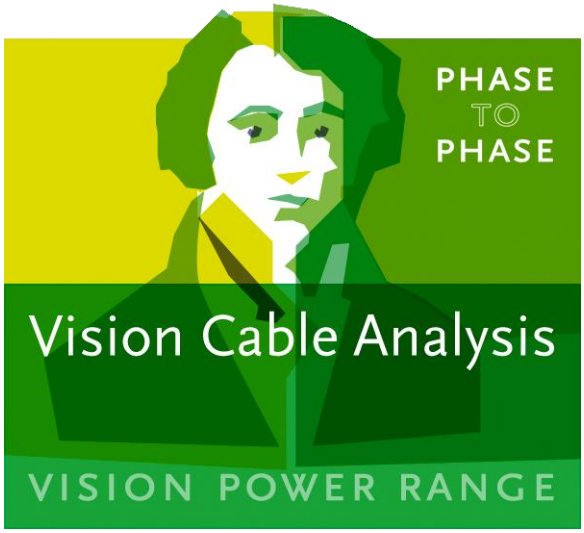
PHASE TO PHASE

Result of the comparison of Vision Cable Analysis with the CIGRE Technical Brochure “Power Cable rating examples for calculation tool verification” (TB 880)

26-049 SNI

05 October 2026



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Version	Date	Author	Comments	Reviewer
v0.50	24-02-2026	Sai Suprabhath Nibhanupudi	Case 0	-
v0.55	20-03-2026	Sai Suprabhath Nibhanupudi	Cases 4 & 10	-
v0.80	24-07-2026	Adebayo Adeyeye	Results update	Sai Suprabhath Nibhanupudi
v0.95	29-07-2026	Sai Suprabhath Nibhanupudi	Conclusions	-
v0.96	28-09-2026	Sai Suprabhath Nibhanupudi	Formatting	-
v1.00	05-10-2026	Sai Suprabhath Nibhanupudi	Next steps	-

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1 INTRODUCTION

CIGRE WG B1.56[1] developed ten case studies in a Technical Brochure (Reference 880)[2] covering a range of cable types installed in different environments. For each case, the maximum current rating is determined based on a series of intermediate calculations that account for both cable characteristics and environmental conditions.

This report selects three of these case studies (including their respective subcases) to compare the calculated results with those obtained using Vision Cable Analysis (VCA). In addition to comparing the resulting maximum current ratings, the report examines any differences in the intermediate calculations, explains their origins, and discusses their impact on the final results.

Within Vision Cable Analysis, several cable dimensions are represented differently in the Cable Type Editor. Because the parameter names are not always unique or directly comparable with those used in the CIGRE brochure, this report adopts terminology for cable diameters and insulation thicknesses that more closely follows the CIGRE notation. Where appropriate, the corresponding parameter names used in the VCA editor are explicitly identified.

The case studies analysed in this report are:

- Introductory Case Study 0
- Case Study 4: A 33 kV Land Cable
- Case Study 10: A 10 kV Three-Core PILC Cable

In the coming chapters, the comparison studies performed are described along with the results.

[1] https://www.e-cigre.org/publications/detail/880-power-cable-rating-examples-for-calculation-tool-verification.html

[2] Power cable rating exampled for calculation tool verification, Ref 880, 2022

2 COMPARISON CIGRE CASE 0 WITH VCA

2.1 Cable properties and environmental parameters

For case 0, a simple cable model was assumed. The cable consists of a round, compactly stranded copper conductor with a metal screen of laminated aluminum foil. This cable is placed in triangular or flat configuration in different environments:

- In triangular configuration, underground without drying out
- In triangular configuration, underground where the cables are laid separately in HDPE pipes
- In a flat configuration, underground where the cables are laid individually in PVC pipes and then embedded in cement
- In triangular configuration, above ground in direct sunlight
- In flat configuration, superficially buried in an unfilled trench

The following sections discuss these situations and compare the CIGRE results with VCA.

