 2, an increase of 1.0 to 2.0 K·m /W in the thermal resistivity of the backfill ρ_{BF} will cause at most a 10% reduction in ampacity, whereas, a similar increase in the thermal resistivity of the native soil will reduce the steady-state current rating of the cables by 20%.

There is, of course, a lot more to consider than merely the steady-state rating of cables when it comes to backfill for power cables. If the cross-sectional dimensions of the backfill are sufficient to keep the native soil from reaching temperatures that will cause moisture migration at ambient moisture levels, only seasonal variations in moisture content need to be considered when considering the suitability of native soil conditions in cable environments. This is, however, not a trivial task. The 65 °C rating chosen for the above illustration keeps cable surface temperatures below temperatures at which moisture migration is likely to occur, even in the backfill region.

It is not the intention in this brief treatment to undermine the importance of cable backfill. The role of backfill is extremely critical when cables are run at higher temperatures. The backfill thermal resistivity is also the most important parameter when it comes to short-duration transients. The purpose here is simply to emphasise the critical role of the overall cable environment when it comes to steady-state or average cable temperatures. Care should be taken that the material placed in areas that have been excavated for cable installation has adequate thermal resistivity at moisture contents that correspond to the driest months of the year. The backfill in the immediate cable vicinity has the added requirement of maintaining thermal stability during high loading, and should extend far enough to cover the critical isotherm that would cause moisture migration in the native soil. The latter of these two observations is most likely to be met, but it has been observed that the former, concerning the native soil, has at times been overlooked in urban cable sites.

CABLE TEMPERATURE MONITORING

Because it is difficult to know precisely the actual operating conditions of a cable, there is increasing interest in directly monitoring the temperature of HV cables and critical MV cables in real time, so that cables are run according to their thermal limits rather than a somewhat arbitrary current rating based on expected environmental parameters. It is now becoming standard practice to manufacture new cables with multi-mode optical fibres, usually located just inside the sheath, to enable temperature monitoring along the entire length of the cable. It is unlikely that many utilities will wish to use this feature for permanent on-line monitoring of temperature, as the sensor instrument is still rather expensive. Distributed fibre optic temperature sensing is extremely useful in revealing hot spots, however, which can then be improved, or fitted with on-line surface temperature-based monitoring.

To maximise utilisation of both new and existing cables, dynamic rating systems can be used, preferably in conjunction with temperature monitoring. [1] describes a simple algorithm that predicts the temperature at the conductor of a cable from its surface temperature and conductor current. The algorithm makes use of a property of the exponential function where the change over one time interval Δt due to a step input is equal to the hypothetical steady-state change multiplied by the factor (1-exp(-Δt / τ)), where τ is the relevant thermal time constant.

In the case of a buried cable, the total temperature rise of the conductor above ambient is not exponential in nature. The temperature rise of a cable conductor over its surface or its sheath is closer to exponential, though, and this fact is used in equation (1), which will henceforth be referred to as the algorithm. However, the temperature dependence of the conductor and sheath resistances, along with the presence of the heat storing and resisting cable environment corrupt the exponential nature of the temperature rise due to a step increase in losses. The algorithm turns out to be remarkably accurate however, and is self-correcting. That is, if an erroneous initial value is given ($\Delta\theta_0$), the algorithm will converge to the 'correct' value after only a few time intervals.

The remainder of this paper will present the algorithm with comments on its practical application using finite element method simulations.

$$\theta_{c,i} = \theta_{surf,i} + \Delta\theta_{i-1} + \left(\Delta\theta_{\infty,i} - \Delta\theta_{i-1}\right)\cdot k_\tau \qquad (1)$$

Equation (1) calculates the conductor temperature at time t_i in terms of: the measured surface temperature $\theta_{surf,i}$, the temperature difference $\Delta\theta_{i-1}$ between the conductor and cable surface at the previous time increment t_{i-1}, and the steady-state value of the temperature difference between the conductor and cable surface $\Delta\theta_{\infty,i}$ that would be reached if the current during the time interval t_{i-1} to t_i were held indefinitely. The current used for each time interval is the thermal equivalent of the average of the current at the beginning and end of each time step, $\sqrt{((I_{i-1}^2+I_i^2)/2)}$. The proportional constant k_τ is used to approximate the actual temperature rise of the conductor over the cable surface as an exponential function. It is, in effect, the per unit value of the temperature rise at the time interval, t_i-t_{i-1} , used in (1). k_τ can be calculated by using a classical lumped parameter transient analysis of the cable in accordance with the standards [2], and dealt with in considerable detail in [3], or can be derived from a transient numerical simulation. The steady-state value $\Delta\theta_{\infty,i}$ that the temperature difference is tending to at each time increment, can be derived in terms of the surface temperature and current from a steady-state analysis of the cable's thermal circuit. For the cable under consideration, this is:

$$\Delta\theta_{\infty,i} = \frac{0.5\left(I_{i-1}^{\ 2} + I_i^{\ 2}\right)R_{20}\left[1 + a_{20}(\theta_{surf,i} - 20)\right]\cdot\left[T_1 + (1+\lambda_1)T_3\right] + (0.5T_1 + T_3)W_d}{1 - I_{i-1}^{\ 2}R_{20}.a_{20}\left[T_1 + (1+\lambda_1)T_3\right]} \tag{2}$$

