# Effects of Backfilling on Cable Ampacity Analyzed With the Finite Element Method

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***Abstract*—Expressions for computing the external thermal resistance $(T_4)$ of buried cables, in both the IEEE and the IEC standards, are applicable to a limited number of installation geometries. In this paper, a method for the computation of $T_4$ using the finite element approach is presented. With this method, a parametric study on how cable ampacity is affected by different configurations of the backfills is performed. The obtained results are compared with those of the IEC and IEEE standards (Neher–McGrath) and published extensions by El-Kady and Horrocks. Important differences can be observed for nonstandardized situations.**

***Index Terms*—Ampacity, backfill, cable thermal rating, external thermal resistance, finite element method, Neher–McGrath, underground cables.**

## I. Introduction

FOR the majority of buried cables, the external thermal resistance accounts for more than 70% of the temperature rise of the conductor, therefore, various means of reducing its value have been applied in practice. In many North American cities medium- and low-voltage cables are often located in duct banks in order to allow a large number of circuits to be laid in the same trench. The ducts are first installed in layers with the aid of spacers, and then a bedding of filler material is compacted after each layer is positioned. Concrete is the material most often used as filler. High- and extra-high-voltage cables are, on the other hand, often placed in an envelope of well-conducting backfill to improve heat dissipation. Both methods of installation have in common the presence of a material with a different thermal resistivity from that of the native soil.

Backfilling is more effective when the thermal resistivity of the native soil is high. Some soils have naturally high thermal resistivity (for example dry sands), but high thermal resistivities can also occur when moisture migration (or soil dry out) takes place. The IEEE Standard 442 [1] describes the procedures for measuring the thermal resistivity and gives values for certain soils according to their moisture content. A backfill can be an effective way to prevent soil dry out in the vicinity of a cable.

The first attempt to model the presence of a duct bank or a backfill in the computation of $T_4$ was presented by Neher and McGrath [2] and later adopted in the IEC Standard 60287 [3]. In later works by El-Kady and Horrocks [4], El-Kady *et al.*, [5], Tarasiewicz *et al.* [6], and Sellers and Black [7], the basic method of Neher and McGrath was extended to take into account backfills and duct banks of elongated rectangular shapes, and to remove the assumption that the external perimeter of the rectangle is isothermal.

The approach for the computation of the external thermal resistance discussed in the above references assumes that the heat path between the cable and the ground surface is composed of a region having uniform thermal resistivity. Even in the case of a backfill or duct bank, the same assumption is made initially, and a correction factor is applied later to account for different thermal resistivities. In practice, several layers of different thermal resistivities may be present between the cable surface and the ground/air interface. To deal with a general case of varying thermal resistivities of the soil, CIGRE Working Group 02 proposed a method using conformal transformation to compute the value of $T_4$; see [8]. An alternative approach, presented in this paper, uses a finite element method allowing analysis of multilayered soils.

A second purpose of this paper is to present the results of a parametric analysis on the effects on ampacity of backfilling. The quantity, shape and location of the backfill with different thermal resistivities for the native soil have been varied. Additionally, the effects the ampacity of installing engineered backfills at the top of the main backfill are studied.

## II. $T_4$—External Thermal Resistance

The ampacity of a cable very much depends on the thermal resistance of the surrounding medium. Apart from the conductor size, the thermal resistance of the soil has the greatest influence on the cable current carrying capability. The value of $T_4$ for an isolated cable depends mainly on the thermal characteristics of the soil/backfill and the installation depth. Fig. 1 shows the variation of ampacity as a function of the thermal resistivity of the soil for cables installed in a duct bank [9]. Note that the ampacity is quite sensitive to the changes in the thermal resistance of the soil (or resistivity for a given installation depth).

In addition to the factors mentioned before, the value of $T_4$ also depends on the positioning of the cables forming a single circuit as well as the shape of the load curve associated with this circuit. In what follows, we will assume a unity load factor, so the last effect will be ignored.

