Return to Session

THERMAL TRANSIENT ANALYSIS OF UNDERGROUND CABLES

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ABSTRACT

For companies active in distribution or transport of electrical energy, it is important to know the maximum short time ampacity of underground high voltage cables. With the knowledge of the transient thermal behaviour of underground cables, the energy companies should be able to operate temporarily in current overload conditions, without exceeding the maximum cable operating temperature. Existing cable standards describe correction factors for different conditions in steady state, but do not deal with transient behaviour.
The proposed research analyses the temperature of underground cables as a function of the initial load conditions, magnitude and duration of the overload, taking into account both cable and soil parameters and cable configuration. A software is developed for transmission system operators in order to simulate thermal transient behaviour of underground cables in a quick and easy way with respect to the boundary conditions.

KEYWORDS

Underground cables, thermal transient behaviour, simulation software, measurements, cable ampacity.

INTRODUCTION

The analysis starts with the description of the simplified model that is used in the simulation software for the calculation of transient temperatures of underground cables. Subsequently the test set-up built for the validation of the software, is presented, as well as the comparison of simulation and experimental results. Finally some conclusions are drawn.

SOFTWARE MODEL

In the software model, only the thermal conduction is considered. Since convection and radiation are neglected, this simplification will lead to worst case results. Also other effects, such as underground water flows who reduce the cable temperature are neglected.

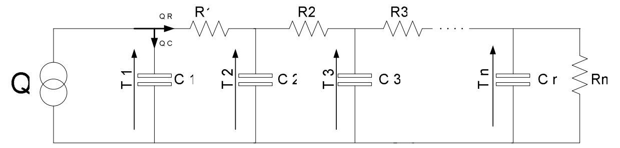

Figure 1: Model for simulating cable temperatures

The analysis of the thermal behaviour of the underground cables is made on the base of a distributed equivalent electrical network (Figure 1) consisting of a current source, resistors and capacitors, representing respectively the heat generation in the cable, the thermal resistances and thermal capacitances of the different cable and earth layers.
The heat generation in the cable due to Joule power losses $R.I^2$, where R represents the electrical cable resistance (temperature dependent) and I the load current. For the determination of the thermal resistances and capacitances, the knowledge of respectively the thermal conductivity and capacity of the different cable and earth layers is required, as well as the layer dimensions. The temperatures of the layers are calculated through the voltages in the equivalent electrical network.

Equations for temperature calculations

Steady state conditions

The temperature T_i in node i (Figure 1) is given by:

$$T_i = Q\sum_{k=i}^{n} R_k \quad [1]$$

In particular, the conductor temperature T_1 equals:

$$T_1 = Q\left(R_1 + R_2 + \ldots + R_n\right) \quad [2]$$

where T_i [K] the temperature in node i, Q [W/m] the heat generation per meter cable and R_i [m.K/W] the thermal resistance of layer i (between nodes i and i+1).

Transient conditions

The relation between the heat flux and the temperature change per time in a volume with thermal capacity C_i is given by:

$$Q_{Ci}^{j} = C_i \frac{T_i^{j+1} - T_i^{j}}{\Delta t} \quad [3]$$

where i and j are indices for place and time respectively, Q_{Ci}^{j} [W/m] the heat flux in volume i at time j, T_i^{j} [K] the temperature in node i at time j, C_i [J/(m.K)] the thermal capacity of volume i, and Δt [s] the time step. The combination of [3] and the heat flux balance in each node results in [4]-[6].

