Evaluation of thermal resistances T3 and T4 for touching formations in IEC 60287-2-1

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ABSTRACT

The formulas in IEC for the external thermal resistance T_4 in touching formations should utilize the temperature contribution from adjacent cables, instead. The factor of 1.6 used for T_3 in trefoil formation should be unity. The grouping in IEC; metal sheathed/non-metal sheathed (= copper wire screen) is not a necessary condition.

In IEC, a discontinuity of T_4 exists when going from non-touching to touching formations. This discontinuity could be smoothed out by a "thermal proximity factor" for all type of configurations. Only the temperature contribution approach for all types of formations could then be used, making the thermal calculations improved.

KEYWORDS

jacket thermal resistance T_3, external thermal resistance, T_4, touching formations

INTRODUCTION

The standard IEC 60287-2-1[1] describes three ways of calculating the external thermal resistance T_4 for equally loaded cables in trefoil and flat formations:

1) Cables are *non-touching*
2) Cables are *touching*
   a. *Metal sheathed*
   b. *Non-metal sheathed (Cu-wire screen)*

The formulas for *non-touching* formations are easiest to understand since the related formulas are based on the temperature contribution from adjacent cables to the hottest cable in the formation. However, there are some conditions that must be fulfilled when utilizing the temperature contribution approach:

a) The metal sheath *and* the jacket of *hottest* cable in the configuration are *treated* as isotherms according to IEC,
b) the adjacent cables are *non-materialized,* i.e. they possess the same thermal properties as the surrounding soil,
c) the adjacent conductors are treated as line sources with a distance s to the hottest cable conductor.

Using the above conditions, it is quite straightforward to derive the formulas in IEC for *non-touching* formations. The basic approach is to calculate the external thermal resistance as:

$$T_4 = \underbrace{\frac{\rho_e}{2\pi} ln\left(u + \sqrt{u^2 - 1}\right)}_{T_{4-hottest}} + T_{4-mutual} \qquad [1]$$

If $u > 10$ the ln -expression may be written as $ln(2u)$ where $u = \frac{2L}{D_e}$. It is also possible to calculate the temperatures individually in the actual formation since all cables (normally two or three) are treated as individuals with a unique location in the soil.

A soon as the distance s equals the diameter D_e, IEC uses the *touching* formation approach. However, there exists an unphysical discontinuity in the value of T_4 when going from infinitesimally separated cables to touching cable. The rationale for this discontinuity is not explicitly explained in IEC.

By using the touching formation approach in IEC, all cables in the formation are now *not* treated as individual cables, but rather as a *group* of cables, virtually placed at the same location in the soil, having a combined virtual diameter for all cables in the group.

The main reason behind, is most likely to average the effect that the heat flux from the conductors is not creating perfect isotherms, i.e. the cables in the same formation are thermally disturbing each other. The premise in IEC is though, that the metal sheath can be regarded as an isotherm. Our understanding of the meaning of IEC is for example that the calculation of T_1 for the insulation system, is not possible without accepting the metal sheath as an isotherm. But we will see that this is not a necessary condition for T_3 and T_4, either.

To summarize: the following conditions apply in IEC for metal sheathed cables in *touching* formations:

a) The metal sheath *only* must be treated as an isotherm, i.e., the metal sheath should have a *high* thermal conductivity,
b) two or three cables are positioned at the same location in soil. The *group* of cables have therefore the same (average) temperature.

In general, the formulas for *touching* formations in IEC 60287-2-1 [1] could be written as:

$$T_4 = n\frac{\rho_e}{2\pi}(ln(2u) - \delta) \qquad [2]$$

The factor n may be either 2 or 3 for the number of cables and the factor δ depends on the formation selected:

- *trefoil* touching: $\delta = 0.630, n = 3$
- flat touching (*dual*): $\delta = 0.451, n = 2$
- flat touching (*triple*): $\delta = 0.760^1, n = 3$

)[1], Eq. (2) for triple formation is written in another form than in IEC. However, if writing the formula in the form of IEC the factor is 0.346. Thus, the formulas are equivalent if using 0.760 as above.