R_{20}, the 20°C ac conductor resistance, and a_{20}, the temperature coefficient of ac resistance, are ac values and must be derived from an analysis of the conductor taking into account skin and proximity effects, so that the conductor losses can be represented in the form $W_c = I^2 R_{20}[1 + a_{20}(\theta_c - 20)]$. $\theta_{surf,i}$ is again the measured cable surface temperature, while T_1 and T_3 represent the thermal resistances of the insulation and cable jacket, respectively. Using the maximum emergency temperature likely to be encountered to derive the ac resistance as a constant significantly simplifies (2), but with some loss in accuracy. λ_1 is the sheath loss coefficient, representing the ratio of the sheath to conductor losses, and is temperature dependent. Fortunately, λ_1 decreases with increasing load, as the sheath temperature increases at a slower rate than the conductor temperature. It is suggested that a 'comfortable' conductor temperature, say 50° C, is used for calculating λ_1 as a constant, which means that equation (2) will err on the conservative side at higher temperatures. W_d represents the dielectric losses, and can be neglected in cables with line voltages less than or equal to 110 kV. Steady-state analysis of cables is detailed in [4].

The procedure outlined above can be applied to the temperature rise of the conductor over the sheath, and is indeed rather simpler.

In order to demonstrate a method for calculating k_τ, and to show how the temperature rise of a conductor over the cable surface deviates from a pure exponential response, Figure 3 shows the per unit finite element method response of a cable (installed as in Figure 1 with ρ_{BS} and ρ_{NS} both equal to 1.0 K·m/W) is compared to an equivalent exponential function. The exponential function has the same per unit value at the chosen time interval of 360 s, and the same steady-state value, but it can be seen that the actual cable response tends to the steady-state value more slowly than an exponential function. This is partly because the cable in question is installed in trefoil, touching two other cables carrying the same load – the heat flux emanating from these cables heats up the cable being monitored from the outside. The main factor is simply the influence of the environment.

The true function is approximated in the way shown, so that at times greater than the time interval t_i-t_{i-1}, the temperature rise will be overestimated rather than underestimated, and for very long transients the result will converge to the true steady-state value.

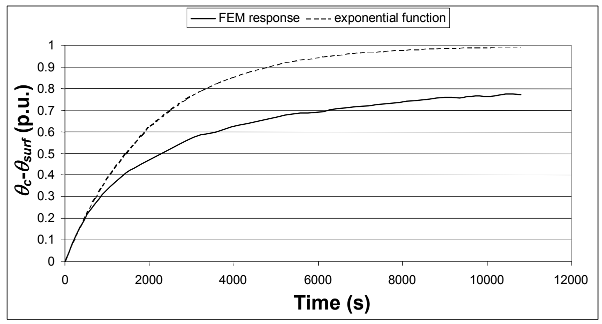

Figure 3 Per unit comparison of a FEM simulated 'actual' response to a step current with an equivalent exponential function.

For the model cable layout shown in Figure 1, the response to a rather erratic load profile is depicted in Figure 4. The transient response is calculated using FEMLAB®, and the response from the online algorithm, equation (1), is based on the surface temperature calculated by FEMLAB.

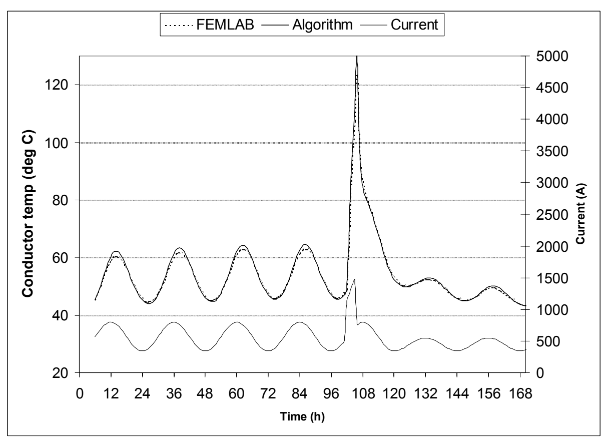

Figure 4 Conductor temperature of the hottest cables in Fig 1 when subjected to the indicated weekly current profile, which includes a four hour emergency period of double loading

The main reason the calculated response tends to overshoot the "actual" temperature difference in Figure 2 is that, as indicated previously, the real response of the temperature difference to a step change in current is not exponential but exhibits a somewhat slower response. The weekly load in Figure 4 was simulated using a time interval of 1 hour, which corresponds to a value of $k_\tau = 0.6$ in the real-time algorithm, equation (1).