$$T_1^{j+1} = \left(1 - \frac{\Delta t}{C_1 R_1}\right) T_1^{j} + \frac{\Delta t}{C_1}\left(Q^{j} + \frac{T_2^{j}}{R_1}\right) \quad [4]$$

$$T_n^{j+1} = \left(1 - \frac{\Delta t}{C_n}\left(\frac{1}{R_{n-1}} + \frac{1}{R_n}\right)\right) T_n^{j} + \frac{\Delta t}{C_n}\frac{T_{n-1}^{j}}{R_{n-1}} \quad [5]$$

$$T_i^{j+1} = \left(1 - \frac{\Delta t}{C_i}\left(\frac{1}{R_{i-1}} + \frac{1}{R_i}\right)\right) T_i^{j} + \frac{\Delta t}{C_i}\left(\frac{T_{i-1}^{j}}{R_{i-1}} + \frac{T_{i+1}^{j}}{R_i}\right) \quad [6]$$

with: i = 1, 2, 3, …, n
and n the number of considered layers

All temperatures at time j+1 can be computed with the temperatures and the cable heat generation (temperature dependent) at time j as input parameters. The time step has to be small enough to converge to a solution.

Calculation of the heat generation

The heat generation in the cable is the Joule power loss and is calculated using [7].

$$Q = \frac{\rho_{20}\left(1+\alpha\left(T_1 - 20\right)\right)}{S} I^2 \qquad [7]$$

where Q [W/m] the heat generation in the cable, ρ_{20} [Ω/m/mm²] the (electrical) resistivity of the conductor material (Al) at 20℃, α [1/K] the temperature coefficient of the resistivity of the conductor material, T_1 [℃] the conductor temperature, S [mm²] the conductor section and I [A] the conductor current.

Calculation of thermal resistances

Cable layers

The thermal resistance of a cable layer is calculated according to [8]:

$$R_i = \frac{1}{2\pi.\lambda_i}\ln\left(\frac{D_i}{d_i}\right) \qquad [8]$$

where R_i [m.K/W], λ_i [W/(m.K)], D_i [mm] and d_i [mm] respectively the thermal resistance (per meter cable length), the thermal conductivity, the outer and inner diameter of cable layer i.

Earth layers

The thermal resistance of the earth is computed through conformal transformation [Ref.1]. The approximation [9] is used. It is assumed that d (cable depth) >> D (core diameter).

$$R_{soil} = \frac{1}{4\pi.\lambda_{soil}} * \sum_{k=1}^{N_C} \ln \frac{\left(0 - s_{k,x} - \delta_{k,x}\right)^2 + \left(-d + s_{k,y} + \delta_{k,y}\right)^2}{\left(0 - s_{k,x} - \delta_{k,x}\right)^2 + \left(-d - s_{k,y} - \delta_{k,y}\right)^2} \qquad [9]$$

where R_{soil} [m.K/W] the thermal resistance of the earth, λ_{soil} [W/(m.K)] the soil thermal conductivity, N_C the number of cores (heat sources), d [mm] the depth at which the cables are buried, ($s_{k,x}$,$s_{k,y}$) [mm,mm] the position (in x-y coordinates) of core centre k, ($\delta_{k,x}$,$\delta_{k,y}$) [mm,mm] the displacement of the source s_k due to the effect of the other sources and image sources and calculated with [10]-[11].

$$\delta_{k,x} = \left(\frac{D}{2}\right)^2 \left[\sum_{\substack{l=1 \\ l\neq k}}^{N_c} \frac{s_{k,x} - s_{l,x}}{\left(s_{k,x} - s_{l,x}\right)^2 + \left(s_{k,y} - s_{l,y}\right)^2} - \sum_{l=1}^{N_c} \frac{s_{k,x} - s_{l,x}}{\left(s_{k,x} - s_{l,x}\right)^2 + \left(s_{k,y} + s_{l,y}\right)^2} \right] \qquad [10]$$

$$\delta_{k,y} = \left(\frac{D}{2}\right)^2 \left[\sum_{\substack{l=1 \\ l\neq k}}^{N_c} \frac{s_{k,y} - s_{l,y}}{\left(s_{k,x} - s_{l,x}\right)^2 + \left(s_{k,y} - s_{l,y}\right)^2} - \sum_{l=1}^{N_c} \frac{s_{k,y} + s_{l,y}}{\left(s_{k,x} - s_{l,x}\right)^2 + \left(s_{k,y} + s_{l,y}\right)^2} \right] \qquad [11]$$

In the software model the earth is divided into 20 layers where the thermal resistance of each layer is a 20th of the total earth thermal resistance.