Note that for Eq. (2), the short-form of the ln -expression is used. Consequently, the touching formulas have some minor limitations on the factor u.

It will later be shown that the only formula of real significance to calculate the external thermal resistance T_4, is to use the temperature contribution approach in § 2.2.3.1 in IEC 60287[1], irrespective of if the cable are touching/non-touching or metal sheathed/non-metal sheathed. The factor of 1.6 for jacket thermal resistance in trefoil formation could also be set to 1.0, as will be shown.

CABLE DESIGN AND PARAMETERS

This paper analyses the thermal resistances outside the metal sheath. It is therefore of minor importance to use a multi-layered cable design. The cables are equally loaded in each formation.

If not otherwise stated, the cable design used for the analysis herein, has the following dimensions:

- Copper conductor: $d_c = 22\ mm$
- XLPE insulation *system:* $t_i = 22\ mm$
- Lead sheath: $t_s = 2.0\ mm$
- PE jacket: $t_j = 4.0\ mm$
- External diameter: $D_e = 100\ mm$

Without loss of generality, it is assumed that the cables have no power loss generation in the metal sheath. All power losses are generated in the conductor. The conductor surface is a perfect isotherm, and the conductor losses are therefore applied to the surface boundary in the FEM analysis. The following parameters are assumed for the cables, if not otherwise stated:

- Conductor loss: $W_c = 30\ W/m$
- Conductor loss (per m^2): $P_c = 217.03\ W/m^2$
- Th. conductivity copper: $\sigma_c = 400\ W/mK$
- Th. resistivity insulation: $\rho_i = 3.5\ Km/W$
- Th. conductivity lead: $\sigma_{pb} = 35\ W/mK$
- Th. resistivity jacket: $\rho_j = 3.5\ Km/W$
- Th. resistivity earth: $\rho_e = 1.0\ Km/W$

HISTORICAL BAKCKROUND – IEC 60287

The touching formulas for the external thermal resistance T_4 in the format of Eq. (2), were not introduced in the first edition of IEC 287 [2] from 1969. The only formula for trefoil formation was Eq. (3) below, which is still used for cables with spaced copper wires, without any metal sheath.

$$T_4 = \frac{\rho_e}{2\pi}(ln(2u) + 2ln(u)) \qquad [3]$$

This formula was used for *any* type of formation in [2], independently of whether the cables were metal sheathed or not. The formula is derived for the *lower left* cable in trefoil touching formation using temperature contributions from the adjacent cables.

The *existing* trefoil touching formulas were developed during the 1970's and were first introduced in 1978 in Amendment-4 [3] of edition-1. During this time, FEM was developed and most likely used to develop the formulas now used in IEC 60287 [1]. The factor 1.6 as is used to increase the thermal resistance T_3 was introduced in 1978 as well, even if the formulas for both T_3 and T_4, used the logarithm with base 10. In edition-2 [4] from 1982, the formulas for flat touching formations were introduced.

Below, a desktop analysis is performed trying to capture the background and relevance of these formulas.

DESKTOP ANALYSIS

Trefoil – 3 cables equally loaded

There are no explicit explanations about the origin of the touching formulas in IEC. However, there is one 'hint' in § 4.2.4.3.2 of [1], which states that the thermal resistance T_3 *shall* be multiplied with a factor of 1.6 for trefoil formation. One may assume that the idea behind this factor is that the heat flux is supposed to be small towards the centre of the trefoil formation. That implies the outer surface of the jacket is only partly used for heat transfer; i.e. $\frac{360^o}{1.6} = 225^o$ is active in the heat transfer to the soil.

Since IEC also prescribes the metal sheath to be an *isotherm* the total thermal resistance of the outer jacket is then (per phase):

$$T_3{}' = \underbrace{0.6T_3}_{\Delta T_3} + T_3 = 1.6\frac{\rho_n}{2\pi}ln\left(1 + \frac{2t_j}{D_e - 2t_j}\right) \qquad [4]$$

Thus, if the thermal resistance T_3' considers a constraint on the heat flux by using the factor of 1.6, the external thermal resistance T_4 must also include the same constraint on the heat flux, which is based on the condition of assuming the metal sheath as an isotherm. In Fig. 1, a geometric visualization for this is shown.

