# CABLES IN STEEL PIPES – VERIFICATION WITH IEC 60287

***Technical documentation***

GRØFT Design® models were verified with reference to the IEC 60287 [1] for the cable rating calculation of cables installed in magnetic pipes. For the range of the application of the IEC standard, GRØFT models are in line with the IEC calculations. Furthermore, GRØFT Design® is based on finite element method (FEM), therefore use of the functionality of magnetic pipes in the software may be used for more complex cable arrangement not covered by the IEC.

## 1. INTRODUCTION

In the verification of GRØFT Design® with TB 880 [2], the software was proven to be able to reproduce with a high accuracy the current ratings of power cables calculated with the theoretical models based on the IEC standard. Furthermore, a better accuracy was found for GRØFT models installed in plastic pipes in comparison to the IEC models, due to more advanced simulations of the heat transfer in the enclosure of pipe supported by the software. This was investigated by comparing GRØFT with empirical models [3] and research carried out by SINTEF [4] . Moreover, as opposed to the IEC calculation, the advantage of the use of GRØFT is that the cables are placed in the bottom of the pipe, that reflect more realistic setup.

## 2. THEORETICAL BACKGROUND

With regards to cables placed in steel pipes, the theoretical thermal resistance of air between cable and pipes is calculated similarly as for cables that are in the plastic pipes, however with the application of different constants U, V, Y (IEC [5] *Table 5*). Furthermore, the following must be considered for the theoretical model based on IEC as cables are placed in magnetic pipe:

a) The additional heat loss factor denoted as $\lambda_2$ must be considered for pipe. The following approximations of $\lambda_2$ is given by IEC [1] (5.4.4):

For closely bounded triangular configuration:

$$\lambda_2 = \left(\frac{11.5s - 1.485d_d}{R_c}\right)10^{-8} \quad (1)$$

For open or cradled formation:

$$\lambda_2 = \left(\frac{4.38s - 2.26d_d}{R_c}\right)10^{-8} \quad (2)$$

Where:

| | | | |
|---|---|---|---|
| $s$ | - | Axial spacing of adjacent conductors | [mm] |
| $d_d$ | - | Internal diameter of pipe | [mm] |
| $R_c$ | - | AC resistance of cable at operating temperature | [Ω/m] |

Heat loss factor $\lambda_2$ accounts for both eddy current and hysteresis losses.

b) The expression for heat loss factor $\lambda_2$ is based on the field studies [6]. It must be emphasized that the tests were carried out for cables in trefoil and cradle formation placed in a single steel pipe. Therefore, the application of $\lambda_2$ in the theoretical model may be considered applicable only for these two configurations [7]. In Fig. 1 the setup used in the reference field study is presented:

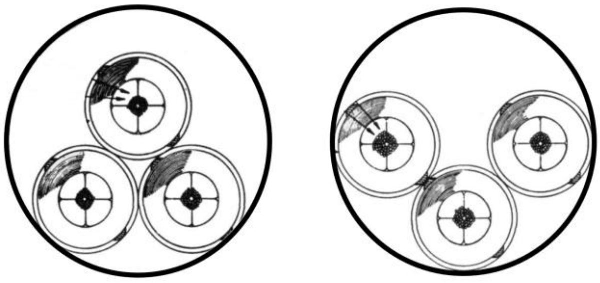

***Fig. 1*** *Setup of cables in steel pipes in the field experiment – trefoil and cradle [6]*

The following parameters for steel pipe are described in [6]:

| | | | | | | |
|---|---|---|---|---|---|---|
| $t$ | - | Thickness of pipe | 0.254 | [inch] | 6.45 | [mm] |
| $d_d$ | - | Internal diameter of pipe | 8.14 | [inch] | 207.1 | [mm] |
| $\rho_{sp}$ | - | Electrical resistivity of steel at room temperature (assumed 20 °C) | 5.92 | [µΩ·inch] | 0.15 | [µΩ·m] |

Cable diameters for which the experiment was carried out varied between 60 mm – 72.4 mm (2.36 inch – 2.85 inch).

c) In the thermal network of cables, the thermal resistance of steel pipe is disregarded (in IEC [5] denoted as $T''_4$).

d) In the IEC calculations, cables are placed in the center of pipe.

