CABLES IN STEEL PIPES – VERIFICATION WITH IEC 60287

Technical documentation

Grøft Design® models have been benchmarked against IEC 60287 [1] calculations for estimating the ampacity of cables installed in magnetic conduits. Although the IEC offers a solid first approximation, Grøft's advanced finite-element model provides a more accurate representation of a physical model by incorporating a broader range of parameters and accommodating cable configurations beyond the IEC's scope.

1. INTRODUCTION

Validation studies [2] conducted against CIGRE Technical Brochure 880 (TB 880), demonstrate that GRØFT Design® accurately reproduces the current-carrying capacity of power cables predicted by IEC-based analytical models. In addition, when cables are installed in plastic conduits, Grøft delivers superior accuracy over the IEC method because its finite-element solver simulates heat transfer within the pipe enclosure in greater detail. This finding was confirmed by benchmarking Grøft results against recognized empirical models [3] and SINTEF's experimental research [4]. Unlike the IEC approach, Grøft assumes that cables lays on the bottom of the conduit - a placement that better reflects real-world installations.

For power cables routed through magnetic conduits, additional heat losses arise in both the conductors and the metallic sheaths. Extra losses are also generated within the conduit itself due to induced eddy currents and hysteresis losses. Although the IEC offers a simplified analytical method to estimate these effects (see Section 2), the underlying physics is complex, which the IEC formulation may not represent accurately.

2. THEORETICAL BACKGROUND

For cables installed in steel conduits, the theoretical thermal resistance of the air gap between the cable and the conduit is calculated in the same manner as for cables in plastic ducts, but with different constants - U, V, and Y (IEC [5] *Table 5*). When applying the IEC model to cables in magnetic conduits, the following additional factors must also be considered:

a) The heat losses denoted as λ_2 must be considered, as they represent losses within the conduit. The following approximations of λ_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 λ_2 accounts for both eddy current and hysteresis losses.

b) The expression for heat loss factor λ_2 is based on the experimental 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 λ_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:

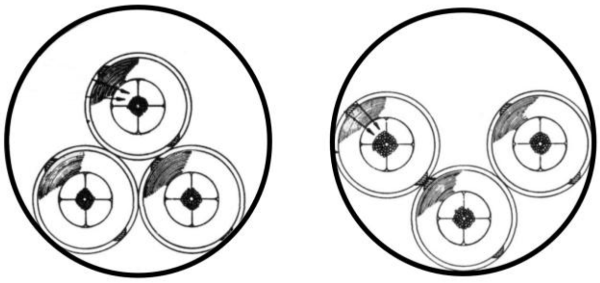

Fig. 1 *Setup of cables in steel pipes in the field experiment – trefoil and cradle [6]*

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]
ρ_{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 λ'_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)

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

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 λ_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 λ'_{1m}, λ'_{11} and λ'_{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 λ_1 should be the average of component λ'_{1m}, λ'_{11} and λ'_{12}. The same applies to λ''_1. In this study, for cables in cradle formation, λ_1 would be calculated as average of these factors for touching flat and trefoil formations.

3. SCOPE OF THE STUDY

This study compares the current rating calculations considering heat losses generated within magnetic conduits as predicted by the IEC method and by GRØFT Design®. The analysis covers cables installed in steel conduits arranged in both trefoil and cradle formations. Because the IEC standard does not explicitly address the cradle configuration, the IEC model should be viewed as a rough approximation—particularly with respect to heat-transfer behavior.

4. SETUP OF THE ANALYSIS

Variations in the geometric and electromagnetic properties of cables installed in steel conduits can create discrepancies between IEC predictions and GRØFT Design® results. It is important to note that the empirical formula proposed in [6] applies only to a narrow operating envelope. Accordingly, the experimental setup described in [6] was recreated within GRØFT Design® and fixed the system frequency at 60 Hz. The steel-conduit parameters used in this study are as follows:

t	-	Thickness of pipe	0.254	[inch]	6.45	[mm]
d_d	-	Internal diameter of pipe	8.14	[inch]	207.1	[mm]
ρ_{sp}	-	Electrical resistivity of steel at 20 °C	5.92	[μΩ·inch]	0.15	[μΩ·m]
μ_r	-	Relative permeability Complex expression	375	[-]		

Steel and Magnetic Stainless Steel which has a ferromagnetic properties, retain some part of induced magnetic moment once an external field is removed [9]. These materials exhibit hysteresis behavior represented with a complex magnetic permeability μ_r. The magnetic flux B reacts with some time lag to magnetic field H [10] and leads to heat losses in a time-varying magnetic field. The permeability μ_r can be described with the real and imaginary part.

$$\mu_r = \mu'_r - j\mu''_r \tag{5}$$

The ratio of the imaginary over the real part of the complex permeability is defined as magnetic loss tangent and expresses the power lost to power stored in the material:

$$tan\delta = \frac{\mu''_r}{\mu'_r} \tag{6}$$

In Grøft Design® the magnetic hysteresis loop is approximated by using a linear relationship [10]. The pipe's magnetic permeability μ_r is crucial for accurately calculating cable losses because it affects losses not only within the pipe itself but also in the conductor and metallic sheaths.