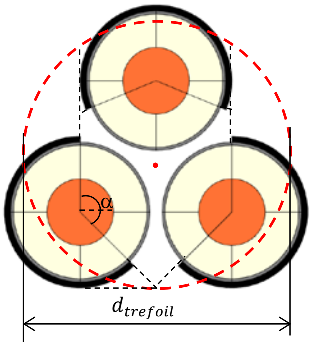

Fig.1 - Geometric visualization for trefoil formation.

The part of the jacket surface active in the heat transfer is as mentioned before 225^o. The remainder of the surface is then according to Fig. 2: $\alpha = 135^o$.

A FEM analysis also *seems* to show, that this angle is well-suited. See Fig. 2 below. It will, however, be shown that this is not the right conclusion.

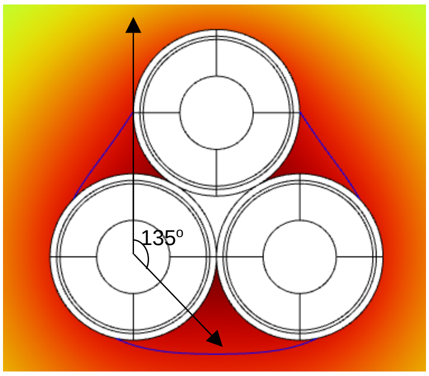

Fig.2 – Confirmation of heat flux angles in FEM.

The idea according to IEC is to place all cables in the centre of the trefoil formation at the same burial depth. Without any consideration to the constraint on the heat flux, with $n = 3$ and $\delta = 0$:

$$T_4 = 3\frac{\rho_e}{2\pi}ln(2u) = 1.5\frac{\rho_e}{\pi}ln\left(\frac{4L}{d}\right) \qquad [5]$$

However, since our premise is that the heat constraint also must be valid for the external thermal resistance, the following condition must apply for the virtual diameter $d_{trefoil}$ of the trefoil group. This diameter is shown in dashed red in Fig. 1.

$$d_{trefoil} = 3\frac{d}{1.6} \quad [6]$$

Using Eq. (6) to exchange d with $d_{trefoil}$ in Eq. (5) we get:

$$T_4 = 1.5\frac{\rho_e}{\pi}(ln(2u) - 0.6286) \quad [7]$$

The factor δ becomes 0.6296 if Eq.1 is used to improve the formula for the limitation of the usage of $u = 10$. It is possible this has been done in [1] to come to $\delta = 0.630$. Thus,

$$ln(20) - 0.6286 \approx ln(10 + \sqrt{99}) - 0.630 \quad [8]$$

From this desktop analysis of trefoil formation, it is then likely that the same approach as was used for T_3 also was used for T_4 in IEC. It also aligns with what one could expect with the premise of using the metal sheath as an isotherm.

Flat – 2 cables equally loaded (dual formation)

In general, the difference between the *dual (D)* formation (2 cables touching) and the trefoil formation is the exclusion of the upper cable in the former. However, using the same kind of reasoning, it should be some, but a smaller constraint on the outer jacket thermal resistance T_3, but it is not included in IEC.

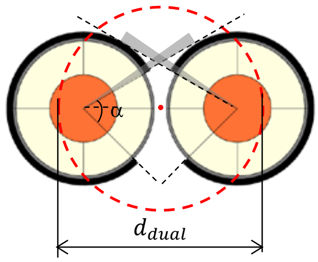

Fig. 3. Geometric visualization of dual formation.

Using the same reasoning as for trefoil, the angle α should be around 75°, as depicted in Fig. 3. The average diameter for dual formation then becomes $d_{dual} = d\frac{19}{12}$.