### A. *Standard Methods for the Calculation of $T_4$*

The external thermal resistance to the cables is computed in both the IEC [3] and IEEE [10] standards using the Neher-McGrath method published in 1957 [2]. The value of $T_4$ is computed with expressions that depend on whether the cables are

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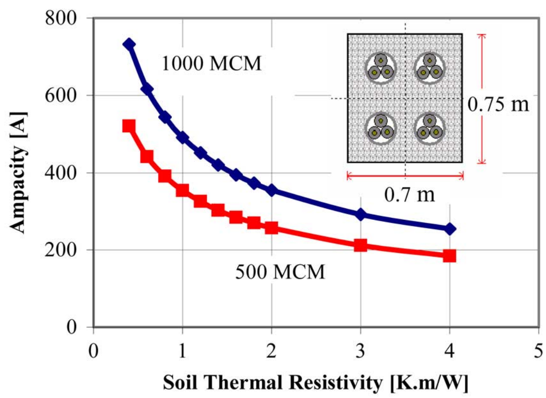


Fig. 1. Ampacity as a function of soil thermal resistivity [9].

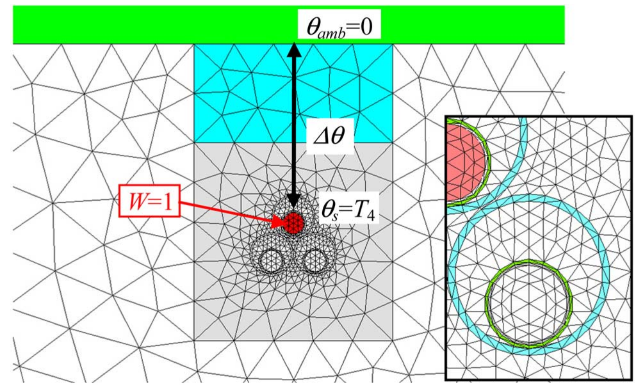


Fig. 2. Procedure to compute $T_4$ for nonhomogenous backfill arrangement.

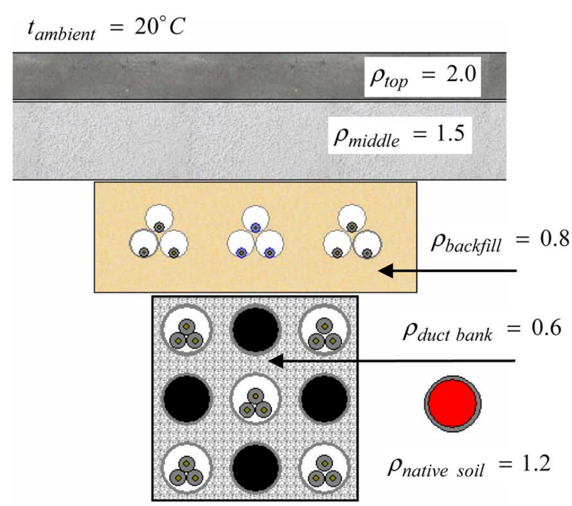


Fig. 3. Complex cable installation suitable for the computation of $T_4$ applying the finite element method proposed in this paper.

installed in conduits or directly buried. When the cables are touching, a difference is made depending on whether the cables are laid in trefoil or flat formations. Different expressions are used for equally and unequally loaded cables. A thorough description of the history and theory of ampacity calculations can be found in [11].

In the Neher–McGrath method, a backfill is treated as an equivalent cylindrical surface whose radius depends on the width and height of the backfill.

### B. Calculation of $T_4$ Using the Finite Element Method

When the medium surrounding the cables is composed of several materials with different thermal resistivities, standard methods cannot be applied. However, an approximate solution can be found using the finite element method. The approach is based on the observation that the temperature rise $\Delta\theta$ at the surface of the cable above ambient is equal to

$$\Delta\theta = T_4 W \tag{1}$$

where $W$ represents the total losses inside the cable. If we set $W = 1$ and $\theta_{\rm amb} = 0$, then

$$T_4 = \theta_s \tag{2}$$

where $\theta_s$ is the cable/duct surface temperature.

The proposed approach requires building a finite element mesh and solving the resulting heat transfer equations for the temperature at the cable surface. Fig. 2 shows an example including the details of the cable. In the majority of cases, the cable surface is not an isotherm; hence there is a question of which temperature to choose for (2). A conservative approach would be to use the highest value. An alternative would be to use an average temperature. The latter approach is taken in the developments that will be presented.

Adiabatic boundaries are set sufficiently far away on both sides and the bottom of the installation (boundaries not shown in Fig. 2). Experience has shown that these boundary conditions result in a negligible error when computing cable temperature [14]. The soil surface can be represented as an isothermal or a convective boundary.