e) For cables in trefoil formation, the sheath loss factor $\lambda'_1$ due to circulating current is multiplied by factor 1.5 (IEC [1] 5.3.12).

$$\lambda'_1 = \frac{R_s}{R_c} \frac{1.5}{1 + \left(\frac{R_s}{X}\right)^2} \tag{3}$$

f) The skin and proximity factors $y_s$ and $y_p$ are multiplied by factor 1.5 (IEC [1] 5.1.6)

$$R_c = R_{DC_{operating}} \left[1 + 1.5 \cdot (y_s + y_p)\right] \tag{4}$$

This is applied for trefoil and cradle formation of cables, according to Silver and Seman [8].

g) For cables in cradle formation, the sheath loss factor $\lambda_1$ would be the approximation of formation between touching flat and trefoil. This approximation would be dependent on the ratio of pipe internal diameter to cable diameter. For flat formation, it seems appropriate to calculate the loss factor in sheath based on factors $\lambda'_{1m}$, $\lambda'_{11}$ and $\lambda'_{12}$ (IEC [1] 5.3.4). However, the standard does not specify the modification of these factors for such arrangement of cables in magnetic pipes. According to IEC2 4.2.4.2.1 $\lambda_1$ should be the average of component $\lambda'_{1m}$, $\lambda'_{11}$ and $\lambda'_{12}$. The same applies to $\lambda''_1$. In this study, for cables in cradle formation, $\lambda_1$ would be calculated as average of these factors for touching flat and trefoil formations.

## 3. SCOPE OF THE STUDY

The aim of this study is the comparison of the generated heat losses in the magnetic pipes between the IEC and GRØFT models. The comparison is made for placed in steel pipe cables in trefoil and cradle formations. With regards to cradle formation, the IEC standard does not describe specifically this arrangement, therefore this model must be considered as a rough approximation, especially in terms of heat transfer.

## 4. SETUP OF THE ANALYSIS

The variability of geometrical and electromagnetic parameters of cables in pipes may contribute to discrepancies between IEC and GRØFT models. It must be emphasized that the empirical expression developed in [6] is related to the narrow range of application. Therefore, the approximation of the case study that correspond the experiments performed in [6] is reproduced in GRØFT Design®. System frequency is therefore 60 Hz. The following parameters for steel pipe were assumed:

| | | | | | | |
|---|---|---|---|---|---|---|
| $t$ | - | Thickness of pipe | 0.254 | [inch] | 6.45 | [mm] |
| $d_d$ | - | Internal diameter of pipe | 8.14 | [inch] | 207.1 | [mm] |
| $\rho_{sp}$ | - | Electrical resistivity of steel at 20 °C | 5.92 | [µΩ·inch] | 0.15 | [µΩ·m] |
| $\mu$ | - | Permeability | 375 | [-] | | |

Three different types of (simplified) cables are considered – see Table 1, Table 2 and Table 3.

**Table 1** MODEL 1 - TSLF 72 kV 400A/35

| No. | Description | Thermal Resistivity [K.m/W] | Nominal Diameter [mm] |
|---|---|---|---|
| 1 | Al Conductor 400 mm² | N/A | 23.6 |
| 2 | XLPE Insulation ($\varepsilon = 2.5, tan\delta = 0.001$) | 3.5 | 47.9 |
| 3 | Copper wires screen ($A_{Cu} = 21mm^2$) | N/A | 48.8 |
| 4 | Aluminum laminate ($A_{Al} = 22.95mm^2$) | N/A | 49.1 |
| 5 | Serving (PE) | 3.5 | 59.0 |

**Table 2** MODEL 2 - TSLF 72 kV 800A/50

| No. | Description | Thermal Resistivity [K.m/W] | Nominal Diameter [mm] |
|---|---|---|---|
| 1 | Al Conductor 800 mm² | N/A | 34.7 |
| 2 | XLPE Insulation ($\varepsilon = 2.5, tan\delta = 0.001$) | 3.5 | 59.5 |
| 3 | Copper wires screen ($A_{Cu} = 30mm^2$) | N/A | 60.5 |
| 4 | Aluminum laminate ($A_{Al} = 32.79mm^2$) | N/A | 60.8 |
| 5 | Serving (PE) | 3.5 | 71.6 |