However, since the heat flux upwards is slightly better than downwards, which can be verified in a coarse FEM-analysis, α should be around 77.5° to correspond with $\delta = 0.451$. The factor δ might also have been adjusted in a similar way as was done in Eq. 8 for trefoil formation but using $u = 5$.

What is important here though, is that the most likely way of calculating the external thermal resistance approach is the same as for trefoil. Using either $\alpha = 75^o$, or $\alpha = 77.5^o$, only implies a temperature change $< 0.09K$ for the defined power loss (30 W/m).

Thus,

$$T_4 = 2\frac{\rho_e}{2\pi}(ln(2u) - 0.451) \quad [9]$$

Flat – 3 cables equally loaded (triple formation)

Using the same approach for *triple* formation, the only difference should be to use $n = 3$ and therefore $d_{triple} = d\frac{26}{12}$ is a kind of average equivalent diameter for three cables, using $\alpha = 75^o$. The middle cable has one constraint towards each of the adjacent cables. According to IEC the factor $\delta = 0.346$ but using the same approach as above for the triple formation, this factor becomes 0.760 when again $\alpha = 77.5^o$. The factor 0.760 is not very close to 0.346, but this IEC-formula is however written in a different form than Eq. (2).

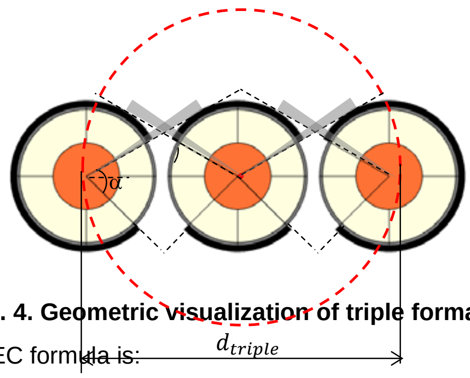

Fig. 4. Geometric visualization of triple formation.

The IEC formula is:

$$T_4 = \rho_e[0.475ln(2u) - 0.346] \quad [10]$$

and if writing the equation in the same form as Eq. (2) it becomes:

$$T_4{}' = 3\frac{\rho_e}{2\pi}(ln(2u) - 0.760) \quad [11]$$

Using $u = 5$, T_4 *equals* 0.7477 and $T_4{}'$ *equals* 0.7365. An additional adjustment with a corresponding approach as in Eq. (7) gives $T_4{}' = 0.7466$, which is again very close. However, this and other touching formulas in IEC seem to be *too low and/or unphysical* as can be seen in the FEM comparison in Table 3.

FACTOR 1.6 FOR T_3 IN TREFOIL

In touching trefoil formation, the adjacent cables are preventing the heat flux from conductor to outer jacket to be equal in all directions. From the lead sheath towards the centre of the formation, the heat flux is almost zero. But is the thermal resistance also about 60% higher, i.e. should T_3 be multiplied with a factor of 1.6?

If we make a FEM analysis of trefoil formation and calculate the thermal resistance T_3 by using the average metal sheath and jacket outer surface temperatures, we get the same value independently of the metal sheath thermal conductivity. Average surface temperatures are used to calculate T_3:

$$T_3 = \frac{\bar{\theta}_j - \bar{\theta}_{sh}}{W_c} \quad [12]$$

The jacket and metal sheath surface temperatures shown in Fig 5 below start from point A and goes counter-clockwise.

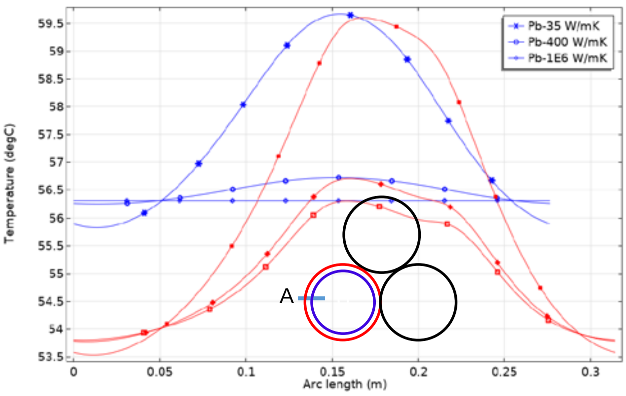

Fig. 5. Surface temperatures for metal sheath and jacket, for different thermal conductivities of metal sheath.

