

Current Rating of Cables Placed at Metallic Ducts Using COMSOL Multiphysics®

C. Boikos, D. Gkitsos, A. Neginhal, P. Parissis, P. Zairis, and D. Chatzipetros
Hellenic Cables, Athens, Greece.

Abstract

Power cables are frequently installed inside ducts for mechanical protection, creating thermal conditions that may limit cable current-carrying capacity. Existing analytical heat transfer approaches for ducted cable rating assume concentric cable placement within the duct, whereas in practice cables mostly rest at the bottom of the duct due to their gravity. This discrepancy becomes particularly important in metallic ducts, where cable position affects total magnetic flux linkage and, consequently, electromagnetic, induced losses. This paper presents a COMSOL Multiphysics® modelling approach that combines analytical heat transfer methods with realistic electromagnetic modelling through a two-component framework. The heat transfer component preserves the concentric cable arrangement required by analytical formulae, while a separate magnetic-fields component captures the actual bottom cable placement and the resulting duct losses. A comparison with CFD modelling demonstrates that the proposed approach provides a more realistic representation of metallic duct losses, while maintaining significantly lower computational requirements. Parametric analyses were performed considering duct-to-cable diameter ratio, duct thickness, and duct emissivity. The duct-to-cable diameter ratio is the dominant factor, increasing duct loss factor by up to 18% and conductor temperature by 8.7 K. Bottom cable placement produced up to 13.7 K higher conductor temperatures than concentric placement. Among the evaluated heat transfer methods, IEC standard [1] was the least conservative for a typical metallic duct emissivity value, highlighting its uncertainty in the radiative heat transfer calculations. The proposed approach provides an efficient and practical tool for improving current rating studies of cables installed in metallic ducts while avoiding the computational burden of CFD simulations. **Keywords:** CFD, current rating, ducted cables, electromagnetics, FEM, heat transfer.

Introduction

Power cables are essential components of modern power systems, transmitting electric power over long distances, and supporting the green energy transition. For mechanical protection, when cables are installed underground or beneath the seabed, they are frequently routed through circular ducts. Inevitably, these ducts create unfavourable thermal conditions for the cabling system making this part of the route a potential thermal bottleneck. Therefore, studying heat transfer between the cable and the duct is of great importance in current rating studies.

To study heat transfer in air-filled ducts, several approaches have been developed to account for the occurring heat transfer mechanisms, namely convection and radiation. The IEC 60287-2-1 Standard provides an analytical formula for the calculation of a combined convective and radiative thermal resistance (T_4) of the unfilled duct [1], depending on the duct and fluid material, average fluid temperature and cable diameter. An applicability range is specified for the cable diameter. This formula is also adopted by CIGRE TB 963 [2], showcasing its application to Finite Element Method (FEM) studies and extending its applicability to even larger cable diameters. Another analytical formula, which defines an effective thermal conductivity of the duct fluid and accounts

for convective effects, is proposed by [3]. When applicable, surface-to-surface radiation physics is commonly combined with the latter approach ([4], [5]).

The analytical approaches of [1], [2], and [3] assume concentric placement of the cable inside the duct and isothermal cable and duct boundaries. In reality, the temperature may vary by 5-10 K along these boundaries, and the cable is typically installed at the bottom of the duct. Most importantly, when the surrounding duct is metallic, additional electromagnetic (EM) loss is generated due to the time-varying EM field. This loss may deviate significantly depending on the cable position inside the duct due to the occurring proximity effects. Proper EM modelling is therefore necessary to accurately account them [5].

To account for the actual physics, Computational Fluid Dynamics (CFD) models can be applied [4], [6], where the fluid flow and heat transfer inside the duct are resolved. However, CFD modelling requires an additional physics interface in COMSOL Multiphysics®, thereby increasing the required level of physics expertise, model setup complexity, and computational burden. In contrast, the analytical approaches presented in [1], [2], and [3] are simpler to implement, requiring less modelling effort and a lower level of physics expertise from the user.

In this work, a modelling technique is proposed in which analytical heat transfer approaches are applied, while preserving the actual cable placement. Specifically, a two-component approach is introduced. The first component accounts for the heat transfer physics, where the analytical approaches are applied assuming concentrically placed cables inside the duct, while the second component accounts only for the electromagnetic physics and the actual cable placement inside the duct, i.e., at its bottom. A practical workflow for model setup, meshing, and execution is presented. The analysis also provides detailed guidelines on the modelling techniques and the physics involved in ducted cable installations.