Once $T_4$ is known, ampacity calculations can be efficiently performed with the standardized procedures. This is an important difference with respect to an approach using only the finite element method for the computation of the thermal fields. In the latter case, much longer simulation times can be expected.

Fig. 3 shows a complex installation that can be solved with this method. In addition to the native soil, the installation comprises several materials with different thermal resistivities, namely: two soil layers, three sets of ducts in trefoil in a backfill, several cables in trefoil installed in a duct bank and a steam pipe.

The first natural question that arises in the approach proposed here is how it compares with the standard methods of $T_4$ calculations for the cases where such comparisons can be made. This question is addressed in the remainder of this paper.

## III. Varying Soil Thermal Resistivity

Several backfilling arrangements are investigated with parametric studies. The thermal resistivity of the native soil is varied between 0.5 and 4.0 K.m/W. The two approaches described above for computing $T_4$ are compared in every case.

### A. Base Case—Directly Buried Cables

The geometry of the base case is shown in Fig. 4. It consists of three trefoil arrangements. The cable construction de-

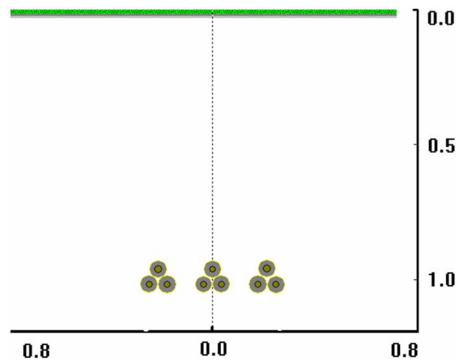


Fig. 4. Case base—directly buried trefoils.

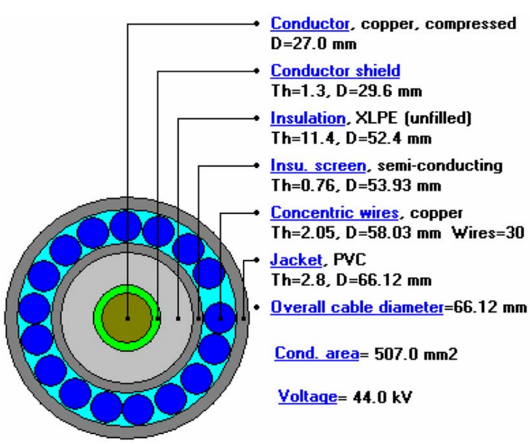


Fig. 5. Construction details of the cable used for the simulations.

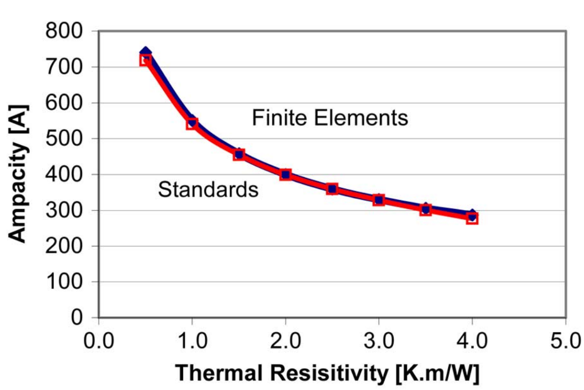


Fig. 6. Ampacity for the case base—directly buried trefoils.

tails are given in Fig. 5. Fig. 6 shows the variation of ampacity with thermal resistivity of the soil comparing the two methods for computing $T_4$. It can be seen that both methods give approximately the same ampacity for the entire range of the soil thermal resistivities. It is interesting to note that the ampacity for a soil resistivity of 4.0 K.m/W is less than half of that for 0.5 K.m/W.

### B. Case with a Thermal Backfill

The effects on ampacity of the cable arrangement in Fig. 4 installed in a backfill with a low value of thermal resistivity are analyzed as a function of the thermal resistivity of the native

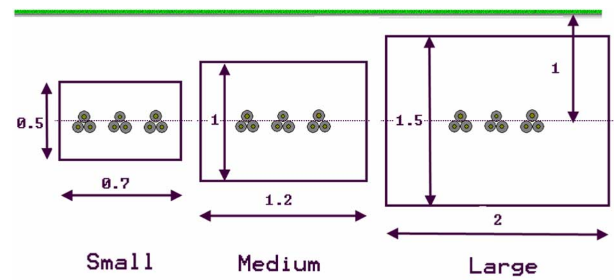


Fig. 7. Three different quantities of backfill.

