Ampacity of buried cables in trenches filled with recycled concrete

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Abstract

In this paper the authors present a model designed to determine, over the course of time, the ampacity of a buried cable, the map of the temperature both inside the cable and in the surrounding soil. The model is quite versatile: analyses can be made for various types of cables, filler materials of the trench and types of soil. Other analyses can simulate various ways of laying configurations, load rates, as well as various environmental conditions. The numerical results presented in this paper refer, in particular, to a typical installation in urban areas of a three-phase underground power line at 20 kV, consisting of three unipolar cables insulated with dampened paper and a lead casing which are then covered in PVC and running at both nominal rate and in overload. The numerical algorithm is based on a finite element model (FEM) developed on a personal computer by means of a general purpose software.

Keywords: power cables, ampacity, transient thermal analysis, recycled concrete.

1 Introduction

In the historical centers of Italian cities there are serious problems due to the placement of service tunnels such as: gas pipes, electric cables, telephone services, etc. The problems are due to the stratification of ancient foundations found out below the cities, namely Rome. With regard to this situation, various companies are putting cables directly into the ground at a depth that ranges between 80 to 110 cm. Electric cables, in particular, are directly placed over the soil at the bottom of a trench. Then, they are covered with protective shingles to mark their presence in case of successive digs. Finally, they are covered with
vegetal soil and sealed with a layer of binder. The thickness of the binder, $\Delta$, is between 10 and 15 cm as shown in fig. 1a. If the procedure is not executed correctly, over time, there could be a dangerous possibility: the binder could cave in at the street level. This problem could be eliminated filling the trench with traditional concrete, but there would be two major drawbacks:

- successive digs would require the use of a pneumatic drill;
- concrete has a lower thermal conductivity than vegetal soil.

There is currently available a recycled concrete which has been studied. It is also known as waste aggregate. It is made from unconventional materials (for example, waste from mills, recycled tires, etc.). The advantages of using recycled concrete are:

- enabling the trench to be covered within 8 hours;
- enabling the use of a thinner layer of binder, as shown in fig. 1b;
- enabling the binder to be easily demolished by a normal hydraulic shovel.

Nevertheless, one disadvantage is that this recycled concrete has a lower conductivity than that of the vegetal soil. As a result, the Italian electrical energy distribution companies are experimenting the recycled concrete in historical centers by placing MV cables. They are using these new techniques to evaluate the reduction of cables nominal ampacity. This experimental research obviously takes long time and it is influenced by purely local factors. This paper illustrates the numerical model developed at the University of Rome [1] in response to this problem. It evaluates the thermal field map inside the cable and in its neighbourhood with specific load and boundary conditions.

The model integrates the Fourier equation of heat transfer with a numerical finite element technique [2, 3, 4]. The software used is the ANSYS program [5], which is frequently used for industrial applications. Our model makes thermal analyses in a parametric way being able to vary easily both geometrical values and material characteristics.

![Figure 1: Cross section of trenches filled by: a) vegetal soil; b) concrete. Typical laying configurations used in urban areas.](image-url)
2 Working hypotheses

A system consisting of three intertwined unipolar MT cables at 20 kV has been studied (see fig. 2). Each cable consists of the following, from the interior to the exterior: an aluminium conductor, a semiconductor layer, an insulation with imbued paper, a screen of metallic paper, a lead casing, and a protective cover in PVC. For thermal calculations, the international standard [6] defines the semiconductor, the screen of metallic paper and the insulation layer as one unit. The characteristics of the cables are also shown in fig. 2.

The trench is rectangular (see fig. 1b) and it has the depth \( h \) and the width \( w \) equal to those of the shovel’s dipper bucket. The soil, which has been assumed having uniform physical characteristics, is placed around the sides and underneath the trench. The trench is uniformly refilled with a recycled aggregate concrete and it is sealed at the surface with thickness \( \Delta \) of asphalt. From a thermal point of view, when the current flows there is a constant and uniform dissipation of power, \( P_J \), due to Joule losses within the core of the cables. The produced heat flows radially to the exterior. In other words, the component of thermal longitudinal flow is neglected.