Calculation of the thermal capacitances

The thermal capacitances of the different concentric layers are initially calculated as the product of the specific heat capacity and the volume (per meter cable) [12].

$$C_i = c_{p,i}\pi\frac{\left(D_i^2 - d_i^2\right)}{4} \qquad [12]$$

where C_i [J/(m.K)], $c_{p,i}$ [J/(m³.K)], D_i [m] and d_i [m] respectively the thermal capacitance (per meter cable length), the specific heat capacity, the outer diameter and the inner diameter of layer i.
The volume of an earth layer is obtained taking into account the thermal resistance and the position of the layer to the cable centre [Ref. 3,4].
The accuracy of the approximate solution using the lumped thermal capacitances obtained by [12] is improved by the technique of [Ref. 2,5], where a part p_i [13] of the thermal capacitance C_i is placed at temperature T_i and ($1-p_i$) at temperature T_{i+1}.

$$p_i = \frac{1}{2 * \ln\frac{D_i}{d_i}} - \frac{1}{\frac{D_i^2}{d_i^2} - 1} \qquad [13]$$

The thermal capacitance C_i^* at T_i is obtained by [14]:

$$C_i^* = p_i * C_i + \left(1 - p_{i-1}\right) * C_{i-1} \qquad [14]$$

Number of earth layers

Figure 2 shows the influence of the number of the earth layers on the simulation results. As a compromise between accuracy and simulation speed, the software model takes into account 20 earth layers.

Return to Session

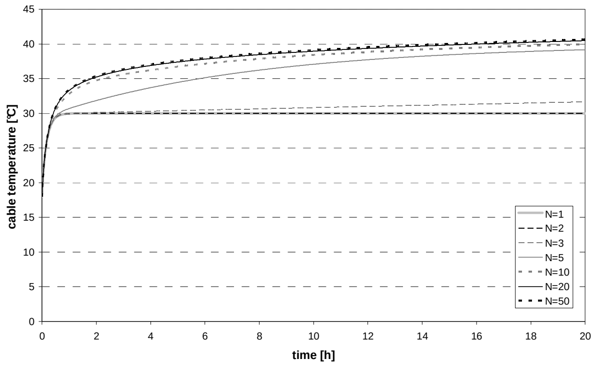

Figure 2: Influence of the number of earth layers (N) on the simulation results

Correction factors for cables in tubes

The temperature of a cable in a tube is estimated using the previous model, taking into account the current correction factors of the Belgian standard [Ref. 6], being approximately 0.75 for sections ≤ 240 mm² and 0.68 for sections ≥ 300 mm². An increased current is determined on the basis of the correction factors and a temperature simulation is performed as if the cables were loaded by the higher current.

EXPERIMENTS

Test set-up

A practical test set up is built (Figures 3-5) in order to verify the cable temperature curves obtained by the theoretical model. Three parallel three phase systems constituting of single core cables, type EAXeCW 20,8/36kV (240mm²), are buried at a depth of 1,20m with a mutual distance of 0,25m. The cable core temperature is measured by thermocouples distributed along the cable length. Different cable configurations are implemented: trefoil configuration in full ground and both trefoil and single cables in tubes. The tubes are filled with air or Bentonite® and sealed up with polyurethane foam. Ampacity tests and measurements of the corresponding cable temperatures are performed for different load conditions and a different number of parallel cables.