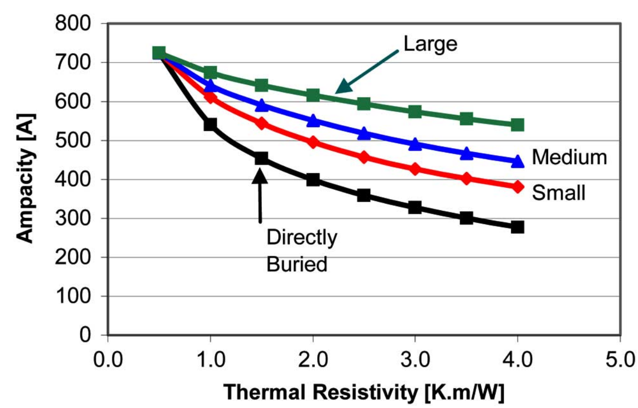


Fig. 8. Ampacity for different quantities of backfill.

soil. Two cases are compared, when $T_4$ is computed as in the standards and with the finite element method.

Three quantities of backfill were examined; see Fig. 7. One (small) has dimensions of $0.7 \times 0.5$ m (area $= 0.35$ m$^2$), another (medium) with dimensions of $1.2 \times 1.0$ m (area $= 1.2$ m$^2$), and the last (large) with dimensions of $2.0 \times 1.5$ m (area $=$ 3 m$^2$). The thermal resistivity of the soil is varied between 0.5 and 4.0 K.m/W. Fig. 8 shows the ampacity for the arrangements when using the finite element method. As expected, a greater quantity of backfill with a greater area yields larger ampacity. In these examples, the ampacity is increased by 37.5% for the small backfill, 72% for the medium backfill, and by 95% for the large one with respect to the directly buried case. Increasing the backfill quantity incurs additional installation costs. There is an optimal amount of backfill beyond which the increase in the cable rating does not compensate the additional costs. This topic is analyzed in [12].

Fig. 9 shows the differences in percent between the ampacities calculated with the two methods. The reference is the ampacity computed with the finite element method. For the directly buried case and the large backfill, the differences are small (mostly less than 3%) and negative. Thus, the standardized method computes ampacities slightly on the optimistic side. However, for the small and medium backfills, the standardized method gives ampacities mostly on the pessimistic side with differences ranging from $-2\%$ to 11%.

### C. Varying the Depth of the Backfill

Numerical experiments were performed to find the differences between the standard and the finite element methods as the depth of the backfill varies. The distance from the top of

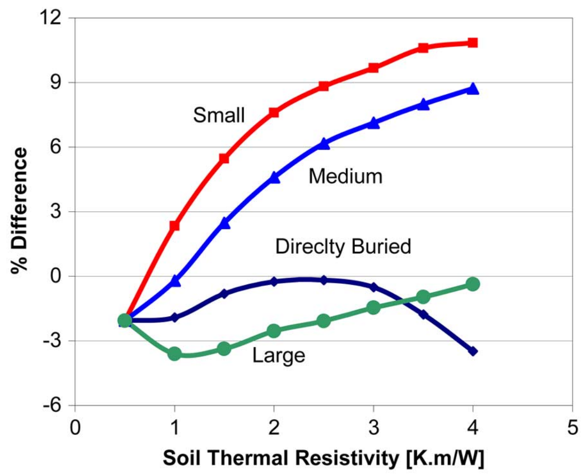


Fig. 9. Difference in ampacities using standard and finite element methods for the calculation of $T_4$ for different backfill quantities.

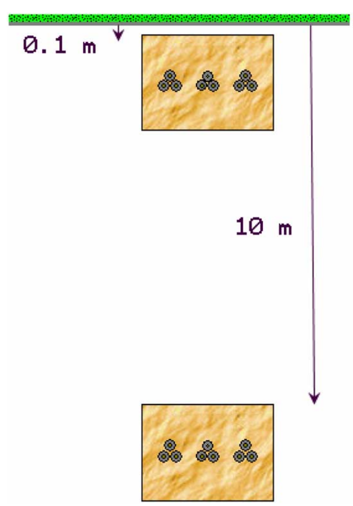


Fig. 10. Varying the depth of the backfill from 0.1 m to 10 m.