The asphalt is directly exposed to solar rays. It exchanges heat by convection with the air and also it exchanges heat by conduction with the underlying material. With these working hypotheses, the authors have evaluated the evolution versus time, and for various load conditions, of the cable’s internal temperature and of the soil temperature. The authors have chosen extreme working conditions (e.g., regarding solar radiation, a tensely hot summer day at a latitude of 40° north) in order to evaluate possible derating of the buried cable ampacity. At the same time, in order to simplify the model, the material that makes up the cables, the filler, the surrounding soil and the layer of binder have

<table>
<thead>
<tr>
<th>Cable parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>( r_c = 9.4 ) mm</td>
</tr>
<tr>
<td>( r_{ins} = 14.9 ) mm</td>
</tr>
<tr>
<td>( r_{Pb} = 16.4 ) mm</td>
</tr>
<tr>
<td>( r_{PVC} = 18.9 ) mm</td>
</tr>
<tr>
<td>( D_c = (2 \ r_{PVC} + 5) ) mm</td>
</tr>
<tr>
<td>( I_n = 360 ) A</td>
</tr>
<tr>
<td>( T_M = 75 ) °C</td>
</tr>
<tr>
<td>( R_{20dc} = 0.125 ) ( \Omega / ) km</td>
</tr>
<tr>
<td>( \alpha_{20} = 0.00403 )</td>
</tr>
</tbody>
</table>

Figure 2: Cross section of a system consisting of three intertwined unipolar cables: (1) aluminium, (2) semiconductor, (3) imbued paper, (4) metallic paper, (5) PVC.
been considered homogenous. In table 1, the assumed values for the material properties are shown [7].

Table 1: Material properties.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda$ [W/m °C]</th>
<th>$\delta$ [kg/m$^3$]</th>
<th>$c$ [kJ/kg °C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminium</td>
<td>210</td>
<td>2700</td>
<td>0.92</td>
</tr>
<tr>
<td>Insulation</td>
<td>0.167</td>
<td>1500</td>
<td>1.339</td>
</tr>
<tr>
<td>Lead</td>
<td>35</td>
<td>11290</td>
<td>0.129</td>
</tr>
<tr>
<td>PVC</td>
<td>0.16</td>
<td>1400</td>
<td>0.8</td>
</tr>
<tr>
<td>Concrete</td>
<td>0.78</td>
<td>1600</td>
<td>0.879</td>
</tr>
<tr>
<td>Asphalt</td>
<td>0.7</td>
<td>2100</td>
<td>0.933</td>
</tr>
<tr>
<td>Soil</td>
<td>1</td>
<td>2200</td>
<td>1.2</td>
</tr>
</tbody>
</table>

The air temperature has been assumed to be equal to 30 °C, whereas the ground temperature is 20 °C, as established by international technical rules [6]. First, in order to determine the thermal dissipation in each conductor, knowing the flowing current, it is necessary to determine the electrical resistance $R_M$ per unit of length at the maximum temperature $T_M$. The standard [6] furnishes the relationships

$$R_M = R_{Mdc} \left(1 + y_s + y_p\right) \quad [\Omega/m]$$

(1)

where $R_{Mdc}$ is the electrical resistance of the d.c. conductor per unit of length at the maximum operating temperature, $y_s$ is the factor that takes into account the skin effect, and $y_p$ is the factor that takes into account the proximity of the cables, therefore with reference to table 1, we have

$$R_{Mdc} = R_{20dc} \left[1 + \alpha_{20}(T_M - 20)\right] \quad [\Omega/m]$$

(2)

$$y_s = x_s^4 / \left[192 + 0.8 x_s^4\right]$$

(3)

$$y_p = \left[x_p^4 / \left[192 + 0.8 x_p^4\right]\right] \left(2 r_c / D_c\right)^2 \left(0.312 \left(2 r_c / D_c\right)^2 + 1.18 / \left[\left(x_p^4 / \left[192 + 0.8 x_p^4\right]\right) + 0.27\right]\right]$$

(4)

with $x_s^2 = 8 \pi f 10^{-7} k_s / R'$ and $x_p^2 = 8 \pi f 10^{-7} k_p / R'$.

The standard [6], for the type of cable under analysis, imposes the use of the values $k_s = 1$, $k_p = 0.8$. The frequency is equal to 50 Hz. When the $R_M$ is determined with the previously defined formulas, in each conductor, the losses per unit of length, due to Joule effect, are

$$P_J = R_M I^2 \quad [W/m]$$

(5)
The dielectric losses in the cables, calculated as suggested in reference [6], are negligible. Therefore, the total thermal power dissipated by each cable coincides with $P_J$. The solar radiation power, $P_{rad}$, has been fixed at a value equal to the daily average value of the solar radiating power found at the ground level in an intensely hot summer day at a latitude of $40^\circ$ north [9].

![Figure 3: a) Cross section of the 2D domain. b) Cross section of the 2D domain modelled by ANSYS. c) Close-up of the trench area.]