During normal loading there is very little error in the conductor temperature predicted by the algorithm. Figure 5, however, focuses on the emergency period, where the limitations of equation (2) are more evident.

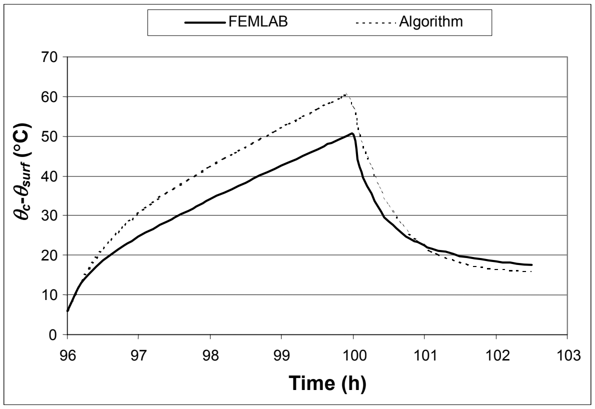

Figure 5 Temperature difference between the conductor and surface of the hottest cables in Fig 1 showing the emergency period of double loading

The conductor temperatures reach 130 °C during the extreme loading scenario depicted in Figure 5, and so a 10 °C error on the safe side is welcome. The slight sacrifice in accuracy of the real-time algorithm is offset by the fact that for a given cable configuration, it is independent of the environment. The reason for using such a transient algorithm is made clear in Figure 5, as it is clear that the conductor to surface (or sheath) temperature difference reaches very high values during emergency periods. The emergency period shown in Figure 5 was simulated using a time interval of 6 minutes, which corresponds to a value of $k_\tau = 0.16$.

A more complete treatment of the derivation of the on-line rating algorithm and the proportional constant k_τ is given in [1].

Given that the algorithm is sufficiently accurate and that accurate temperature measuring equipment is available[1], the question of where to locate the sensor on the cable surface is a primary practical issue. The algorithms derived above assume that the cable sheath and surface are isotherms, which in fact is not true, especially if the cables are located near the earth surface. Unless temperature sensors are to be located around the surface of the cable and an average taken, it is necessary to locate the sensor at a point that represents the average surface temperature of the hottest cable, if such a point can be found. Suitable points for mounting temperature sensors can be found with finite element simulations and this matter is given general treatment below.

For a trefoil installation it is found that a convenient point that represents the average surface temperature of the hottest cables lies near the top point of one of the lower cables in the trefoil. The point is found by integrating the temperature around the surface boundary and dividing it by the perimeter, and then locating the point that corresponds to this temperature.

If the cables are located at a shallow burial depth, the position of a surface temperature sensor becomes critical for the accurate prediction of the hottest conductor temperature according to equation (1). This is shown in Figure 6, which depicts the thermal field in and around the cables in a trefoil installation of the model cables, but at a burial depth to the centre of the trefoil of only 0.17 m. The simulation used for this figure was a steady-state current of 960 A, and moisture migration was modelled in the backfill and native soil environments.

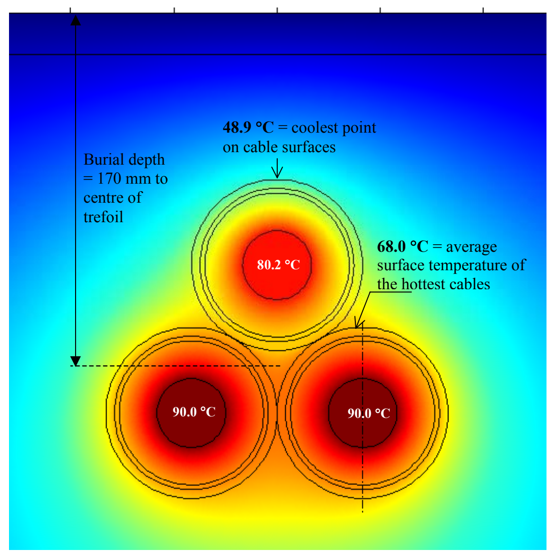

Figure 6 The thermal field round the AHXLMK800 110kV cables installed in trefoil at a burial depth of 170 mm. The average surface temperature of the hottest cables and the point at which it occurs is shown.