Theory and Challenges

The total thermal resistance (T_4) of the cable's environment is described in the following equation:

$$T_4 = T'_4 + T''_4 + T'''_4 \quad (1)$$

where T'_4 , T''_4 , and T'''_4 are the thermal resistances of the fluid, the duct and the surrounding soil, respectively.

The IEC 60287-2-1 Standard [1] and the CIGRE TB 963 [2] propose the following analytical formulae for the calculation of the fluid thermal resistance (T'_4) and the equivalent thermal resistivity (ρ_{eq}) between the cable and the duct in current rating studies:

$$T'_4 = \frac{U}{1 + 0.1(V + Y\theta_m)D_e} \quad (2)$$

$$\rho_{eq} = \frac{2\pi \cdot T'_4}{\ln(D_d/D_e)} \quad (3)$$

where U , V , and Y are semi-empirical constants, depending on the duct and the gap-filling materials, D_e is the external or the equivalent diameter of the cable in mm, D_d the internal diameter of the duct in mm and θ_m is the mean temperature of the filling material in °C.

While the IEC 60287-2-1 Standard method [1] confines the use of (1) at D_e values up to 100 mm and 125 mm for single and three cables in duct, respectively, CIGRE TB 963 [2] extends its applicability to even larger cable diameters. It is noted that ρ_{eq} constitutes an equivalent thermal resistivity accounting for both convective and radiative (when applicable) heat transfer effects. An alternative analytical formula only for convective heat transfer in fluid-filled ducts is presented in [3]:

$$\rho_{eq,conv} = \frac{1}{0.386k} \left(\frac{0.861 + Pr}{Pr} \right)^{\frac{1}{4}} \frac{1}{Ra^{\frac{1}{4}}} \quad (4)$$

where k is the thermal conductivity of the fluid, Pr and Ra is the Prandtl and Rayleigh number, respectively. When (4) is applied, additional modelling of radiative heat transfer is needed in case fully transparent media fill the duct interior.

The main disadvantage of the approaches presented in [1], [2], and [3] is that they assume concentric placement of the cable inside the duct (Figure 1a), whereas, in practice, the cable mostly rests at the bottom of the duct under the influence of gravity (Figure 1b), leading to noticeable deviations in the results. These deviations can become even more significant in metallic duct installations, where the discrepancy in cable placement inside the duct affects the additional loss generated due to electromagnetic induction and the stronger proximity effects.

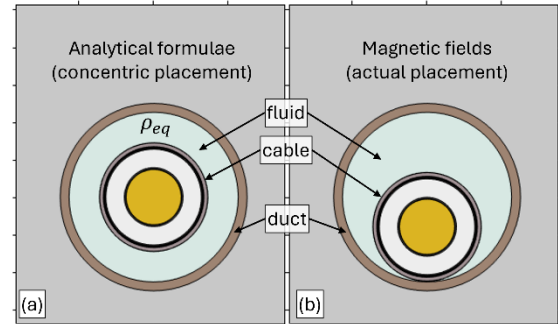


Figure 1. Cable placement inside duct (a) assumed from analytical formulae [1], [2], and [3]; (b) in actual installation.

Proposed Approach

To deal with the discrepancy in cable placement inside the duct, an approach that combines concentric cable placement of heat transfer approaches [1], [2], and [3] and bottom-placed cable in EM modelling is proposed. In this approach, two separate components are created, one solely accounting for Heat Transfer (HT) physics and one for Magnetic Fields (MF) physics, which are coupled under the same COMSOL Multiphysics® file.

Heat Transfer (HT) Component (component 1)

In this component, Heat Transfer in Solids and Surface-to-Surface (S2S) radiation, where applicable, are coupled in COMSOL Multiphysics®. The cable is concentrically placed respecting the analytical formulae assumptions (Figure 1a). The average temperature of the electromagnetically active parts is calculated, in order for it to be used in the MF component.