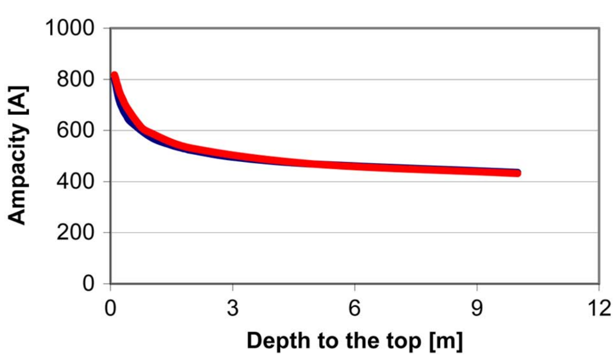


Fig. 11. Ampacity versus installation depth comparing the two methods for computing $T_4$.

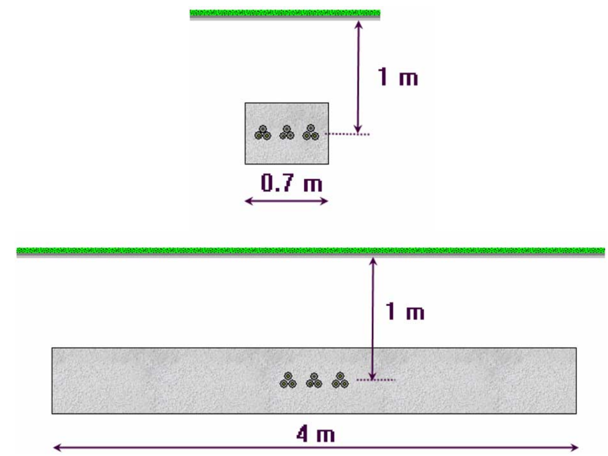


Fig. 12. Extreme cases for varying the width of the backfill.

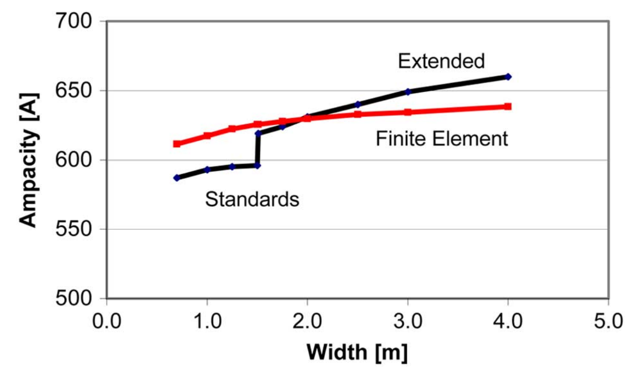


Fig. 13. Ampacity versus backfill width.

the backfill to the surface was varied from 0.1 m to 10 m; see Fig. 10. The results are shown in Fig. 11 for thermal resistivities of 1.0 and 0.5 K.m/W for the native soil and the backfill, respectively. As expected, the ampacity decreases as the depth increases. Both methods give virtually the same results for every depth. The largest difference is under 2% and happens for the shallowest case (0.1 m), the finite element results are somewhat optimistic. Similar results were obtained for other combinations of the thermal resistivities.[1]

## IV. Varying Width and Height

The standardized methods for the computation of cable ampacity for backfill installations are valid for the ratios of width to height ranging from 1/3 to 3. In reference [4], extensions to the standard methods were given. Here, we compare the standardized methods, including the extensions, against the finite element results.

### A. *Varying Width*

The width of the backfill was varied from 0.7 m to 4.0 m; the thermal resistivities for the native soil and backfill are 1.0 and 0.5 K.m/W, respectively. Fig. 12 shows the arrangement for the extreme cases and Fig. 13 displays the comparative results. The width to height ratios were varied between 1.4 and 8.

From Fig. 13, we can observe that the standardized methods compute the ampacity on the conservative side of around 4% (for this case). This fact was previously noticed in [4]. The authors showed that the geometric factor obtained with the Neher–McGrath method decreases as the height to width ratio

[1]The finite element approach has one more advantage over the standard method for shallow buried cables. Namely, it allows performing analysis with a nonisothermal earth surface. This feature was not explored in this study.