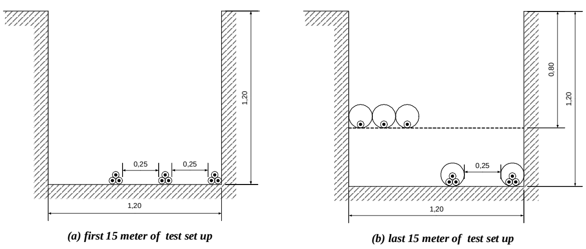

Figure 3: Positioning of the cables

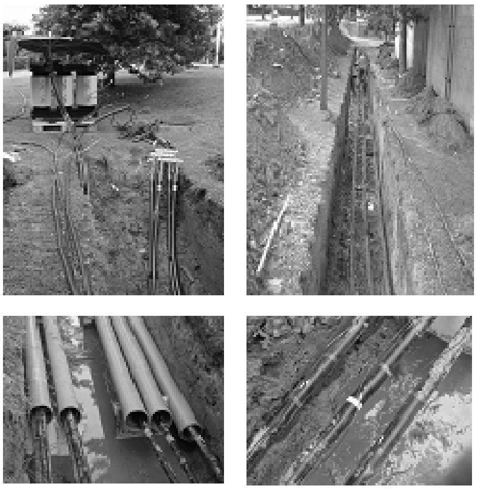

Figure 4: Construction of the test set-up

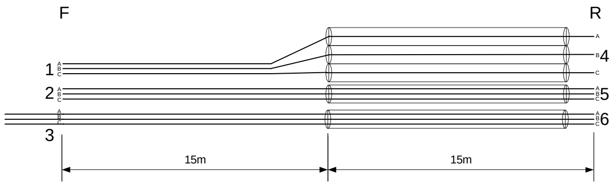

Figure 5: Top view of the positioning of the cables (first 15 m in earth, last 15m in tube)

Measurement results

At the beginning of the measurements the cable current was changed from 0 A to the current mentioned in the figures 6-8. The differences in the initial temperatures are due to the difference of the soil temperature in winter and summer.

Figure 6 gives the results for cables in earth. The temperature-time curves consist roughly of two parts. The first hours, while the cable heats up, a rapid temperature increase can be seen. After that the temperature increases more slowly due to the heating of the surrounding earth.

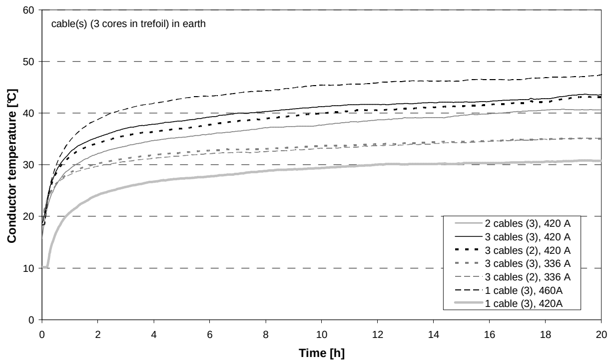

Figure 6: Measured temperatures on cables in earth (with label 2 or 3, see Figure 5): influence of number of parallel cables and current

Figure 7 shows the results for cables in tube. Lower temperatures are obtained when the tube is filled with Bentonite® instead of air.

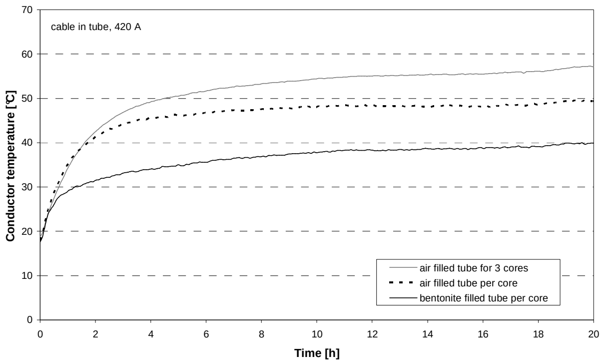

Figure 7: Measured temperatures on cable in tube for different configurations

Figure 8 gives the results at the tube end. There is a significant temperature increase at the polyurethane foam. The cable temperature in the tube, just behind the foam, is also high because the cable does not make contact with the tube.