Magnetic Fields (MF) Component (component 2)

In this component, only the MF physics is activated and the cable is positioned at the bottom of the duct (Figure 1b). A separate coil domain is defined for each electromagnetically active part. The electrical resistivity of those coil domains is calculated at the aforementioned average temperature, as obtained by the HT component. Then, the average volumetric loss density (W/m³) of each metallic part is imported to the corresponding domains of the HT component. Particular attention should be paid to mesh generation when cables are installed inside metallic ducts. Under AC operation, skin effect develops near the inner surface of the metallic duct, since it is closer to the cable. To accurately capture this phenomenon, either a finer mesh can be applied within the duct domain or, even better, a boundary-layer mesh can be created along the inner duct surface. Skin depth can be expressed as follows [7]:

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (5)$$

where f is the frequency of AC, and μ and σ the duct's magnetic permeability and electrical conductivity, respectively.

A boundary-layer mesh is then applied along the inner surface of the duct. For the purposes of this study, 10 boundary layers of equal thickness (0.25δ) were employed to accurately capture skin effect within the duct wall (Figure 2).

While coupling MF with HT physics could be implemented through Electromagnetic Heating Multiphysics under the same component, a common geometry should be shared in such a case. The proposed approach of two components effectively couples the two different physics overcoming the common-geometry restriction when physics are coupled under a single component.

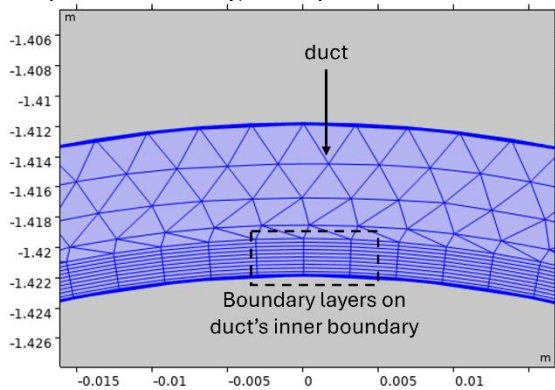


Figure 2. Boundary layer meshing inside the metallic duct.

Case Study

Installation

A circuit consisting of three 1200 mm² Cu conductor cables with aluminium sheaths in flat formation is considered. The outer cable diameter is about 104 mm. The cables are installed in separate air-filled ducts, spaced 1.5 m apart and buried 1.5 m below the soil surface. The cables are assumed to operate at an AC of 1260 A RMS and a frequency of 50 Hz, with an applied phase-to-phase voltage of 220 kV. The cable sheaths are assumed single-point bonded. For scenarios with metallic duct installations, ducts were assumed to be open bonded, as they are not actually grounded. The thermal resistivity of the surrounding soil is 1 Km/W. Ambient temperature was considered equal to 25 °C. A two-dimensional (2D) analysis was conducted, considering adequately large cable routing.

Boundary Conditions and Excitations

Figure 3 presents the boundary conditions (BCs) applied in the 2D FEM model. An isothermal boundary condition is imposed at the soil surface, with the temperature set equal to the ambient temperature. Infinite Element Domains are applied along the outer boundaries of the soil, effectively extending the solution domain to infinity [8]. Thermal Insulation BCs are applied at the outer boundaries of the infinite domains. The HT geometry is confined by the infinite domains at the latter and bottom sides, and the soil surface at the top side. In the MF geometry, an additional domain above the soil surface with top infinite element domain is considered to represent the open space for the magnetic field.

Where applicable, HT with S2S radiation physics is considered between the cable and the inner boundaries of the duct [5]. The heat sources are defined in the MF component by applying the aforementioned AC to all phases, with phase differences of +120°, 0°, and -120° for the leading, centre, and lagging phase conductors, respectively. For the cable sheaths and metallic ducts, the current excitation is set to 0 A, as they are single-point and open bonded, respectively [2].

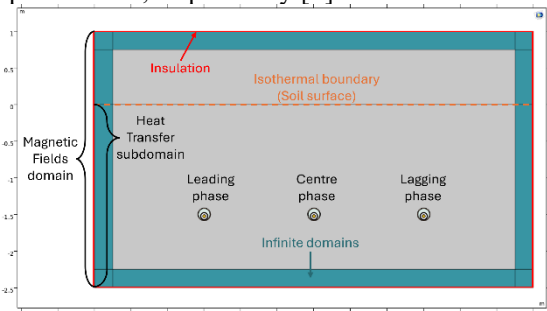


Figure 3. 2D FEM model and applied boundary conditions.