It can be seen that at such a shallow burial depth, which is typical in subterranean service tunnels in the Helsinki area, the position for sensor positioning is critical. If it is located on the top surface of the top (coolest) cable, the actual steady-state maximum conductor temperature would be underestimated by more than 20 °C for the operating conditions depicted in Figure 6, and by even more in emergency conditions. It is suggested that to err on the safe side, the sensors, which should be as small as possible, should be thermally bonded to the top surface of one of the lower cables as close to the centre of the trefoil as possible.

Figures 7a to 7c show temperature sensor positions that will give the average surface temperature of the hottest cable with sufficient accuracy for trefoil and flat installations, regardless of burial depth.

1 We have successfully run a pilot installation consisting of 3-wire Pt100 sensors, each connected to an R/I converter which in turn delivers a current proportional to temperature to the utility's SCADA system, where the algorithm calculates the conductor temperature in real time.

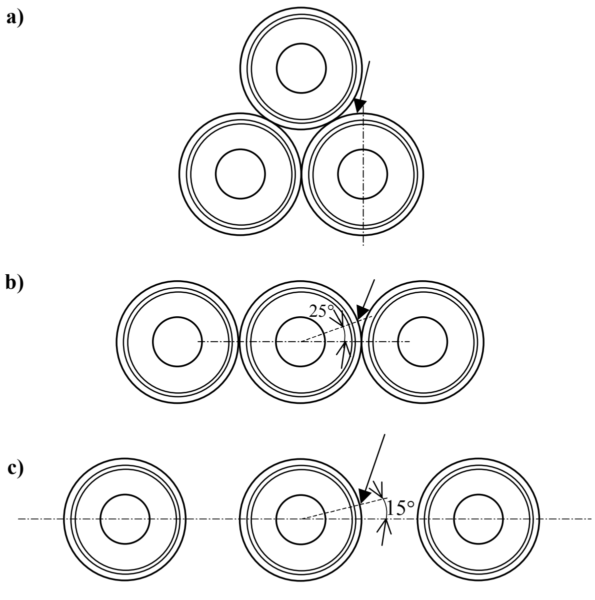

Figure 7 The solid arrows show suitable sensor positions for a) trefoil, b) flat touching, and c) flat spaced installation configurations.

It should be stressed that, all other things being equal, a cable will run hottest at deep burial depths. Fortunately, at deep burial depths, cable surfaces are much closer to being 'isothermal' than when located close to the earth surface. The sensor positions shown in Figure 7 tend to move out from the marked centre lines as burial depth increases, but the positions shown represent the average or slightly higher than average surface temperatures of the hottest cable in each 3 phase configuration and should be suitable for a wide range of cables sizes provided the cables have metallic sheaths near the surface.

The inside of a cable sheath is very close to an isotherm, and in cases where the temperature monitoring is based on an optical fibre located inside the cable sheath, the only stipulation is that the monitored cable should be the hottest one!

One final point can be made with regard to temperature monitoring. If a foreign heat source exists in the vicinity of the cables being monitored, the temperature sensor should be mounted on the hottest cable, or the side of the hottest cable, that is nearest the heat source. This will cause the algorithm to yield a conductor temperature that is too high, rather than too low.

CONCLUSIONS

The first part of this paper serves as a reminder that all parts of an installed cable's thermal circuit are important when endeavouring to maximise the ampacity of a given cable type. A lot of effort is made nowadays to find thermally stable backfill but care must be taken, especially in built-up urban environments, to ensure that the general thermal environment of a cable system has good heat dissipating properties throughout the year.

Because of the many factors that govern the operating temperature of buried power cables, some of which are impossible to accurately predict, a useful approach to real-time temperature monitoring has been presented in the second section. The algorithm presented as equation (1) has various theoretical shortcomings, but nevertheless enables remarkably accurate prediction of conductor temperature regardless of the external thermal environment of the cable. The algorithm can be adapted to estimate the critical conductor temperature from either surface or sheath temperature measurements. The latter is of relevance when newer cables are fitted with distributed optical fibre temperature monitoring. The application of surface temperature-based monitoring to cables without fibre optics requires the risky assessment of hot-spots along the cable length, and suitable safety margins should be applied.

While individual installation configurations require individual treatment for optimum sensor placement, general guidelines are given for the practical installation of surface mounted temperature sensors so that they supply the algorithm with the average temperature of the cable surface.

It is hoped that the paper makes a useful contribution to the efficient management of MV and HV underground cables, which are critical and expensive items in the asset base of today's electricity companies.

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