

# Ampacity simulation of a high voltage cable to connecting off shore wind farms

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**Abstract:** The ampacity of a cable depends on the cross-section of its conductor. When selecting a cable design for a specific application, it is of interest to choose the lowest possible conductor cross-section in order to reduce material costs. Therefore, an exact calculation of the ampacity is necessary; it is usually limited by the thermal resistance of the insulating cable materials. Commonly, the ampacity is determined using semi-empirical methods to evaluate the maximum temperatures. These methods include safety margins that may result in low ampacity values. In this study, COMSOL Multiphysics is used to determine temperature conditions in a high-voltage cable connecting offshore wind turbines. It is shown that the conventional analytical methods do not apply to the given conditions and the simulation is able to demonstrate alternative methods to determine the ampacity.

**Keywords:** cable ampacity, thermal resistance, heat conductivity, temperature profile, cable simulation

## 1. Introduction

The procedure for cable design is described in the ICE standard. One of the typical demands to be observed is the maximum permissible temperature of the conductor, in particular with a view to keeping the temperatures in the insulation material low. To meet this demand, it is usual to select a cable cross-section appropriate to the desired maximum current, as the conductor cross-section directly influences the heat losses arising in the conductor concerned. As the costs of conductor materials are very high, precise calculation of the current carrying capacity is of extreme importance. The ICE standard describes the procedure for calculation of this capacity in accordance with defined limit temperatures. The calculations are based on simple heat conductivity calculations and semi-empirical models.

In the following, two simple examples are first presented to illustrate the comparison

between the standardised ICE calculation and a COMSOL simulation. Furthermore, it is to be shown that COMSOL Multiphysics may serve as an alternative to conventional calculation methods, particularly where an increasingly complex cable structure and cable periphery is to be taken into account.

## 2. Comparison of ICE calculation and COMSOL simulation

### 2.1 Single-conductor cable

For the first example, the ampacity of a single-conductor cable is determined in accordance with a maximum permissible conductor temperature.

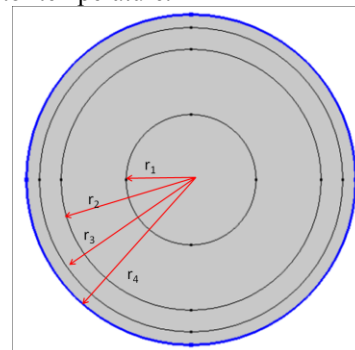


Figure 1. Geometry of single-conductor cable

As this case is a simple calculation of radial heat conduction, it can be assumed that the calculated results will coincide with the simulation. The equations shown here are taken from the standard calculation.

The first step for calculation of the ampacity is to determine the thermal resistance of the individual cable layers using Eq. (1).

$$R_n = \frac{1}{2 \cdot \pi \cdot \Lambda_n} \cdot \log\left(\frac{d_n}{d_{n-1}}\right) \quad (1)$$

The temperature differences between the individual layers are determined using Eq. (2):

$$dT_n = Q \cdot R_n \quad (2)$$

The heat flow is calculated by way of the power loss in the conductor, namely in accordance with Eq. (3) and (4):

$$Q = n \cdot I^2 \cdot R_{wr} \quad (3)$$

$$R_{wr} = R_{20^\circ C} \cdot \left[ 1 + \alpha_{20} \cdot (v_{Lr} - 20) \right] \quad (4)$$

Both convective cooling and ambient heat radiation are assumed at the surface of the cable. To describe the corresponding heat flow, separate heat transfer coefficients are determined for the convection and radiation components and then combined into a thermal resistance relating to the ambient temperature. The convective heat transfer coefficient is calculated with:

$$\alpha_{convective} = k_{1,s} \cdot \frac{0.0185}{k \cdot d_{cable}} + k_{2,s} \cdot 1.08 \cdot \left( \frac{dT_{surface}}{k \cdot d_{cable}} \right)^{1/4} \quad (4)$$

The constants  $k_{1,s}$ ,  $k_{2,s}$  are calculated using the following empirically determined models:

$$k_{1,s} = 0.919 + \frac{(T_{surface} - T_{ambient})}{2.369} \quad (5)$$

$$k_{2,s} = 1.033 - \frac{(T_{surface} - T_{ambient})}{2.909} \quad (6)$$

The heat transfer coefficient to take into account the radiation is calculated using the emission coefficient  $\varepsilon$  and the Stefan Boltzmann constant  $\sigma$  in the equation:

$$\alpha_{radiation} = \frac{\varepsilon \cdot \sigma \cdot \left( (273.15 + T_{surface})^4 - (273.15 + T_{ambient})^4 \right)}{dT_{surface}} \quad (7)$$

These factors are converted into a thermal resistance relative to the environment:

$$R_{surface/ambient} = \frac{1}{\pi \cdot d_{cable} \cdot (\alpha_{convection} + \alpha_{radiation})} \quad (8)$$

The arising temperature difference between the conductor surface and the cable surface thus amounts to:

$$dT_{surface} = Q \cdot \left( \sum_{n=1}^{N_{layer}} R_n + R_{surface/ambient} \right) \quad (9)$$

By way of Eq. (2), it is then also possible to determine the temperatures of the individual layers. To calculate the ampacity, a maximum conductor temperature is specified, and the corresponding maximum permissible current is determined by iteration.