### 3 Finite element model

#### 3.1 Calculation procedure

The ANSYS program can be advantageously used to point out electrical, magnetic, thermal, and structural analyses, as well as it can be also used for analyses of coupled problems [5]. Our study deals with a thermal problem, which is specifically of two-dimensional type, and it is focused on a rectangular domain including the trench (see fig. 3a). This cross section is perpendicular to the cables, and it has horizontal dimensions $W$ and vertical dimension $H$. These dimensions (and then the boundary of the domain) have been chosen in such a way as to be sufficiently far away from the cables. Thus, it is possible to assume that there is an absence of heat flow in the soil across the sides $1'1'$, $1'2'$, $2'2'$, fig. 3a. With reference to fig. 3a and fig. 3b, the $aa'$ symmetry plane line has been assumed to be perpendicular to the isothermal curves. Then, the heat transfer can be studied in one of the two “semi-areas” defined by $aa'$ line and by the boundary lines (see fig. 3b). Figure 3c shows a close-up of the trench area in the 2D fixed domain, while table 2 shows the main data used for all simulations. The imposed conditions are: the power $P_J$ on each conductor, the radiant power $P_{rad}$ and the convection coefficient on the asphalt surface. All transient thermal analyses start assuming as initial condition the temperature of 20 °C for cables, trench and soil surrounding the trench.
During the simulations, the soil, which is subject to thermal phenomena, will undergo a natural rise in temperature. The transient simulations stop when the cable temperatures converge to stable values.

### 3.2 Ampacity calculation

The proposed model calculates, under steady state conditions, the temperature in each cable and in the surrounding soil, for assigned laying conditions and dissipated power $P_J$. Then, the ampacity of the cables is computed by an iterative procedure, which consists of the following steps:

- the initial current value, $I$, is set to $I_n$, which is provided by the manufacturer;
- equations (1)-(5) are used to calculate the thermal power $P_{JI} = P_{Jn}$ in each cable;
- the final temperature $T_{fI}$ of the cables is determined by using the model developed by ANSYS;
- if the final temperature $T_{fI} > T_M$ (which is the maximum operating temperature of the cables), the $P_{JI}$ value is be reduced, e.g. $P_{JI}^* < 0.9 P_{JI}$, and with this new value the final temperature $T_{fI}^*$ is computed again;
- the iterative procedure stops when $T_{fI}^* \approx T_M$, and the current value $I^*$, related to the last value of the thermal power $P_{J^*}$, is the ampacity of the cable.

Note that, in this procedure, $P_J$ is the only quantity that changes ($P_{rad}$ is fixed).

### 4 Numerical results

#### 4.1 Derating coefficient

The model previously described has been used to predict the ampacity of the assigned power line configuration. Referring to the nominal current value $I_n$, the iterative procedure starts imposing $P_{JI} = P_{Jn}$.

In figure 4, the evolutions of the temperatures versus time are plotted. In particular, curve “a” shows the temperature of the upper cable related to the nominal current value $I_n$. The cable temperature converges to a stable value after a period of 60 days: in fact, during the last ten days, the temperature increases only of 1.2 °C. For this reason, and considering that an extremely hot summer would not last for more than 60 days, all remaining steps of the iterative procedure have been projected for this time period.
Figure 4: Temperature versus time plotted with reference to: the nominal current $I_n$, curve a; the current $I^{\text{III}}$, curve b; the operating current $I^{\text{V}}$, curve c.

Temperatures of the two lower cables are one degree lower than that of the upper cable, this is due to the soil, which has a higher thermal conductivity than that of the concrete; therefore, the lower cables dissipate heat more easily than the upper one.

Table 3: Numeric values of iteration steps.

<table>
<thead>
<tr>
<th>Step Number</th>
<th>$P_J$ [W/m]</th>
<th>$I$ [A]</th>
<th>$T$ [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>19.7</td>
<td>360</td>
<td>87.1</td>
</tr>
<tr>
<td>II</td>
<td>16.74</td>
<td>331</td>
<td>79.1</td>
</tr>
<tr>
<td>III</td>
<td>14.77</td>
<td>312</td>
<td>73.8</td>
</tr>
<tr>
<td>IV</td>
<td>15.23</td>
<td>316</td>
<td>75</td>
</tr>
<tr>
<td>V</td>
<td>9.85</td>
<td>254</td>
<td>60.5</td>
</tr>
<tr>
<td>VI</td>
<td>14.17</td>
<td>305</td>
<td>68.6</td>
</tr>
</tbody>
</table>

The current value $I^{\text{IV}} = I^* = \sqrt{0.773 I_n} = 0.879 I_n = 316$ [A], is the ampacity of the cables for the assigned laying configuration and steady state conditions, while 0.879 is the "derating" coefficient.

current value \( I^R = \sqrt{0.85} I_n = 0.922 I_n = 331 \, [A] \) and the computed final temperature, reached by the conductor, was \( T_{f}^{R} = 79.1 \, ^{\circ}C > T_M = 75 \, ^{\circ}C \). Since this value was too high yet, the iterative procedure worked according to numerical values in table 3 up to step IV.