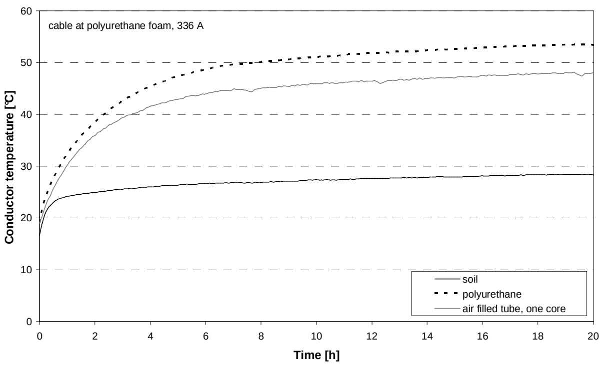

Figure 8: Measured cable temperatures at the transition of the soil and the tube that is sealed up with polyurethane foam

COMPARISON BETWEEN EXPERIMENTS AND SIMULATIONS

In figures 9-13 experimental and simulation results are compared. The simulations are performed with the following values for the soil parameters: thermal conductivity λ_{soil} = 0.6 W/(m.K), specific heat capacity $c_{p,soil}$ = 1.32E6 J/(m³.K). For cables in earth, there is a good correspondence between simulation and experimental results, in short as well as long term. For cables in tubes, the simulations give a good estimation (+/- 5℃) of the cable temperatur e.

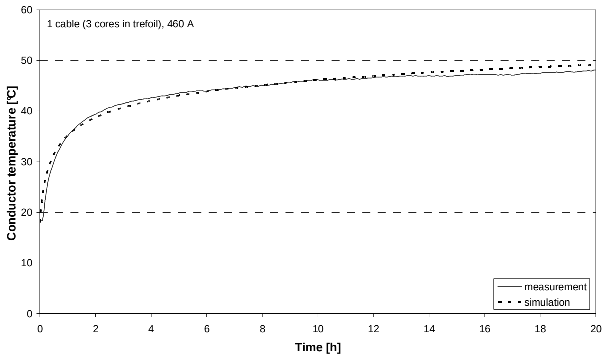

Figure 9: Comparison between experiments and simulations for 1 cable in earth

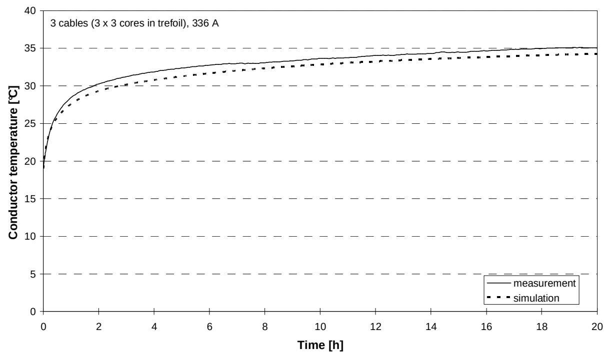

Figure 10: Comparison between experiments and simulations for 3 parallel cables in earth, short term

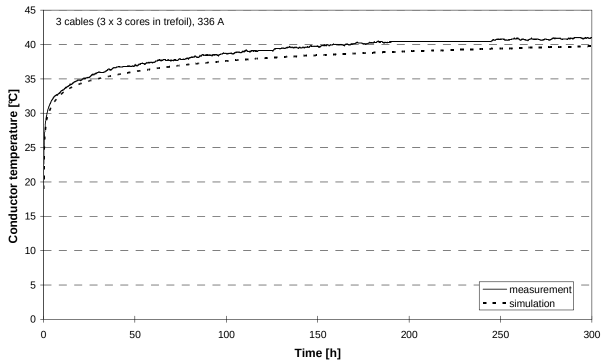

Figure 11: Comparison between experiments and simulations for 3 parallel cables in earth, long term

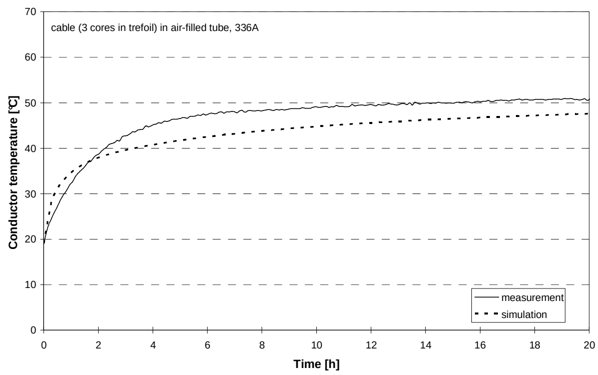

Figure 12: Comparison between experiments and simulations for cable in tube, short term