Existing Heat Transfer Approaches

An initial thermal analysis was conducted to compare the analytical approaches [1] and [3] with the COMSOL Multiphysics® CFD model, which was considered the benchmark, for both plastic (HDPE) and metallic (stainless steel) duct installations. The emissivity of the plastic ducts was set to 0.9. For metallic ducts, emissivity was set to 0.5, representing the average value obtained from in-house measurements. The thermal and electrical properties of the materials were defined according to IEC 60287-1-1 Standard [9] CIGRE TB 963 [2]. In approaches [1] and [3], the cables were placed concentrically within the ducts, whereas in the CFD model, the cables were positioned at the bottom of the ducts. The duct inner diameter was set to 1.5 times the cable diameter with a wall thickness of 10 mm.

Figure 4 presents the temperature and velocity fields of the centre (hottest) phase for the plastic duct installation, as obtained using the analytical approaches and the CFD model.

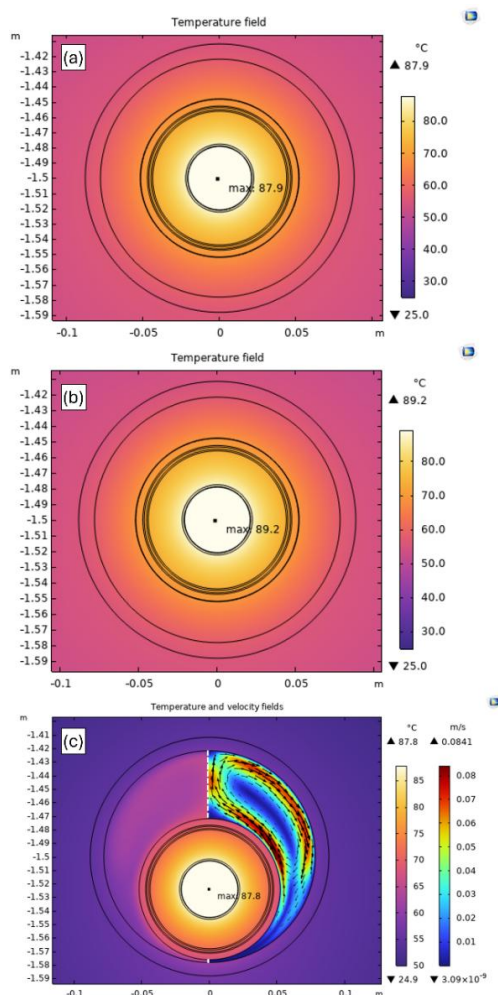


Figure 4. Temperature and velocity fields for plastic duct installation on centre phase: (a) IEC approach [1]; (b) approach [3]; (c) CFD modelling.

Approaches [1] and [3] result in maximum conductor temperatures of 87.9°C and 89.2°C, respectively, while the CFD model predicts a maximum conductor temperature of 87.8°C. Similar results are observed when comparing the thermal resistance of the air-filled duct for the various methods, with the CFD model emerging as the least conservative approach (Table 1). The IEC approach [1] shows better agreement with the CFD model (used as the benchmark) than approach [3], resulting in a conductor temperature that is only 0.1 K higher than the benchmark value. Another key factor in selecting the most appropriate approach is the simulation time, as well as the underlying theoretical framework. As shown in Table 1, the IEC approach [1] provides a very fast solution, whereas approach [3] requires approximately an order of magnitude more computational time. CFD modelling demands three to four orders of magnitude more computational time, making it potentially prohibitive for typical engineering studies.

The reason for these differences in computational time lies in the theoretical basis of each approach and the heat transfer phenomena considered. In the IEC approach [1], only conduction is explicitly modelled, with the air-filled duct represented by an equivalent solid material having an effective thermal resistivity that incorporates both convection and radiation effects. In approach [3], an equivalent solid material resistivity is also adopted to account for convection, while radiation is modelled separately, resulting in increased computational requirements. In CFD modelling, in addition to radiation, fluid flow and turbulence are explicitly simulated, leading to significantly higher computational demands.

Table 1. Maximum conductor temperature and air thermal resistance of the centre phase for plastic duct installation for IEC [1], approach [3], and CFD modelling.