**Table 3** MODEL 3 - TSLF 170 kV 630A/50

| No. | Description | Thermal Resistivity [K.m/W] | Nominal Diameter [mm] |
|---|---|---|---|
| 1 | Al Conductor 630 mm² | N/A | 30.4 |
| 2 | XLPE Insulation ($\varepsilon = 2.5, tan\delta = 0.001$) | 3.5 | 67.2 |
| 3 | Copper wires screen ($A_{Cu} = 30mm^2$) | N/A | 68.1 |
| 4 | Aluminum laminate ($A_{Al} = 32.79mm^2$) | N/A | 68.4 |
| 5 | Serving (PE) | 3.5 | 81.0 |

The cable arrangements are presented in Fig. 2:

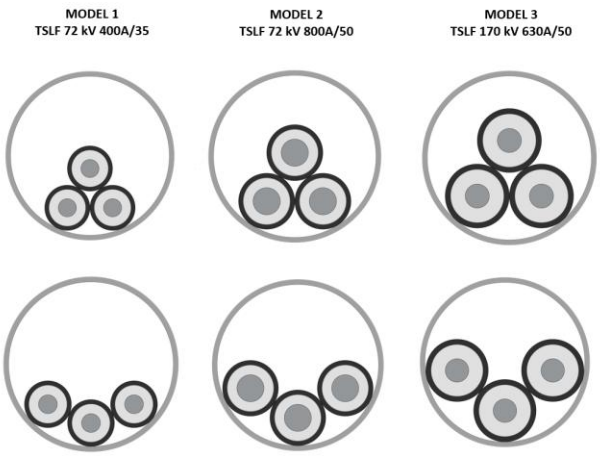


***Fig. 2*** *Cable arrangements for MODEL 1, MODEL 2 and MODEL 3*

Cable sheaths are solidly bonded. The pipe is buried 1 m under the ground surface that is an isotherm of temperature 20 °C. A thermal resistivity of 1 K.m/W is assigned to the soil. For cables in trefoil, the thermal resistance of air in the pipe is calculated according to the empirical model developed by SINTEF [4]. For cables in cradle arrangement the convective heat transfer in pipe is simulated.

Furthermore, the additional analysis is performed in GRØFT that implements the thermal resistance of the air $T'_4$ according to IEC model [5]. The setup of this feature in the software is presented in Fig. 3. Constants U, V, Y used for the calculation of $T'_4$ (7) are chosen by the software automatically upon the material of the pipe. For these models, cables are placed in the middle of the pipe, as presented in Fig. 5.

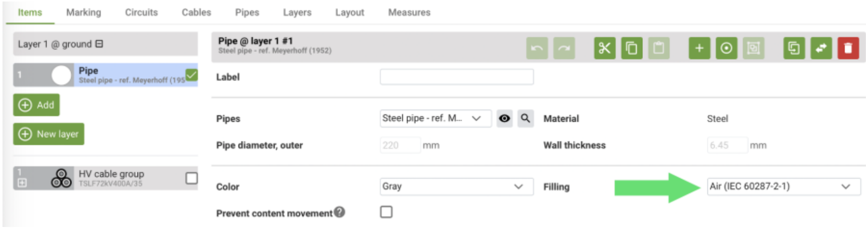


***Fig. 3*** *Setup in GRØFT for the calculation of the thermal resistance $T'_4$ in the pipe according to IEC*

## 5. THERMAL NETWORK OF CABLE IN STEEL PIPE – THEORETICAL MODEL

The thermal network of cables in steel pipe is presented in Fig. 4. The current rating equation based on IEC is modified accordingly (5).