Three different types of (simplified) cable constructions 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 1 - 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 1 - 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:

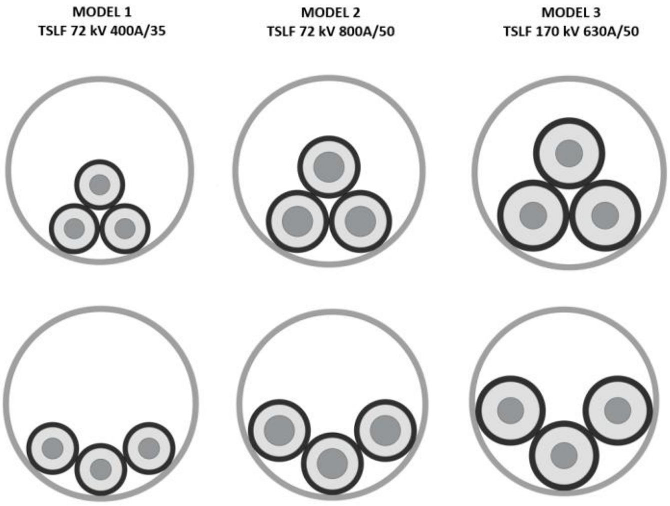

Fig. 2 *Cable arrangements for MODEL 1, MODEL 2 and MODEL 3*

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 and radiative 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.

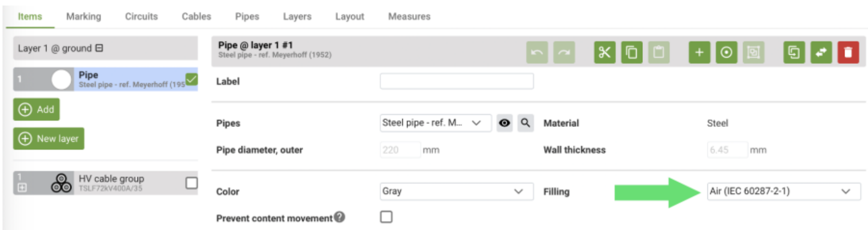

Fig. 3 *Setup in GRØFT for the calculation of the thermal resistance T'_4 in the pipe according to IEC*

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 in the software.

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).

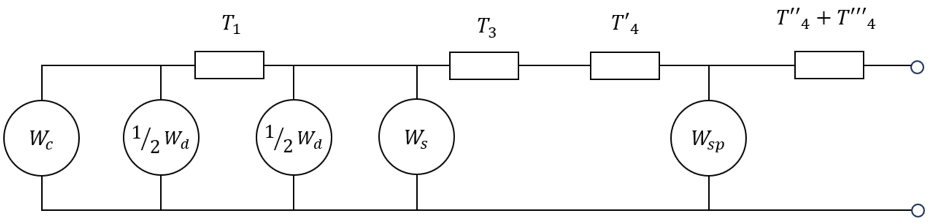

Fig. 4 *Thermal network of cables in steel pipe*

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

For the calculation of λ_2 (2), the resistivity of pipe is temperature dependent. The temperature of the pipe is expressed as follows:

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

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.

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

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 θ_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 presented here, however with minor effect. T'''_4 is calculated as for single duct/cable (IEC [5] 4.2.2).