To compare the calculation model based on the aforementioned equations with a COMSOL simulation, a corresponding model can be established in COMSOL. Figure 1 shows the first model. To calculate the ampacity, the *Heat Transfer in Solids* mode is used. To this end, a *Heat Source* is defined in the conductor in accordance with Eq. (3) and (4).

Equivalently to the ICE model, a *Convective Cooling* boundary condition is also applied at the cable surface, based on Eq. (4) and (7).

For iteration of the ampacity, an additional global constraint is set to specify the maximum temperature in the conductor. Table 1 provides an overview of the parameters used.

**Table 1:** Values used for single-conductor cable

$r_1$	7.5 mm	$\lambda_1$	400 W/(m <sup>2</sup> K)
$r_2$	15 mm	$\lambda_2$	0.3 W/(m <sup>2</sup> K)
$r_3$	35 mm	$\lambda_3$	44 W/(m <sup>2</sup> K)
$r_4$	38 mm	$\lambda_4$	0.3 W/(m <sup>2</sup> K)
$R_{20}$	0.125 $\Omega$ /km	$\alpha_{20}$	0.00393 1/K
$T_{max}$	90 °C		

As was to be expected, the resultant values and temperatures coincide in this case. Figure 2

shows the temperatures for the individual layers of the cable, referring in each case to the outer radius of the layer concerned.

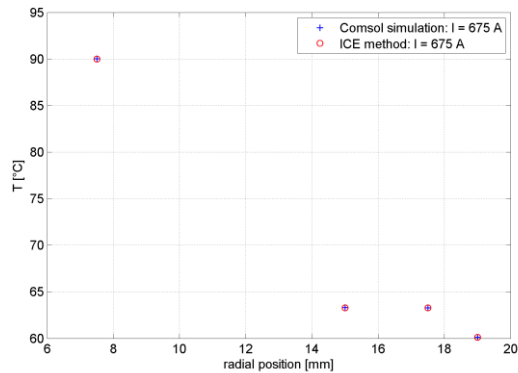


Figure 2. Temperatures in single-conductor cable

## 2.2 Three-conductor cable

The next step is now to show that, when dealing with models which, although still simple, nevertheless display increasing complexity, the differences between a standard calculation and the COMSOL simulation increase accordingly. To this end, a configuration comprising a bundle of three single-conductor cables in air was chosen. In the ICE model, the bundling of three single-conductor cables is taken into account by incorporating an additional factor into the thermal resistance calculation. The equation is thus modified as follows:

$$R_{\text{surface/ambient}} = \frac{1}{\pi \cdot d_{\text{cable}} \cdot (f_{ks} \cdot \alpha_{\text{convection}} + f_{rs} \cdot \alpha_{\text{radiation}})} \quad (11)$$

The values of  $f_{ks}$  and  $f_{rs}$  change in accordance with the configuration and layout of the different cables [1]. Furthermore, the additional conductors are taken into account in Eq. (3) and (4) by way of the additionally generated heat flow.

Here, too, as in the previous case, an equivalent model is implemented in COMSOL. Figure 3 shows the calculated geometry, for which a *Convective Cooling* boundary condition is again defined at the cable surface in accordance with Eq. (11). A *Heat Source* is calculated for the conductors in accordance with Eq. (3) and (4).

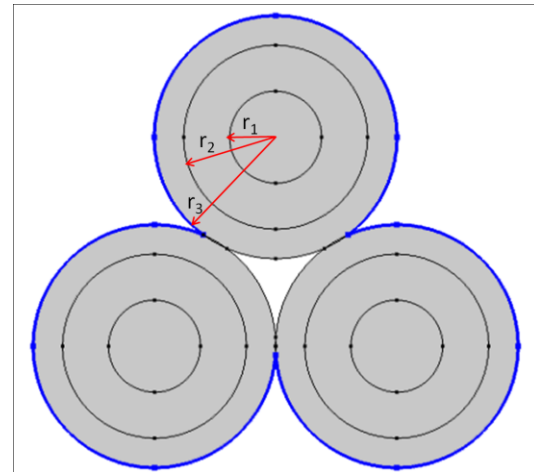
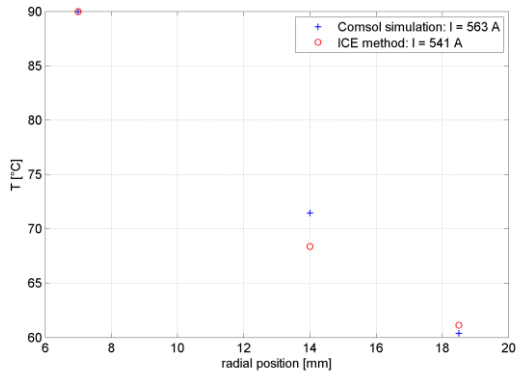


Figure 3. Geometry of single-conductor cable

Table 2: Values used for three bundled single-conductor cables

$r_1$	7 mm	$\lambda_1$	400 W/(m <sup>2</sup> K)
$r_2$	14 mm	$\lambda_2$	0.3 W/(m <sup>2</sup> K)
$r_3$	18.5 mm	$\lambda_3$	0.3 W/(m <sup>2</sup> K)
$R_{20}$	0.125 Ω/km	$\alpha_{20}$	0.00393 1/K
$T_{\text{max}}$	90 °C		

Iteration of the ampacity with the two models already results in differences. The standard calculation produces a current value of 541 A, whereas COMSOL indicates an ampacity of 563 A. Figure 4 reveals also the different temperatures for the individual layers. This can be explained by the fact that the simple assumptions from the ICE calculation model, which are here again based on the calculation of radially symmetrical cables, no longer apply properly for this configuration.