	$T_{c,max}$ [°C]	T'_4 [Km/W]	Simulation time
IEC [1]	87.9	0.281	2 min
Appr. [3]	89.2	0.311	21 min
CFD	87.8	0.266	542 min

Table 2 presents the maximum conductor temperature of the centre phase, the air thermal resistance, and the loss factor of the duct ($\lambda_{2,duct}$), expressed per conductor loss, for the metallic duct installation. A temperature rise of approximately 2 K is observed with the proposed approach (two components) compared to the one-component approach in both [1] and [3]. This can be attributed to the stronger proximity effects in the duct predicted by the proposed approach, as the cable is placed closer to the duct wall, resulting in higher loss factor

(0.062) than that obtained with the one-component approach (0.007). For the same reason, the model involving CFD results in similar duct loss.

Adopting the proposed approach, which better accounts for duct losses, brings the IEC [1] results closer to the CFD predictions in comparison with the one-component method, whereas the results of [3] tend to deviate from the CFD model. The CFD-calculated air thermal resistance (0.333 Km/W) and conductor temperature (89.4°C) lie between the values predicted by IEC [1] (0.230 Km/W, 85.0°C) and [3] (0.401 Km/W, 92.3°C). It can therefore be argued that the IEC method [1] does not provide conservative results for metallic duct installations, contrary to the analysis for the plastic duct installation (Table 1). Nevertheless, this behaviour may be partly attributed to the uncertainty regarding the wide range of metallic duct emissivity [10]. In this analysis, we have assumed an emissivity of 0.5 when applying both CFD modelling and [3], whereas IEC Standard [1] provides no information regarding duct emissivity. Even when a duct emissivity of 1 is adopted using the two-components approach, CFD modelling and [3] predict conductor temperatures that are 2.9°C and 1.2°C higher than those obtained from IEC model [1], respectively, further highlighting the uncertainty into the radiative heat transfer calculations of the IEC Standard [1]. It is also proved that the assumption of an emissivity of 0.5 in S2S radiation module is rather conservative. Although CFD is considered the benchmark heat transfer approach, it requires substantially greater computational resources. For this reason, it is not included in the analysis that follows.

Table 2. Maximum conductor temperature, air thermal resistance and duct loss factor of the centre phase for metallic duct installation for IEC [1], approach [3], and CFD modelling approaches.

	$T_{c,max}$ [°C]	T'_4 [Km/W]	$\lambda_{2,duct}$ [-]
IEC [1] one comp.	83.2	0.233	0.007
IEC [1] two comp.	85.0	0.230	0.062
Appr. [3] one comp. ($\epsilon: 0.5$)	90.5	0.405	0.007
Appr. [3] two comp. ($\epsilon: 0.5$)	92.3	0.401	0.061
Appr. [3] two comp. ($\epsilon: 1$)	87.9	0.299	0.062
CFD ($\epsilon: 0.5$)	89.4	0.333	0.057
CFD ($\epsilon: 1$)	86.2	0.259	0.057

Similar results were also obtained for cables installed in trefoil formation inside a common

stainless-steel duct. An equivalent diameter 2.15 times greater than the cable diameter was used in equations (2)-(4) in both [1] and [3], as reported in IEC Standard [1]. The two-component approach resulted in a conductor temperature 1.2°C higher than that predicted by the one-component approach for both [1] and [3].

Considering a duct emissivity of 0.5, [3] was found to be the most conservative approach cables installed in individual ducts and for cables arranged in a trefoil formation within a common duct, while [1] was the least conservative. CFD modelling yielded intermediate results. This behavior aligns with [6] for similar cable sizes, whereas for older-generation cables, which are typically smaller, [1] becomes the most conservative approach. Conductor temperatures similar to those predicted by [1] were obtained for duct emissivity values greater than 0.8. This demonstrates that adopting [3] together with a duct emissivity of 0.5 for metallic ducts results in more conservative thermal predictions than those obtained using the IEC Standard [1].

Parametric Analysis

In this section, the effect of several parameters on metallic duct losses and, consequently, on the thermal behaviour of the cable is examined. The parameters investigated are the ratio of the duct inner diameter to the cable outer diameter (diameter ratio), the duct thickness, and the duct emissivity. The corresponding values for the baseline scenario are 1.5, 10 mm, and 0.5, respectively. The range of the parameter values examined was selected to be representative of real cable installations.