A summary of the metal sheath/jacket is shown in Table 1.

Case	σ_{pb} (W/mK)	$\overline{\theta_J}$ (^{0}C)	$\overline{\theta_{sh}}$ (^{0}C)	$\overline{\Delta\theta_J}$ (^{0}C)	T_3 (Km/W)
1	FEM - 35 (Pb)	56.21	57.61	1.393	0.0466
2	FEM - 400 (Cu)	55.08	56.48	1.393	0.0465
3	FEM - 1E6 (Isotherm)	54.91	56.31	1.394	0.0464
4	IEC-Eq. 2)[1]	53.89	55.28	1.393	0.0464
5	IEC-Eq. 2)[2]	53.89	56.12	2.229	0.0743
6	IEC-Eq. 3)[3]	56.30	57.69	1.393	0.0464

)[1] T_3 calculated without a factor of 1.6. T_4 - acc. to Eq.2.

)[2] T_3 calculated with a factor of 1.6. T_4 - acc. to Eq.2.

)[3] L is measured to the centre of formation as per IEC.

Table. 1. Jacket temperatures and thermal resistances.

From Fig 5 and Table 1, one concludes that the heat flux from the conductor and metal sheath will be *redistributed* across the jacket and that the requirement of an isotherm on the metal sheath is not needed for an ordinary metal sheath, e.g. a lead sheath. Why requiring the lead sheath temperature as an isotherm when the jacket temperature varies along the surface almost in the same way? It is thus sufficient to study the average temperatures. The metal sheath temperature is decreased if using a *super-conducting* metal sheath, but this decrease is only attributed to the decrease of T_4 due to the redirection of heat flux towards adjacent cables, as will be shown.

One further concludes that the jacket temperatures become too low according to IEC (Case 4 and 5), implying that the thermal resistance T_4 is too low, or rather the rating is too optimistic. The external thermal resistance for trefoil formation will therefore be analysed further in this paper.

It should be noted that IEC does not make a corresponding adjustment for T_3 for dual and triple flat touching formations, which could be expected, if the same idea would be applied, since the heat flux is partly prevented there as well.

THERMAL RESISTANCE T_4 IN TREFOIL

From the foregoing analysis, it is evident that the jacket thermal resistance should *not* be adjusted by a factor of 1.6. In fact, adjustments for both T_1 and T_3 for other kinds of formations and cable types in IEC, could be questioned by the same reasoning. Instead, one could focus on T_4, from the following perspectives:

- i) Effect of thermal conductivity of metal sheath
  - a. Effect of insulation thermal resistivity
- ii) Effect of spaced copper wires
- iii) Effect of jacket thermal resistivity

The most relevant combinations of the above parameters are analysed below.

In Fig. 6 below, the sensitivity of the metal sheath thermal conductivity is shown, using a parameterization of the jacket thermal resistivity to soil resistivity ratio $r_j = \frac{\rho_j}{\rho_e}$ of 1, 3.5 and 10 in A FEM analysis. The insulation system (layers combined beneath metal sheath) thermal resistivity to soil resistivity ratio $r_i = \frac{\rho_i}{\rho_e}$ is selected to 1 and 3.5 (dotted lines).