Return to Session

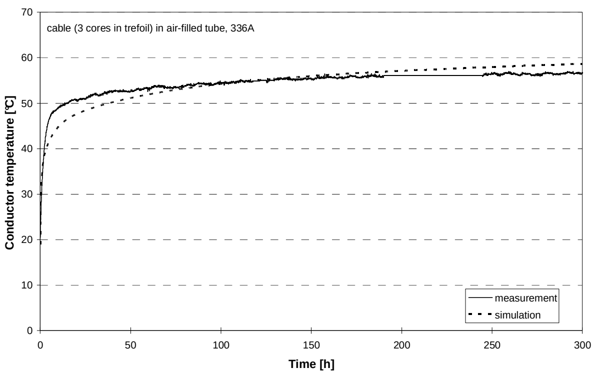

Figure 13: Comparison between experiments and simulations for cable in tube, long term

CONCLUSIONS

A software is developed for transmission system operators in order to simulate the thermal transient behaviour of underground cables in a quick and easy way. Only elementary data is required in order to calculate cable temperature (Figure 14). All other data is implemented or calculated by the software it selves. This results in a convenient software tool, easy to use for non experts in simulation techniques.

Figure 14: Simulation software: input data

As shown is the Figure 9 up to Figure 13, there is a good correspondence between simulations and the measurements performed with a realistic test set up as discussed . It is also shown that, starting from typical exploiting conditions, the cable current substantially can be increased above the nominal rated ampacity given by the cable manufacturers or by normative correction factors, for several hours, without reaching the maximum cable operating temperature.

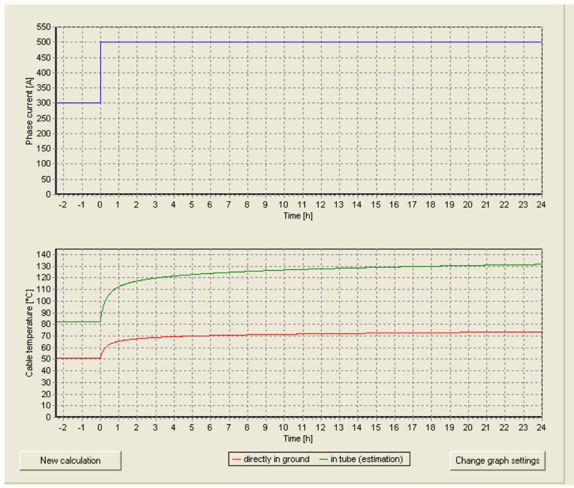

Figure 15: Simulation software for transient temperatures of underground cables.

REFERENCES

[1] G. Luoni, A. Morello and H.W. Holdup, 1972 *"Calculation of the thermal resistance of buried cables through conformal transformation"*, Proc.IEE, vol.119, no.5, 575-586.

[2] F.C. Van Wormer, 1955, *"An Improved Approximate Technique for Calculating Cable Temperature Transients"*, Trans. Amer. Inst. Elect. Eng., vol.74, part 3, 277-280.

[3] J.P. Holman, 1981, *"Heat transfer"*, McGraw-Hill.

[4] Y.A. Cengel,1998, *Heat transfer, a practical approach*, New York: McGraw-Hill, p.418.

[5] F. Donazzi, E. Occhhini, A. Seppi, june 1979, "Soil thermal and hydrological characteristics in designing underground cables," Proceedings IEEE Vol 126. No.6, pp506-516

[6] NBN 259 (C33-112), 1967, *"Loodkabels en gepantserde kabels geïsoleerd met geïmpregneerd papier voor wisselstroomnetten onder spanningen van 20 tot en met 75 kV".*