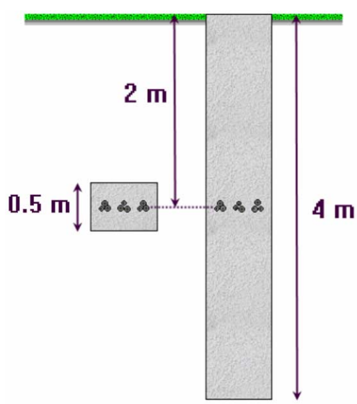


Fig. 14. Extreme cases for varying the height of the backfill.

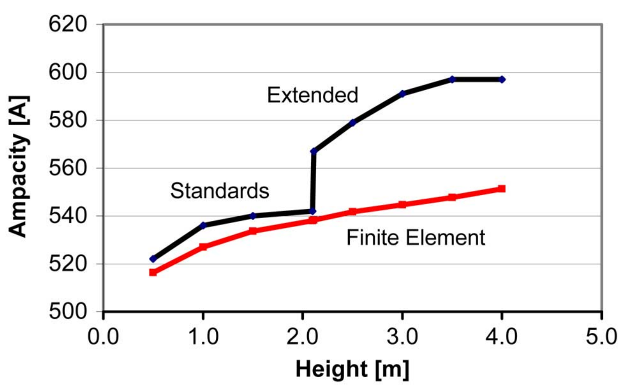


Fig. 15. Ampacity versus backfill height.

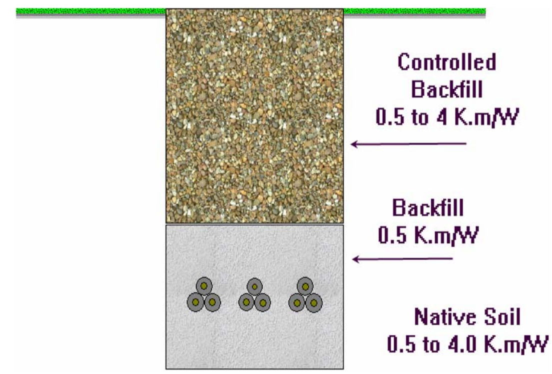


Fig. 16. Cable backfill plus a controlled backfill on top.

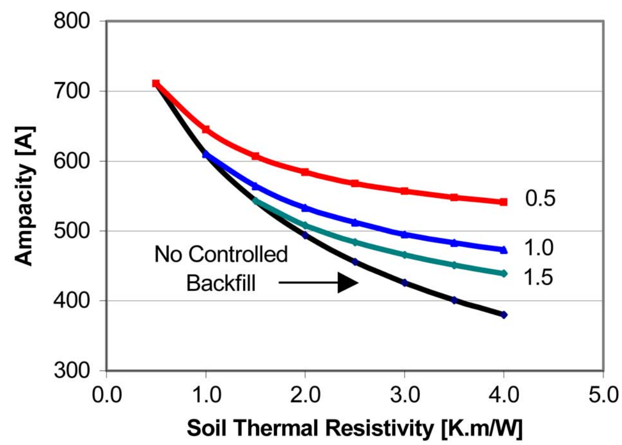


Fig. 17. Ampacity gains using a controlled backfill on top.

increases contradicting the results of their (finite element) scheme. The reason is that in the standard approach, the surface of the backfill is assumed to be an isothermal cylinder. For very large (or small) width/height ratios, this is not true, especially when the cables are clustered together as in our example. The regions of the backfill close to the cables are hotter than the far away regions.

### *B. Varying Height*

The height of the backfill was varied from 0.5 to 4.0 m with a constant width of 0.7 m. This range covers width to height ratios from 0.714 to 5.71. The initial position of the backfill is now 2 m (rather than 1 m) to give more room for the variations. Fig. 14 depicts the extreme situations and Fig. 15 shows the computed ampacities with the standardized methods, the extensions published in [4] and the finite element approach.

We can observe that the standardized method (up to a ratio of width to height of 3) computes the ampacity with less than 2% difference with respect to the finite element approach. The extensions give maximum differences of 9%. In both cases, the differences are on the optimistic side (i.e., the computed ampacity is larger than the reference ampacity computed with the finite element method).

## V. CONTROLLED BACKFILLS ON TOP

After digging a trench for the installation of underground cables, it is a common practice to place the native soil on top of the backfill. However, when the native soil has unfavorable thermal resistivity (high value or it is prone to drying out), a controlled backfill with a lower thermal resistivity than the soil can be used. Fig. 16 depicts such a situation.