4.2 Operating current

Under steady state conditions and during normal use, the cable temperatures must always remain below \( T_M \). In addition, cables must be able to support overloads for limited time periods without being damaged. For these reasons, it is important to determine the operating current corresponding to a temperature lower than \( T_M \) of 20% (i.e., a temperature of 60 °C). The results of this investigation are shown in table 3 - step V. It is possible to discovered that by imposing the power \( P_J^V = 0.5 \, P_{Jn} \), the corresponding current was \( I^V = \sqrt{0.5} I_n = 0.707 \, I_n = 254 \, [A] \) (this value equals the current being sought for normal operation) and the final temperature of the upper cable changed to \( T_f = 60.5 \, ^{\circ}C \approx 60 \, ^{\circ}C \), as curve “c” in fig. 4 also shows.

4.3 Overload

Referring to the operating current and starting from the steady state conditions reached after 60 days, the authors imposed a step variation (+20%) of the current, i.e., passing from \( I^V \) to the new value \( I^{VI} = 1.21^V = 0.848 \, I_n = 305[A] \) (see table 3). The analysis was prolonged for 24 hours, increasing the imposed power during the last day (i.e., the 61st) from \( P_J^V \) to \( P_J^{VI} = 1.2^2 \, P_J^V = 0.848^2 \, P_{Jn} \). Figure 6 shows the evolution of the temperature versus time during the overload of the power line. The final temperature, reached by the upper cable, was \( T_f^{VI} = 68.6 \, ^{\circ}C < T_M = 75 \, ^{\circ}C \); thus, the cable is able to withstand the overload.

Figure 5: Temperature evolution in the upper cable along r axis (I=I_n, P_J=P_{Jn}).
Figure 6: Temperature versus time plotted for an overload of 20% during the 61st day.

4.4 Electrical resistance as function of the temperature

All simulations have been executed according to the international standard [6]. It assumes a value of the resistance $R_M$ (calculated at 75 °C), which remains constant with respect to the temperature variations during transient thermal analyses. In order to improve the accuracy of the model, the same simulations have been performed taking into account the dependence of $R_M$ from the temperature, according to

$$R_M = R_{M0} = R_{20\degree C}[1 + \alpha_{20}(T - 20)] \ [\Omega / m] \quad (6)$$

Introducing equation (6), the program iteratively updates the new value of resistance as result of a temperature variation. The results obtained for constant and variable resistances are shown in table 4, where the percentage variation for each case is also highlighted. This percentage is positive for temperatures above 75 °C and negative for temperatures below 75 °C.

<table>
<thead>
<tr>
<th>Current (% of $I_n$)</th>
<th>100</th>
<th>92.2</th>
<th>87.9</th>
<th>86.6</th>
<th>70.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_M$ $T'$ [°C]</td>
<td>87.1</td>
<td>79.1</td>
<td>75</td>
<td>73.8</td>
<td>60.5</td>
</tr>
<tr>
<td>$R_M(T)$ $T''$ [°C]</td>
<td>89.5</td>
<td>79.7</td>
<td>75</td>
<td>73.5</td>
<td>58.7</td>
</tr>
<tr>
<td>($T'' - T'$) 100 / $T''$</td>
<td>+2.7%</td>
<td>+0.8%</td>
<td>0%</td>
<td>-0.4%</td>
<td>-3.1%</td>
</tr>
</tbody>
</table>

This behaviour can be justified observing that for temperatures above 75 °C, variable resistances are greater than constant resistances, this generate higher
heat dissipation due to Joule effect. The difference thus increases as we move away from the temperature of 75 °C. Note that, in this study and for the considered temperature range, the differences highlighted in table 4 were always negligible. So, a constant resistance can be advantageously used for all analyses, as the standard [6] suggests.

5 Conclusions

From the analysis of the results, it is possible to conclude that, for the power cable line configuration tested in this paper, the use of recycled concrete can be an efficient solution when the right of way is in urban areas. From one hand, the derating coefficient is acceptable and, on the other hand, the recycled concrete presents the well-known advantages previously discussed. In addition, the proposed model can be easily adapted to run transient thermal simulations varying geometrical and physical characteristics of the system (e.g., it can be used to evaluate the cable ampacity and the derating coefficient varying the filler material, the type of soil, the shape of trench, the environmental temperature, the value of solar radiation, the laying configuration of cables and so on).

Therefore, the model proposed by the authors is an efficient tool for the planning and the design of underground MV distribution networks in urban areas. The accuracy that can be achieved is also adequate for this purpose.

References