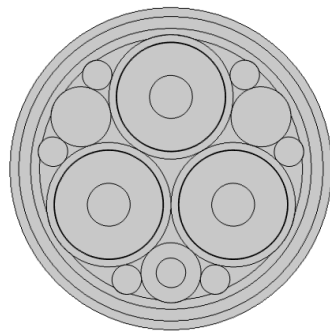


**Figure 4.** Temperatures of three bundled single-conductor cables

### 3. Calculation of a more complex configuration with COMSOL

#### 3.1 COMSOL model

On the basis of the assumptions from the previous section, this section describes a model to determine the ampacity of an increasingly more complex configuration, as used in offshore wind farms, for example. The cable shown here is a multiple-core high-voltage cable which runs vertically through an air-filled metal cylinder. Such cylinders are typically used to route the cable to the generator in a wind turbine. The critical point for this application – in respect of the maximum temperature – is that the cables here hang free in air, whereas they are elsewhere typically routed over the sea bed and are thus adequately cooled.

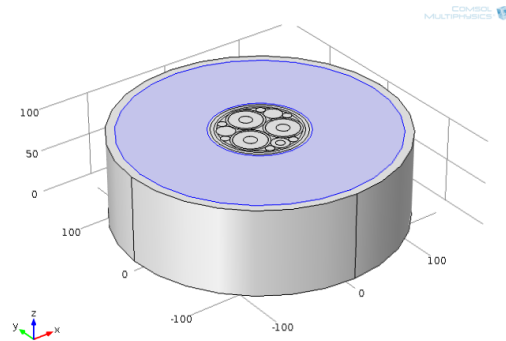


**Figure 5.** Geometry of high-voltage three-conductor cable

Figure 5 shows the cross-section of a cable. In addition to the heat losses in the conductors, it

is here necessary to take into account also the losses in the shield and the armouring.

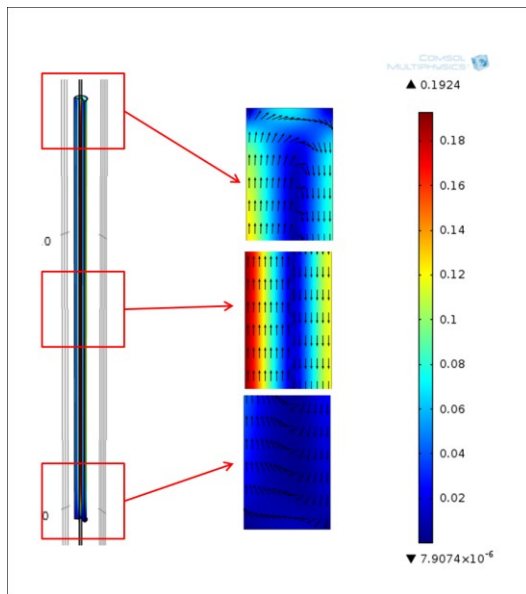
Furthermore, the cable is surrounded by an air-filled cylinder. Figure 6 shows a partially extruded cylinder with cable. The full extrusion is not depicted for the sake of clarity; the total height is typically over 20 m.



**Figure 6.** Extruded geometry of cable in cylinder, blue shows air domain

For this case, it is necessary to investigate not only the heat conduction, but also the flows attributable to free convection in the cylinder. To this end, the *Conjugate Heat Transfer* mode is applied. To model the arising air flow, a gravitational force was defined for the air. For the heat conduction at the outer jacket, the boundary conditions *Convective Cooling* and *Surface to Ambient Radiation* were selected.

Figure 7 shows the arising flow for a stationary load case with a constant current flowing through the conductors. The resultant temperature difference between the cable and the environment produces a free convection flow in the air-filled cylinder.



**Figure 7.** Velocity in cable casing

## 7. Conclusions

It was possible to demonstrate that COMSOL Multiphysics can be used to calculate cable ampacity. As presumed, increasingly more complex cable configurations lead to differences between the standard calculation and the simulation. As the standard calculation cannot take into account complex geometries, it incorporates additional safety margins which are in part not required in the simulation. In a further step, a complete model for temperature calculation with a high-voltage cable suitable to connect an offshore wind turbine was determined. This model enabled explicit investigation and evaluation of the influence of the cable periphery.

## 8. References

1. L. Heinhold, R. Stubbe, Kabel und Leitungen für Starkstrom, *MCD Verlag*, (1999)