A parametric study has been performed to find the ampacity gains for installations with a controlled (or engineered) backfill. The cables are installed in a small backfill centered at a depth of 1 m with a thermal resistivity of 0.5 K.m/W. The thermal resistivities of both the soil and the controlled backfill have been varied between 0.5 and 4.0 K.m/W.

Fig. 17 shows the variation in ampacity for several conditions: No controlled backfill on top, adding controlled backfill with thermal resistivities of 0.5, 1.0, and 1.5 K.m/W. From Fig. 17 one can appreciate that substituting the native soil with a material of lower thermal resistivity can substantially increase the ampacity of the cables. As expected, greater ampacity benefits are obtained when the thermal resistivity of the native soil is higher. In our example, the improvement in ampacity is more than 42% when we add a controlled backfill of 0.5 K.m/W substituting a soil with a thermal resistivity of 4.0 K.m/W.

All simulations in this section have been performed with the finite element method. The standardized procedures do not have

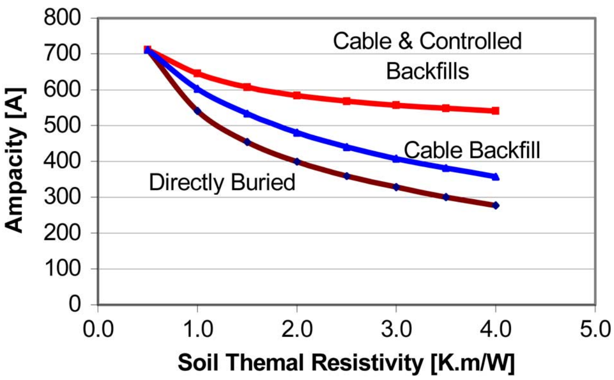


Fig. 18. Ampacity for three important cases: directly buried cables, cables in backfill, and cables in backfill plus a controlled backfill on top.

expressions for computing $T_4$ for the geometrical arrangement depicted in Fig. 16.

## VI. Summary of Results

Fig. 18 compares the three most important cases: the worst-case scenario, when the cables are directly buried as in Fig. 4; the standard backfill case; and the best-case scenario, when the cables are installed in a backfill and with a controlled backfill on top (Fig. 16). The increase in ampacity when the cables are installed in a backfill varies between 0% and 37.5% with respect to the directly buried case. When a controlled backfill is added, the increase in ampacity varies from 0% to 95% of the ampacity for directly buried cables.

## VII. Conclusion

A finite element method for the computation of the thermal resistance external to the cable $(T_4)$ has been proposed. The method represents an effective alternative to the use of a full thermal finite element program. Once $T_4$ is computed, the proposed approach applies the standardized rating procedures. This combination of methods gives the possibility of efficiently rating cables installed in nonhomogenous soils and/or backfill arrangements.

A parametrical study on the effects of backfilling on cable ampacity has been presented. The analysis includes the comparison of two methods for computing the external thermal resistance. The most important conclusions on the use of the backfills are as follows.

- Backfilling is an effective (technically speaking) way to increase ampacity. Installing a small quantity of backfill can produce sizable ampacity gains.
- The improvements in ampacity of backfilling are more significant when the thermal resistivity of the native soil is high.
- The quantity of the backfill substantially affects the ampacity.
- Controlled backfills on top of already backfilled cables can significantly increase the ampacity when the native soil has high thermal resistivity.

The most important conclusions on the comparison of the standardized methods for the computation of the value of $T_4$, against the method using the finite element approach are as follows.

- The standard methods accurately match the results from finite element when the cables are directly buried.
- The standardized methods tend to slightly underestimate the ampacity when the cables are installed in a well-shaped backfill (ratio width/height from 1/3 to 3) by a few percentage points. As the installation depth increases, the differences between the two methods decrease.
- The extensions to the calculation of the geometric factors proposed by El-Kady and Horrocks work relatively well for backfills with ratios width to height larger than 3. However, for backfills with ratios width to height smaller than 1/3, the El-Kady/Horrocks approach overestimates the ampacity from 5 to 10%.
- In the standards, there is no procedure for computing $T_4$ in cases where a controlled backfill is used on top of the main backfill.

All of the simulations in this paper have been carried out with the commercially available program for thermally rating cables, CYMCAP, where the algorithms presented in this paper have been included [13].

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