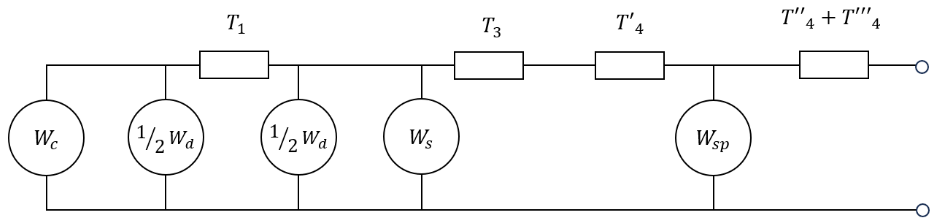


***Fig. 4*** *Thermal network of cables in steel pipe*

$$\Delta\theta = \left(I^2R_c + \frac{1}{2}W_d\right)T_1 + 3\cdot\left(I^2R_c(1+\lambda_1) + W_d\right)(T_3 + T'_4) + 3\cdot\left(I^2R_c(1+\lambda_1+\lambda_2) + W_d\right)(T''_4 + T'''_4) \qquad (5)$$

For the calculation of $\lambda_2$ (2), the resistivity of pipe is temperature dependent. The temperature of the pipe is expressed as follows:

$$\theta_{sp} = \theta - \left\{\left(I^2R_c + \tfrac{1}{2}W_d\right)T_1 + 3\cdot\left(I^2R_c(1+\lambda_1) + W_d\right)(T_3 + T'_4) + 3\cdot\left(I^2R_c(1+\lambda_1+\lambda_2) + W_d\right)(T''_4)\right\} \qquad (6)$$

The temperature coefficient for steel $\alpha_{sp} = 0.004\left[\frac{1}{K}\right]$.

Thermal resistance $T'_4$ (7), i.e. air in pipes, is calculated according to IEC [5] (4.2.6.3). Factors U, V, Y are respectively equal to 5.2, 1.4 and 0.011.

$$T_4^{'} = \frac{U}{1+0{,}1(V+Y\theta_m)D'_e} \qquad (7)$$

Cable group is placed in the middle of the pipe (see Fig. 5). The diameter of cable is denoted as $D_e$. The mean temperature of air in the pipe $\theta_m$ is calculated iteratively, both in IEC calculations and in GRØFT Design®. The equivalent diameter $D'_e$ for cables in trefoil is calculated based on IEC [1] (4.2.6.3) $D'_e = 2.15\cdot D_e$. For cables in cradle formation the same value is applied, therefore a slight discrepancy is expected for the calculated maximum temperature of conductor with regards to the GRØFT analysis.

According to IEC [5] (4.2.6.3), the expression for thermal resistance $T'_4$ is valid for group of cables with equivalent diameter $D'_e$ up to 125 mm. It is outside the range of MODEL 2 and MODEL 3, however it is applied since no other approximation is given in the IEC standard.

As opposed to the IEC standard, the thermal resistance $T''_4$ is included in the calculations, however with minor effect. $T'''_4$ is calculated as for single duct/cable (IEC [5] 4.2.2).

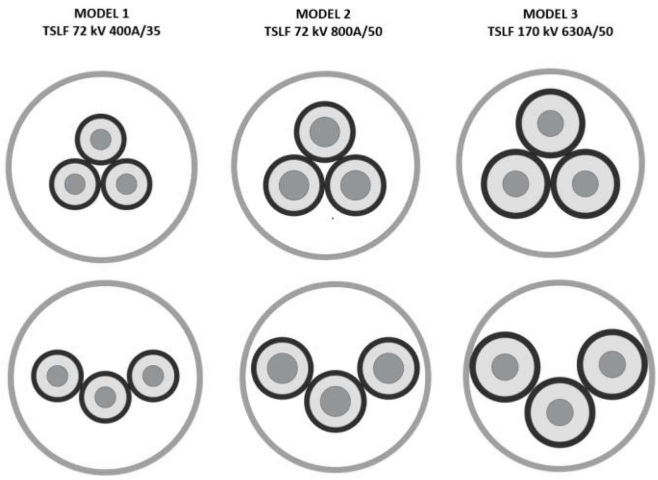


***Fig. 5*** *Cable arrangements according to IEC calculations for MODEL 1, MODEL 2 and MODEL 3*

## 6. RESULTS

The comparison of the results between analyses performed in GRØFT Design® and with the IEC analytical models are presented in Table 4-Table 9. All presented models built in the software can be made available upon request.