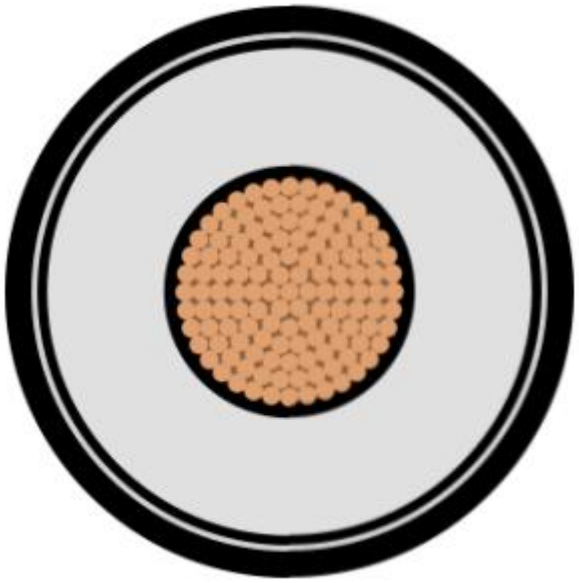


Figure 1 1-core XLPE cable from case 0 taken from the CIGRE report.

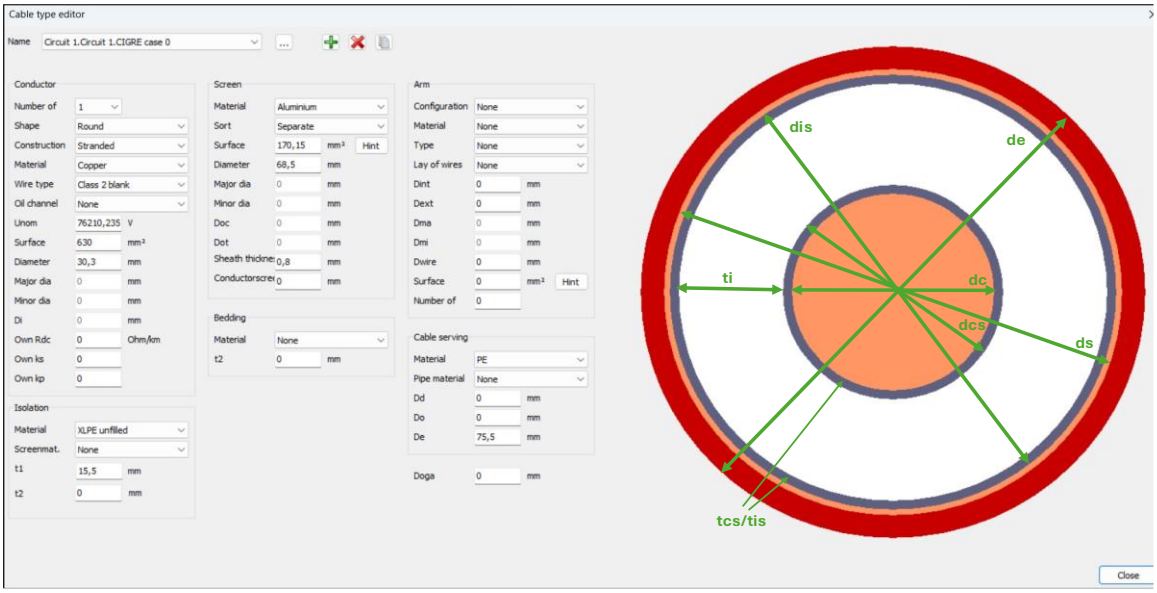


Figure 2 XLPE cable simulated in the cable type editor of VCA based on the values from Table 1 and Table 2.

Here: d_g = diameter of the conductor, d_{gs} = diameter of the conductor screen, t_i = thickness of the insulation, t_{gs} = thickness of the conductor screen, d_{is} = diameter of the insulation screen, tis = thickness of the insulation screen, d_s = diameter of the screen and d_e = external diameter of the cable.

Construction	Value	Unit	Symbol
Rated voltage level (U)	132	kV	
Conductor, Surface area	630	mm^2	
Conductor, material	Copper	Material	
Conductor, type	Circular compacted stranded	Type	
Conductor, DC resistance at 20 °C	2.83×10^{-5}	Ω/m	R_0
Tape over conductor type/material	Semiconductor	Type	
Insulation, type	XLPE unfilled	Type	
Maximum conductor temperature	90	°C	θ_g
Insulation permittivity	2.5		ε
Insulation losses	0.001		tan(δ)
Screen, material	Aluminum	Material	
Outer sheath, material	HDPE	Material	

Table 1 Cable specifications of case 0 taken from the CIGRE report.