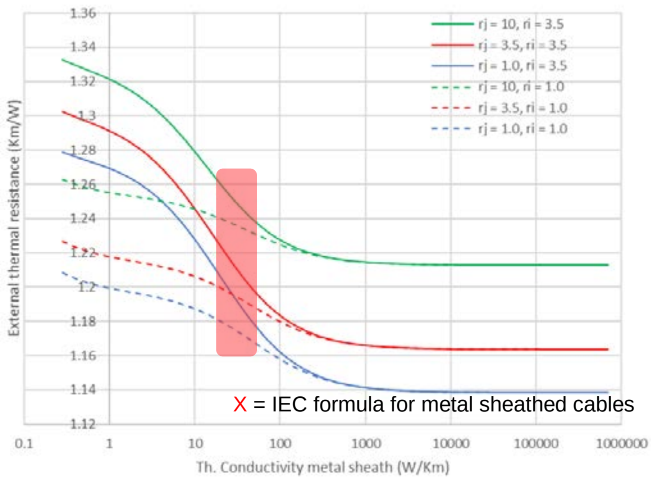

Fig. 6. FEM analysis for sensitivity of T_4 in trefoil formation when r_j and r_i are parameterized.

Above in Fig. 6, practically all metal sheathed cables can be grouped in the red-dashed area, but the IEC formula for trefoil (red cross in Fig. 6) is too optimistic (even when a factor of 1.6 is multiplied with T_3).

The reasons behind the appearance in Fig 6 are mainly three-fold for metal sheathed cables:

- The metal sheaths of *adjacent* cables function as a "thermal shunt" for the heat flux and therefore T_4 varies with metal sheath thermal conductivity.
- The jacket thermal resistivity, if large, will prevent the heat flux to be "thermally shunted" and therefore T_4 varies with jacket thermal resistivity.
- The thermal resistivity beneath the metal sheath (mainly the insulation system) tends to be less sensitive when an ordinary metal sheath is applied to the cables (red-dashed area above). This can be observed by the fact that the difference between the straight and dashed lines vanishes when a lead sheath is applied to the cables.

Now, when comparing T_4 from FEM with Eq. (2) and Eq. (3) the results, shown in Table 2 are obtained. We only compare for $\sigma_{pb} = 35\ W/mK$, meaning Case 2 and 3 from Table 1 are not included. Furthermore, $r_i = 3.5$, for conservative reasons.

Case	Type	r_j	$\bar{\theta}_j$	T_4
1	FEM - 35 (Pb)	1	55.65	1.184
		3.5	56.21	1.207
		10	57.38	1.246
4	IEC-Eq. 2)[1]	N.A.	53.89	1.129
5	IEC-Eq. 2)[2]	N.A.	53.89	1.157
6	IEC-Eq. 3)[3]	N.A.	56.30	1.210

)[1,3] as per Table 1

)[2] The effect of +60% higher T_3 is included in T_4.

Table 2. Comparison of T4 with FEM and IEC.

From Table 2, one concludes that IEC formulas imply a too optimistic rating for touching trefoil formation. This is also true for the other formulas of metal sheathed cables in IEC, for example the *dual* and *triple* flat formations.

The difference in temperature (for this calculation example) between Case 6 and Case 4 and 5, is for 30 W/m power loss between 1.6 to 2.4 K. It should be noted that Eq. 3, i.e., the original equation from the IEC standard from 1969 [2], is far better aligned with FEM.

We now embed a corresponding copper wire screen of 53 mm^2. The wire diameter is 1 mm, and we use 67 wires, with around 3.5 mm spacing, to get a thermal resistance equal to the ordinary lead sheath. We can now again study the effect of copper wires in the lead sheath by varying the thermal conductivity as in Fig. 6. We compare to a pure metal sheath as above.

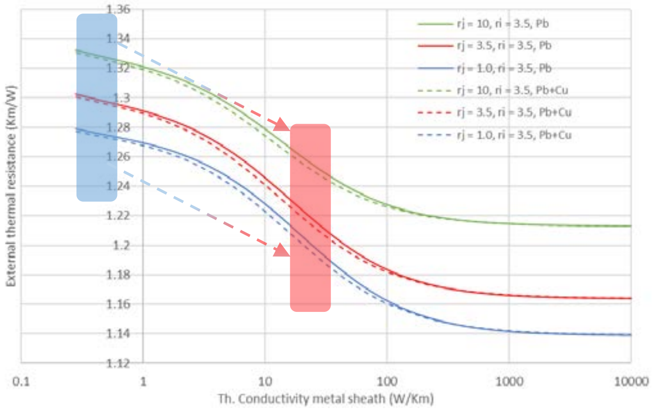

Fig. 7. Sensitivity of external thermal resistance for trefoil formation when spaced wires as embedded in the metal sheath.