**Table 4** Results MODEL 1 - trefoil

| | Cable | MODEL 1 - TSLF 72 kV 400A/35 | | | | |
|---|---|---|---|---|---|---|
| | Configuration | Trefoil | | | | |
| Parameter | | Symbol | Unit | IEC[3] | GRØFT + IEC air [2] | GRØFT |
| $I = 480.42\ A$ | Loss conductor[1] | $Wc$ | W/m | 23.67 | 23.50 | 23.65 |
| | Loss Screen[1] | $Ws$ | W/m | 2.80 | 2.38 | 2.96 |
| | Dielectric loss of insulation | $Wd$ | W/m | 0.128 | 0.128 | 0.128 |
| | Loss pipe | $Wsp$ | W/m | **2.57** | **2.31** | **3.18** |
| | Max temperature of conductor | $\theta_{max}$ | °C | 90.00 | 89.50 | 92.90 |

[1] Mean heat loss
[2] GRØFT model with implemented resistance of air in pipe $T'_4$ according to IEC. Cables are placed in the center of the pipe

**Table 5** Results MODEL 1 - cradle

| | Cable | MODEL 1 - TSLF 72 kV 400A/35 | | | | |
|---|---|---|---|---|---|---|
| | Configuration | Cradle | | | | |
| Parameter | | Symbol | Unit | IEC[3] | GRØFT + IEC air [2] | GRØFT[4] |
| $I = 4768.28\ A$ | Loss conductor[1] | $Wc$ | W/m | 22.49 | 22.10 | 23.33 |
| | Loss Screen[1] | $Ws$ | W/m | 3.75 | 3.98 | 5.09 |
| | Dielectric loss of insulation | $Wd$ | W/m | 0.128 | 0.128 | 0.128 |
| | Loss pipe | $Wsp$ | W/m | **4.78** | **3.76** | **5.24** |
| | Max temperature of conductor | $\theta_{max}$ | °C | 90.00 | 88.30 | 92.80 |

[1] Mean heat loss
[2] GRØFT model with implemented resistance of air in pipe $T'_4$ according to IEC. Cables are placed in the center of the pipe
[3] $\lambda_1$ is assumed as an average of this factor for trefoil and flat formation. In both cases $\lambda'_1$ is multiplied with 1.5
[4] Convective heat transfer is simulated

**Table 6** Results MODEL 2 - trefoil

| | Cable | MODEL 2 - TSLF 72 kV 800A/50 | | | | |
|---|---|---|---|---|---|---|
| | Configuration | Trefoil | | | | |
| Parameter | | Symbol | Unit | IEC[3] | GRØFT + IEC air [2] | GRØFT |
| $I = 641.5\ A$ | Loss conductor[1] | $Wc$ | W/m | 21.90 | 21.60 | 21.90 |
| | Loss Screen[1] | $Ws$ | W/m | 6.71 | 5.85 | 6.62 |
| | Dielectric loss of insulation | $Wd$ | W/m | 0.168 | 0.168 | 0.168 |
| | Loss pipe | $Wsp$ | W/m | **6.37** | **5.37** | **6.17** |
| | Max temperature of conductor | $\theta_{max}$ | °C | 90.00 | 89.80 | 92.00 |

[1] Mean heat loss
[2] GRØFT model with implemented resistance of air in pipe $T'_4$ according to IEC. Cables are placed in the center of the pipe

Table 7 Results MODEL 2 - cradle

| | Cable | MODEL 2 - TSLF 72 kV 800A/50 | | | | |
|---|---|---|---|---|---|---|
| | Configuration | Cradle | | | | |
| | Parameter | Symbol | Unit | IEC[3] | GRØFT + IEC air[2] | GRØFT[4] |
| $I$ = 610.55 $A$ | Loss conductor[1] | $Wc$ | W/m | 19.83 | 19.33 | 20.27 |
| | Loss Screen[1] | $Ws$ | W/m | 8.57 | 8.81 | 9.77 |
| | Dielectric loss of insulation | $Wd$ | W/m | 0.168 | 0.168 | 0.168 |
| | Loss pipe | $Wsp$ | W/m | **8.74** | **7.54** | **8.67** |
| | Max temperature of conductor | $\theta_{max}$ | °C | 90.00 | 87.70 | 91.20 |

[1] Mean heat loss
[2] GRØFT model with implemented resistance of air in pipe $T'_4$ according to IEC. Cables are placed in the center of the pipe
[3] $\lambda_1$ is assumed as an average of this factor for trefoil and flat formation. In both cases $\lambda'_1$ is multiplied with 1.5
[4] Convective heat transfer is simulated