Figure 5 presents the influence of the diameter ratio on the maximum conductor temperature, air-gap thermal resistance (T'_4), and metallic duct losses for the one-component method and the proposed approach (two-component method) on the centre phase. For high diameter ratios, metallic duct losses become up to 17.2 W/m higher in the proposed approach than in the one-component approach.

In the one-component approach, the gap between the cable and the duct increases uniformly with the duct-to-cable diameter ratio, whereas in the proposed approach the cable remains positioned at the bottom of the duct. Consequently, in the proposed approach, higher loss is generated in the duct, worsening the thermal behaviour of both the duct and the cable. As a result, the conductor temperature increases by up to 8.7 K with increasing diameter ratio in the proposed approach, whereas it decreases by up to 4.3 K in the one-component approach, leading to a maximum temperature difference of 13.7 K between the two approaches. The thermal resistance of the air gap exhibits only minor variations in both methods, indicating that the observed temperature differences

are primarily driven by the different predictions of metallic duct losses rather than by changes in the heat-transfer characteristics of the air gap.

Similarly, Figure 6 presents the effect of duct thickness on the thermal behaviour of the cable. Duct loss factor increases with duct thickness by 0.002 over the examined thickness range for the proposed approach and by 0.07 for the one-component approach, resulting in 3.4 W/m higher duct losses. In the proposed approach, this translates into a 1.3 K temperature rise in conductor. In contrast, conductor temperature drops by 0.3 K in the one-component approach, indicating that the relatively small increase in duct losses has a negligible effect on the cable thermal behaviour due to its concentric placement within the duct. This temperature reduction can be attributed to the increase in duct thickness, which reduces the overall thermal resistance of the duct-soil system ($T_4'' + T_4'''$). The maximum conductor temperature difference between the two approaches occurs at 22 mm duct thickness.

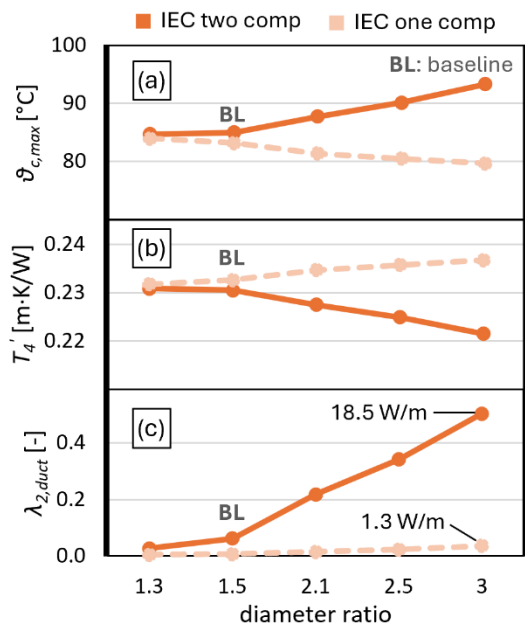


Figure 5. (a) Maximum conductor temperature; (b) air gap thermal resistance; (c) metallic duct loss factor for different diameter ratios for the centre phase, according to IEC approach [1].

An analysis of the metallic duct emissivity was conducted, as a wide range of stainless-steel emissivity values has been reported in the literature [10]. For this analysis, convection was modelled according to the analytical approach presented in [3], while radiation was resolved using the Surface-to-Surface Radiation physics interface in COMSOL Multiphysics® [5], since the IEC Standard [1] assumes an equivalent thermal resistivity for both convection and radiation. Figure 7 illustrates the effect of metallic duct emissivity

on cable thermal behaviour, considering different emissivity values. The results are compared with the IEC approach [1].