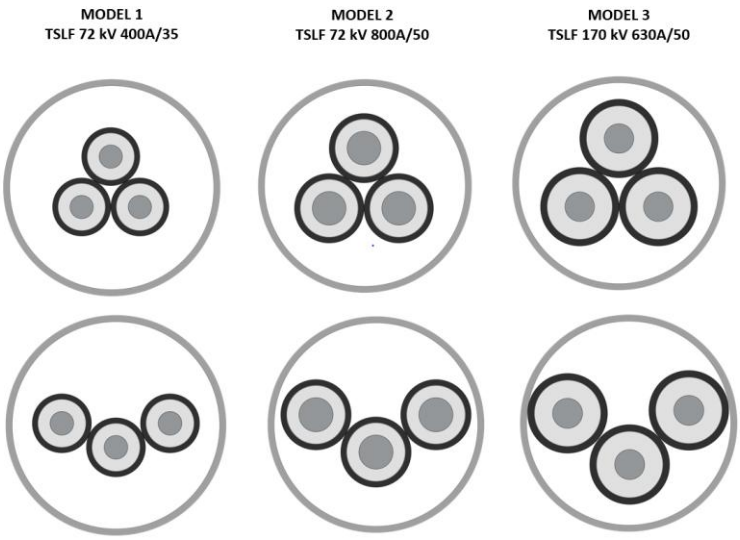

Fig. 5 *Cable arrangements according to IEC calculations for MODEL 1, MODEL 2 and MODEL 3*

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.

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	23.52	23.70
	Loss Screen[1]	Ws	W/m	2.80	2.41	3.01
	Dielectric loss of insulation	Wd	W/m	0.128	0.128	0.128
	Loss pipe	Wsp	W/m	**2.57**	**3.07**	**4.17**
	Max temperature of conductor	θ_{max}	°C	90.00	89.80	93.40

[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	22.14	23.03
	Loss Screen[1]	Ws	W/m	3.75	4.05	5.18
	Dielectric loss of insulation	Wd	W/m	0.128	0.128	0.128
	Loss pipe	Wsp	W/m	**4.78**	**4.96**	**6.83**
	Max temperature of conductor	θ_{max}	°C	90.00	88.90	93.60

[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] λ_1 is assumed as an average of this factor for trefoil and flat formation. In both cases λ'_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	21.68	21.95
	Loss Screen[1]	Ws	W/m	6.71	5.92	6.72
	Dielectric loss of insulation	Wd	W/m	0.168	0.168	0.168
	Loss pipe	Wsp	W/m	**6.37**	**7.07**	**8.06**
	Max temperature of conductor	θ_{max}	°C	90.00	90.80	93.10

[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	19.45	20.27
	Loss Screen[1]	Ws	W/m	8.57	9.77	9.89
	Dielectric loss of insulation	Wd	W/m	0.168	0.168	0.168
	Loss pipe	Wsp	W/m	**8.74**	**7.54**	**11.22**
	Max temperature of conductor	θ_{max}	°C	90.00	88.90	93.7

[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] λ_1 is assumed as an average of this factor for trefoil and flat formation. In both cases λ'_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	19.80	19.70
	Loss Screen[1]	Ws	W/m	5.13	5.21	5.61
	Dielectric loss of insulation	Wd	W/m	0.64	0.64	0.64
	Loss pipe	Wsp	W/m	**6.3**	**7.15**	**7.57**
	Max temperature of conductor	θ_{max}	°C	90.00	89.70	88.80

[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

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	19.77	20.36
	Loss Screen[1]	Ws	W/m	7.25	7.13	8.00
	Dielectric loss of insulation	Wd	W/m	0.64	0.64	0.64
	Loss pipe	Wsp	W/m	**7.68**	**9.28**	**10.38**
	Max temperature of conductor	θ_{max}	°C	90.00	90.10	92.90

[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] λ_1 is assumed as an average of this factor for trefoil and flat formation. In both cases λ'_1 is multiplied with 1.5
[4] Convective heat transfer is simulated

7. DISCUSSION AND CONCLUSIONS

Grøft models that adopt the IEC assumptions - cables centered inside the pipe and the air-gap thermal resistance calculated as per the IEC standard, agree closely with IEC results. The maximum difference in predicted conductor temperature is just 1%, and conductor heat losses differ by the same 1%. Although the deviations for metallic sheath and pipe losses are larger, up to 14% and 21% respectively, their impact on the final cable rating is minor.

However, when the full Grøft model is compared with the IEC method, the gaps in results increase. Grøft indicates that the current ratings derived from the IEC formulation produce a conductor temperature up to 3.7 °C above the 90 °C limit. Losses in the conductor, sheath, and pipe are underestimated by up to 2%, 38%, and 62%, respectively.

These discrepancies arise mainly from different cable positions within the pipe; geometry strongly influences losses in the pipe, conductor, and sheath. In addition, the IEC analytical formula keeps the pipe's relative permeability fixed, whereas Grøft lets users specify this property. While the IEC approach provides a reasonable first estimate for cables installed in magnetic pipes, higher accuracy is achieved with Grøft's more sophisticated finite-element model, which accounts for a larger set of parameters than the generalized IEC method.

References

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