Table 8 Results MODEL 3 - trefoil

| | Cable | MODEL 3 - TSLF 170 kV 630A/50 | | | | |
|---|---|---|---|---|---|---|
| | Configuration | Trefoil | | | | |
| | Parameter | Symbol | Unit | IEC[3] | GRØFT + IEC air[2] | GRØFT |
| $I$ = 556.90 $A$ | Loss conductor[1] | $Wc$ | W/m | 19.91 | 19.70 | 19.60 |
| | Loss Screen[1] | $Ws$ | W/m | 5.13 | 5.01 | 5.49 |
| | Dielectric loss of insulation | $Wd$ | W/m | 0.64 | 0.64 | 0.64 |
| | Loss pipe | $Wsp$ | W/m | **6.3** | **5.44** | **5.79** |
| | Max temperature of conductor | $\theta_{max}$ | °C | 90.00 | 89.00 | 87.90 |

[1] Mean heat loss
[2] GRØFT model with implemented resistance of air in pipe $T'_4$ according to IEC. Cables are placed in the center of the pipe

Table 9 Results MODEL 3 - cradle

| | Cable | MODEL 3 - TSLF 170 kV 630A/50 | | | | |
|---|---|---|---|---|---|---|
| | Configuration | Cradle | | | | |
| | Parameter | Symbol | Unit | IEC[3] | GRØFT + IEC air[2] | GRØFT[4] |
| $I$ = 557.85 $A$ | Loss conductor[1] | $Wc$ | W/m | 19.98 | 19.70 | 20.50 |
| | Loss Screen[1] | $Ws$ | W/m | 7.25 | 6.98 | 7.91 |
| | Dielectric loss of insulation | $Wd$ | W/m | 0.64 | 0.64 | 0.64 |
| | Loss pipe | $Wsp$ | W/m | **7.68** | **7.11** | **8.02** |
| | Max temperature of conductor | $\theta_{max}$ | °C | 90.00 | 87.90 | 90.80 |

[1] Mean heat loss
[2] GRØFT model with implemented resistance of air in pipe $T'_4$ according to IEC. Cables placed in the center of the pipe
[3] $\lambda_1$ is assumed as an average of this factor for trefoil and flat formation. In both cases $\lambda'_1$ is multiplied with 1.5
[4] Convective heat transfer is simulated

## 7. DISCUSSION AND CONCLUSIONS

GRØFT models correlates well with the IEC calculations. Resulting heat losses in pipes for GRØFT models are close to the IEC calculations for all presented cases. Several minor discrepancies for resulting temperature of conductor between the analytical and the GRØFT models are observed. This is the consequence of different placement of the cables in pipe. The geometric setup is of a major relevance in terms of losses in pipe, conductor and sheath.

Furthermore, the analytical formula found in IEC does not account for the variation of the relative permeability of pipe material. In GRØFT this parameter may be defined by the user.

In order to calculate accurately the losses in magnetic pipes, which varies as a function of the eddy currents penetration depth, a mesh sensitivity study was carried out. The meshing technique was modified accordingly.

## References

[1] *NEK IEC 60287-1-1:2006 Calculation of the current rating Part 1-1: Current rating equations (100% load factor) and calculation of losses,* Norsk Elektroteknisk Komite.

[2] "2302-02-04001 Verification of GRØFT Design with TB 880," [Online]. Available: https://docs.groftdesign.net/papers/TB880.pdf?_cchid=ac3df6f3fafbd3d4b8f1277d7a2d33cf.

[3] G. D. Raithby and . K. T. Hollands, "A General Method of Obtaining Approximate Solutions to Laminar and Turbulent Free Convection Problems," Elsevier, 1975.

[4] E. Eberg and S. M. Hellesø, "Simplified Model for Heat Transport for Cables in Pipes," *IEEE Transactions on Power Delivery,* vol. 37, no. 5, pp. 3812-3822, 2021.

[5] IEC 60287-2-1 Electric cables - Calculation of the current rating - Part 2-1: Thermal resistance - Calculation of thermal resistance.

[6] L. Meyerhoff, "A-C Resistance of Pipe-Cable Systems with Segmental Conductors," *AIEE. Trans.,* vol. 71, no. III, pp. 393-414, 1952.

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