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Study Committee B1

Insulated Cables

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Determination of soil thermal resistance: A holistic approach

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Motivation

- Soil thermal resistance has a severe impact on the current rating calculations of modern cable projects
- Multilayer soil, backfill materials and adjacent cables must be considered as accurately as possible
- Various analytical and numerical approaches exist, all based on the application of superposition principle
- The validity of this principle is rather questionable in cases where the cables are placed in proximity
- This work presents a new, holistic approach to the determination of soil thermal resistance, overcoming the above limitation

Method/Approach

- Determination of the so-called ***thermal conductance matrix*** G $[WK^{-1}m^{-1}]$ by employing FEM and without resorting to the superposition principle:

$$Q = G\Delta\theta$$

where $\Delta\theta$ [°C] the column vector of temperature rise of all cable surfaces with respect to temperature soil surface, and Q $[Wm^{-1}]$ the column vector of total power losses per unit length of all cables

- Conceptual example with two adjacent cables, randomly laid in an arbitrary multilayer soil

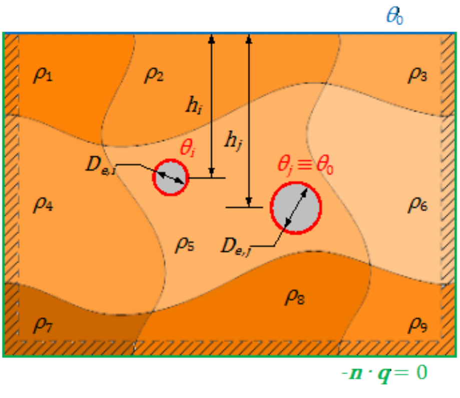

Figure 1: Indicative FEM representation of multilayer soil with two randomly laid adjacent cables. Inclusion of appropriate boundary conditions for the calculation of column *i* in matrix G.

- Heat transfer in solids under steady-state conditions in FEM
  - Top soil surface – Kennelly hypothesis with Dirichlet boundary condition
  - Rest soil edges – Coordinate scaling to infinity and Neumann boundary condition
  - Cable surfaces – Consecutively setting one to arbitrary and remaining to ambient temperature with Dirichlet boundary condition
- After the solution of the thermal problem, Q dissipated or absorbed by each cable is calculated by numerical integration
- Column i of G is determined (column-wise manner):

$$G_{ii} = \frac{Q_i}{\Delta\theta_i} = \frac{Q_i}{\theta_i - \theta_0}$$
$$G_{ji} = -\frac{Q_j}{\Delta\theta_i} = -\frac{Q_j}{\theta_i - \theta_0}$$

- The total execution time can be reduced by exploiting possible matrix symmetry of G
- By inverting G, the final thermal resistance R matrix is obtained

System under study

- Typical underground cable with D_e equal to 100 mm
- Investigation of different installation cases of buried underground cables
- Comparison with analytical and numerical approaches
- Relative difference:

$$err = \frac{R^{proposed} - R^{other}}{R^{proposed}} 100\%$$

Numerical results – Two single-core cables in flat formation

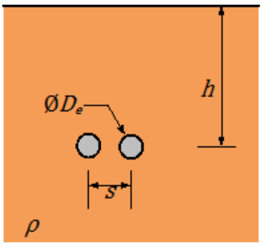

Figure 2: Two single-core cables in flat formation.

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Determination of soil thermal resistance: A holistic approach (continued)

- Matrices G and R of order 2×2

$$G = \begin{bmatrix} G_{11} & G_{12} \\ G_{12} & G_{11} \end{bmatrix} \rightarrow R = \begin{bmatrix} R_{11} & R_{12} \\ R_{12} & R_{11} \end{bmatrix}$$

- Due to cable symmetry, only one column needs to be calculated

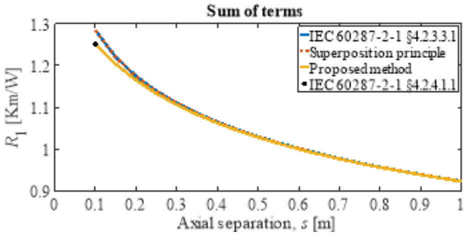


Figure 3: Two single-core cables in flat formation. Sum of thermal resistance matrix.

- Results from the first two methods coincide, leading to more conservative results
- For touching cables, the proposed method agrees with IEC standard
- For larger axial distances, all methods converge

Numerical results – Three single-core cables in flat formation

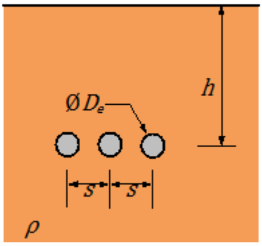


Figure 4: Three single-core cables in flat formation.