Thickness and diameters	Thermal resistance (ρ)	Layer thickness (t)	Diameter (d)
Unit	K·m/W	mm	mm
Conductor (g)			30.3 (=d_g)
Conductor screen (g_s)		1.5 (=t_{gs})	33.3 (= d_{gs})
Insulation (i)	3.5 (= ρ_i)	15.5 (= t_i)	64.3 (= d_i)

Insulation screen (i_s)		1.3 (= t_{is})	66.9 (=d_{is})
Screen(s)		0.8 (= t_s)	68.5 (=d_s)
Outer sheath (e)	3.5 (= ρ_e)	3.5	75.5 (= d_e)

Table 2 Dimensions of the XLPE cable from the CIGRE report.

In the CIGRE case data, the conductor screen and insulation screen thicknesses differ. VCA cannot enter (at the moment) these thicknesses separately (assumes the thicknesses are the same): they are derived from the conductor diameter and the insulation diameter/thickness, which forces equal screen thicknesses (t_{gs} = t_{is}=1.4 mm). This assumption affects the calculated capacitance and dielectric losses and therefore propagates into later quantities that depend on those values.

Parameters	Value	Unit	Symbol
Environment	Underground	Above ground/underground	
Configuration	Triangle	Triangle/flat	
Depth underground to center of triangle (cable)	1000	mm	L
CC distance	Near	Near/mm	
Thermal resistance of the ground	1.0	K·m/W	ρ
Ambient temperature	20	°C	θa
Earth screen connection	Both sides		

Table 3 Properties of the installation and the environment.

Parameters	Value (from CIGRE and VCA)	Unit	Symbol
Conductor, temperature coefficient per K at 20°C	3.93 x 10^{-3}		α_{20}
Skin effect factor	1		k_s
Proximity effect factor	1		k_p
System frequency	50	Hz	f
Distance between axes of guide	75.5	mm	s (= d_e)
Thermal resistance of sheath at 20°C	2.84 x 10^{-8}	Ωm	ρ_s

Table 4 Other parameters needed for further calculations. These are derivatives of the cable construction.

2.2 Calculation of AC resistance of the cable at operating temperature

The data from Table 1, Table 2 and Table 4 are used for the calculations for the AC resistance.

$$R' = R_0 \cdot \left[1 + \alpha_{20} \cdot (\theta_g - 20)\right]$$

Equation 1. DC resistance of the conductor at operating temperature.

$$x_s{}^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_s$$

Equation 2. Argument of Bessel function, necessary to calculate skin effect factor y_s.

$$y_s = \frac{x_s{}^4}{192 + 0.8 \cdot x_s{}^4}, \text{voor: } 0 < x_s \leq 2.8$$

Equation 3. Skin effect factor.

$$x_p{}^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_p$$

Equation 4. Argument of Bessel function, necessary to calculate proximity effect factor y_p.

$$y_p = \frac{{x_p}^4}{192 + 0.8 \cdot {x_p}^4} \cdot \left(\frac{d_g}{s}\right)^2 \cdot \left[0.312 \cdot \left(\frac{d_g}{s}\right)^2 + \frac{1.18}{\frac{{x_p}^4}{192 + 0.8 \cdot {x_p}^4} + 0.27}\right]$$

Equation 5. Proximity effect factor.

$$R = R' \cdot (1 + y_s + y_p)$$

Equation 6. AC resistance of the conductor.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
DC resistance of the conductor at 20 °C	R’	3.6085 x 10^{-5}	3.6085 x 10^{-5}	Ω/m
Argument of Bessel function - skin effect	x_s^2	3.4824	3.4824	
Skin effect factor	y_s	6.0124 x 10^{-2}	6.0124 x 10^{-2}	
Argument of Bessel function – proximity effect factor	x_p^2	3.4824	3.4824	
Proximity effect factor	y_p	3.5100 x 10^{-2}	3.5100 x 10^{-2}	
AC resistance of the conductor	R	3.9522 x 10^{-5}	3.9522 x 10^{-5}	Ω/m

Table 5 Results of the intermediate calculations to determine the AC resistance of the conductor.