Spaced copper wires embedded in low-conductivity inner sheath (PE-sheath) should be referred to the blue-dashed area above. However, the pitch of the copper wire screen is not included and most likely the formula for spaced wires was developed in a 2D FEA. It is possible to show in 3D-FEA, that the pitch of the copper wires, is averaging the surface temperatures, implying an effect equal to the metal-sheathed cables in Fig.2. The heat flux along the copper wire will smooth out the surface temperatures, implying a situation similar to a metal sheath.

Therefore, the blue-dashed area in Fig. 7 should be moved to the red-dashed area, meaning the external thermal resistance T_4 for spaced copper wires could be treated as metal-sheathed cables. The same formulas therefore apply.

Since Eq. (3) is based on the temperature contribution approach from adjacent cables, it is natural to analyze this further. Such an approach is very convenient and straight-forward since it also ease the treatment of dynamic rating [6] and cables installed in stratified soils [5].

However, the ratio r_j for metal sheathed cables could be a relevant parameter used to define a "*thermal proximity factor*" y_m for T_4, since this could make the transition from non-touching to touching formations smoother, without any discontinuity. For this purpose, it is sufficient to investigate the *dual* formation.

THERMAL PROXIMITY FACTOR FOR T$_4$

Now we analyse the ratio r_j's dependence on the separation distance s in *dual* formation, using again a lead sheath (2 mm) with a thermal conductivity of 35 W/mK due to conservative reasons.

Since the external thermal resistance varies strongly with the separation, the reference case is performed with the temperature contribution approach in IEC when $y_m = 1$. This is however modelled in FEM with adjacent line heat sources in soil, to be consistent with the relative changes. At large separations, the actual external thermal resistance is of course not affected by r_j.

The thermal proximity factor $y_m = 1$ when cable gap g is "large", is in practice more than 1m. To cover practically all cases, we let r_j take the values 1 and 12. The average value of $r_j = 6$, for $y_m = 1$ in touching configuration. In Fig. 8, the sensitivity of y_m is shown.

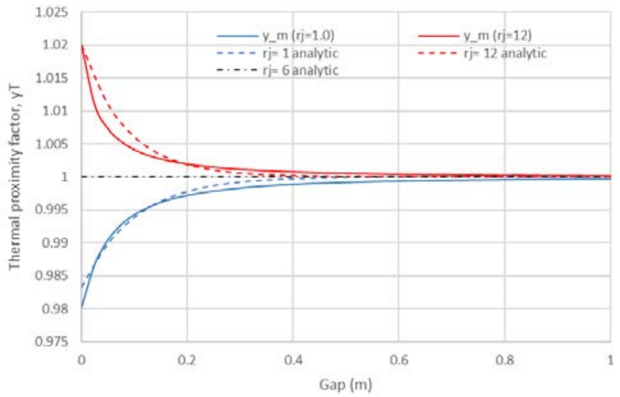

Fig. 8 Sensitivity of y_m

From Fig 8, one concludes that the heat flux is thermally shunted via the metal sheath for low TR of the jacket (blue curve), making y_m slightly less than 1. For high TR (red curve), the heat flux is prevented from being thermally shunted via the metal sheath, making y_m slightly higher than 1.

A common expression for the dependence can be derived from Fig 8 above.

$$y_m = 1 + (n-1)\left(\frac{r_j - \overline{r_j}}{\overline{r_j}}\right)0.02e^{-12g\left|\frac{r_j-\overline{r_j}}{\overline{r_j}}\right|} \quad [13]$$

n: number of cables in the formation (2 or 3). For trefoil and triple formation, the lower and middle cable apply.

g: gap distance between cable outer surfaces (m)

Thus, if one then treats all cables as individuals, irrespective of if they are touching or non-touching, metal sheathed or non-metal sheathed the general temperature contribution formula in IEC could be used, using a small modification by the inclusion of y_m (if needed at all). The complete formula is then for all formations:

$$T_4 = \underbrace{y_m \frac{\rho_e}{2\pi} ln\left(u + \sqrt{u^2-1}\right)}_{T_{4-actual}} + T_{4-mutual} \quad [14]$$

where $T_{4-mutual}$ is calculated by using the temperature contribution approach in IEC.