- Matrices G and R of order 3×3

$$G = \begin{bmatrix} G_{11} & G_{12} & G_{13} \\ G_{12} & G_{22} & G_{12} \\ G_{13} & G_{12} & G_{11} \end{bmatrix} \rightarrow R = \begin{bmatrix} R_{11} & R_{12} & R_{13} \\ R_{12} & R_{22} & R_{12} \\ R_{13} & R_{12} & R_{11} \end{bmatrix}$$

- Due to cable symmetry, only two columns need to be calculated
- Similar conclusions with the case of two single-core cables in flat formation

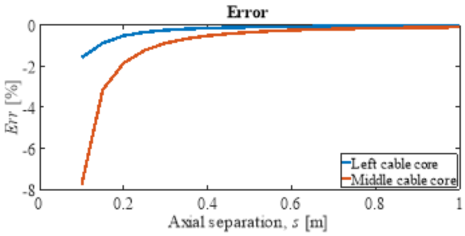


Figure 5: Three single-core cables in flat formation. Relative error for left and middle cable cores.

Numerical results – Three single-core cables in trefoil formation

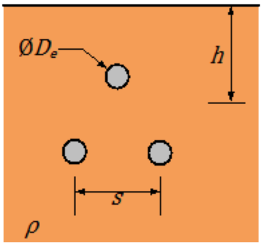
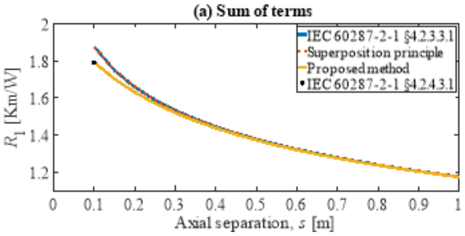


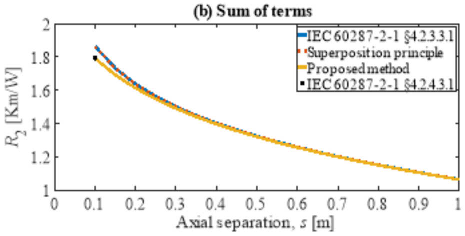
Figure 6: Three single-core cables in trefoil formation.

- Matrix structure as in the case of flat formation
- Similar conclusions with the previous cases

(a) Sum of terms



(b) Sum of terms



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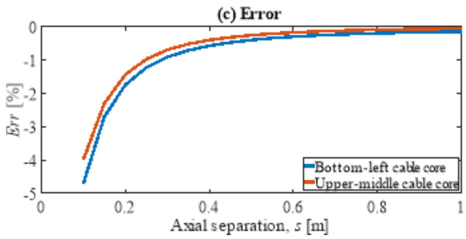


Figure 7: Three single-core cables in trefoil formation. Total thermal resistance of (a) bottom left and (b) upper-middle cable with respect to axial separation. (c) Relative error for both cable cores.

Numerical results – Effect on current rating

- The effect of T_4 on current rating gives a more meaningful and informative outcome
- Maximum design temperature of 90 °C
- Typical cable with AL conductor 1200 mm^2
- Cross-bonding configuration with equal minor sections
- Flat formation of cables enclosed in a backfill

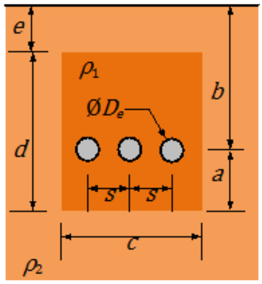
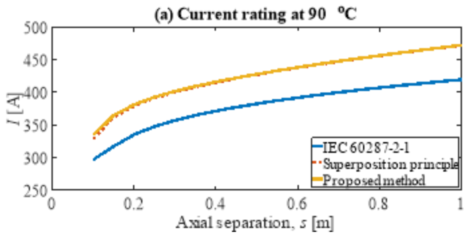


Figure 8: Three single-core cables in flat formation installed within a backfill.



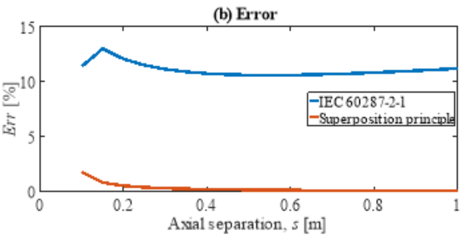


Figure 9: Three single-core cables in flat formation within a backfill. (a) Current rating and (b) relative error between existing and proposed methods.

- Current rating between the proposed method and the superposition principle deviate for cables in closer physical proximity
- Difference with the IEC standard is pronounced, since the latter cannot consider the multilayer soil thermal resistance

Conclusion and future work

- New, holistic approach for the calculation of the external cable thermal resistance T_4
- Calculation of the so-called thermal conductance matrix G without relying on the superposition principle
- High accuracy even in cases of touching cables, where other methods fail
- Ability to consider multilayer soil, backfill materials and adjacent cables in any distance
- Fully compatible with IEC standard formulation in terms of current rating
- Cannot include nonlinear phenomena such as the effect of moisture migration
- Restricted to steady-state thermal conditions
    - A time domain solution is currently being developed and will be presented in the future