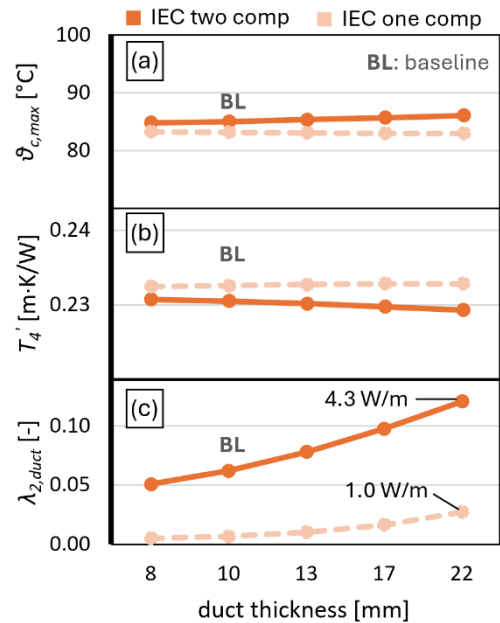


Figure 6. (a) Maximum conductor temperature; (b) air gap thermal resistance; (c) metallic duct loss factor for different duct thicknesses for the centre phase, according to IEC approach [1].

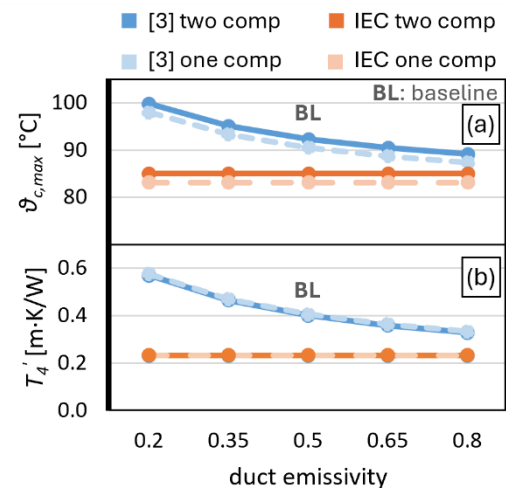


Figure 7. (a) Maximum conductor temperature; (b) air gap thermal resistance for the centre phase for different duct emissivity values according to approach [3] and IEC approach [1].

As emissivity increases, radiative heat transfer is enhanced, improving heat dissipation to the environment. Consequently, both the air thermal resistance and the maximum conductor temperature decrease by up to 0.24 Km/W and 10.6 K, respectively. Furthermore, in the proposed approach, the conductor temperature remains 1.8 K higher than

in the one-component model across the examined emissivity range, as a result from the higher metallic duct losses. Results from [3] tend to converge towards the IEC [1] as emissivity increases, which is consistent with the findings reported in [6].

Conclusions

This paper introduces an approach that considers bottom-placed cable inside a metallic duct to properly account for electromagnetic losses generated in the duct while respecting the concentric placement required by analytical heat transfer methods. A preliminary thermal analysis between two analytical heat transfer methods ([1], [3]) and CFD modelling, showcased that the adoption of the proposed approach can lead to noticeable differences in the thermal behaviour of the cable compared to a concentric cable placement as analytical methods propose.

Parametric analyses of the duct-to-cable diameter ratio, duct thickness, and duct emissivity were then conducted under a constant AC of 1260 A. The diameter ratio emerged as the most influential parameter, increasing the duct loss factor ($\lambda_{2,duct}$) by up to 18% within the examined range and consequently causing a conductor temperature rise of up to 8.7 K. Comparison of the proposed approach with that assuming concentric cable placement showed up to 13.7 K higher conductor temperatures due to the increased losses generated in the metallic duct resulting from bottom cable placement.

Different heat transfer methods were also compared, including CFD modelling and the analytical approaches of [1] and [3]. For a metallic duct emissivity of 0.5, which is a typical value, [3] was found to be the most conservative approach, while [1] was the least conservative, for cables installed both in individual ducts and in a common duct with trefoil formation. CFD modelling yielded intermediate results. For cables installed in individual ducts, even at an emissivity of 1, CFD modelling and [3] predicted higher conductor temperatures than [1], highlighting the uncertainty in the radiative heat transfer calculations of IEC Standard [1].

Overall, modelling the thermal behaviour of a cable installed inside a metallic duct can significantly be affected by its placement inside it, as induced losses are affected by its proximity to the cable. When analytical heat transfer approaches, like [1] and [3], are applied, under the burden of the prohibitive computational cost of advanced methods, like CFD modelling, the proposed approach with the two components can constitute a useful tool in current rating studies as it can efficiently combine the concentric cable placement demanded by the analytical methods, while respecting the actual cable

placement in the magnetic fields problem and correctly accounting for the generated electromagnetic losses.

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