PROPOSED APPROACH

- All cable temperatures are calculated individually, even for trefoil where the burial depth refers to the actual location.
- No consideration needs to be taken for touching /non-touching discontinuity if a "thermal proximity factor" is used.
- No consideration needs to be taken to the distinction between metal sheathed / non -metal sheathed cables if the effect from the wire pitch is included.
- In case both ends bonding is applied, the adjustment for loss factors on the external thermal resistance should be used for the outer phases as proposed by IEC. This can also in fact be performed individually on each cable. In IEC only an average loss factor is applied for the middle cable.

Case	*Type*	*Trefoil* $u = 10$	*Dual* $u = 5$	*Triple* $u = 5$
7	FEM	1.207)[1]	0.620	0.869)[1]
		1.191)[2]		0.808)[2]
8	IEC-Eq. 2	1.129)[2]	0.589	0.747)[2]
9	Proposal	1.205)[1]	0.622	0.870)[1]
		1.191)[2]		0.807)[2]

Table 3. External thermal resistance T_4 for touching formations using the referenced cable design.

)[1] Lower or middle cable.
)[2] Average of three cables. (If $0.6T_3$ is added for trefoil formation it gives 1.141 Km/W, only).

As mentioned earlier, the Triple formation as per IEC does not align well with FEM or to the proposed approach. The IEC methods for Trefoil and Dual formations are too optimistic, as well.

When the temperature contribution approach is used as in Table 4 below, the conformity is very good.

Case	*Type*	*Trefoil* $u = 10$	*Dual* $u = 5$	*Triple* $u = 5$
10	FEM	0.950)[1]	0.493	0.620)[1]
11	IEC-Eq. 1	0.954	0.493	0.621
12	Proposal	0.949)[1]	0.492	0.618)[1]

Table 4. External thermal resistance T_4 for non-touching (separation/gap = 250/150 mm) formations using referenced cable design.

)[1] Lower or middle cable.

The above approach will also ease the treatment of dynamic rating[6] and stratified soils[5]. For example, the formula for the partial transient for buried cables (§ 4.2.4.1 in [6]) is developed for *individual* positioned cables. Now, one must modify the formula to include touching formations, treated as one cable even if it is in fact two or three cables. As follows, when letting $t \to \infty$, the formula for the partial transient goes towards $\frac{\rho_e}{2\pi}\left(W ln(2u) + \sum_{k=1,p\neq k}^{n} W_k ln\left(\frac{d'_{pk}}{d_{pk}}\right)\right)$ as is used for *isolated (individual)* cables and equals the formula for single cable + temperature contributions in [1].

Thus, we have shown that the use of the IEC touching formulas is not very robust and do not agree with FEM and the approach proposed. *IEC prescribes an isotherm on the metal sheath, only, but at the same time allows another virtual diameter = isotherm for the touching formation outside the formation. This is illogical*. Furthermore, the division in metal sheathed/non-metal sheathed cables is not necessary, since it is not a requirement that the metal sheath surface temperature must be an isotherm for T_1, T_3 and T_4 to be accurately calculated and if copper wires screens include the effect of the pitch. The jacket resistance should not be multiplied with a factor of 1.6. The external thermal resistance discontinuity from non-touching to touching formations can be resolved by a "thermal proximity factor", but still the ordinary temperature contribution approach in IEC may be sufficiently good. However, for any TR value of the jacket, the proposed approach is an improvement.

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[6] IEC 60853-2, Calculation of the cyclic and emergency current rating of cables – Part 2 1989