The intermediate results and outcome for the AC resistance from the CIGRE report correspond to the results of VCA.

2.3 Dielectric losses

The data from Table 1, Table 2 and Table 4 were used to calculate the dielectric losses.

$$C = \frac{\varepsilon}{18 \cdot ln\left(\frac{d_i}{d_{gs}}\right)} \cdot 10^{-9}$$

Equation 7. Capacitance. Here d_i stands for the diameter of the insulation and d_{gs} for the diameter of the conductor and the conductor screen, as can also be found in Table 2.

$$\omega = 2\pi f$$

Equation 8. Angular frequency of the system.

$$W_d = \omega \cdot C \cdot {U_0}^2 \cdot tan(\delta)$$

Equation 9. Dielectric losses per unit length per phase.

$$U = \sqrt{3} U_0$$

Equation 10. Conversion of phase voltage (U_0) to line to line voltage (U).

Equation 10 shows the conversion from line to line voltage to phase voltage, where VCA expects the phase voltage as input. Case 0 states only the line-to-line voltage, so the phase voltage was obtained by dividing the line-to-line voltage by $\sqrt{3}$.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Capacitance	c	2.1108 x 10^{-10}	2.1015 x 10^{-10}	F/m
Angular frequency of the system	ω	314.16	314.16	rad/s
Dielectric losses per unit length in each phase	W_d	0.38514	0.38344	W/m

Table 6 Results of the intermediate calculations to determine the dielectric losses.

The difference between the values of the capacitance and the dielectric losses in the CIGRE report (g_s = 1.5 and i_s = 1.3) and VCA can be explained by the fact that the thickness of the conductor screen is not

equal to the thickness of the insulation screen. In VCA it is assumed that the thickness of both screens are equal (g_s = i_s = 1.4). It follows directly from the modelling limitation

2.4 Losses in metallic sheath (λ_1)

To calculate the losses in the sheath, the data from tables 2, 5 and 6 were used.

$$R_{s0} = \frac{\rho_s}{A_s}$$

Equation 11. AC resistance of the screen at 20°C per unit length.

$$R_s = R_{s0} \cdot [1 + \alpha_{20} \cdot (\theta_s - 20)]$$

Equation 12. Sheath resistance at operating temperature.

$$X = 2 \cdot \omega \cdot 10^{-7} \cdot ln\left(\frac{2s}{d_{gem}}\right)$$

Equation 13. Reactance per unit length of screen, where d_{gem} = average diameter of screen (d_{is}+t_s).

$$\lambda'_{1,s} = \frac{R_s}{R} \cdot \frac{1}{1 + \left(\frac{R_s}{X}\right)^2}$$

Equation 14. Loss factor due to currents induced in the screen.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Cross section of the wires of the screen.	A_s	170.15	170.15	m^2
AC resistance of the screen at 20°C	R_{s0}	1.6691 x 10^{-4}	1.6691 x 10^{-4}	Ω/m
Resistance of the jacket to the operating temperature	R_s	2.0641 x 10^{-4}	2.0641 x 10^{-4}	Ω/m
Reactance per unit length of screen	X	5.0403 x 10^{-5}	5.0403 x 10^{-5}	Ω/m
Loss factor due to currents induced in the screen	λ'_{1_s}= λ_1	0.29390	0.29390	

Table 7 Results of the intermediate calculations to determine the loss factor in the screen.

2.5 Thermal resistance between conductor and screen (T_1)

$$\boldsymbol{T_1 = \frac{\rho_i}{2 \cdot \pi} ln\left[1 + \frac{2 \cdot t_1}{d_g}\right]}$$

Equation 15. The formula from IEC 60287-2-1: 4.1.2.1, which is applied in VCA (per layer)

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Thermal resistance of the conductor screen	T_{1_gs}	0.037564	0.035167	K·m/W
Thermal resistance of insulation	T_{1_i}	0.36654	0.36816	K·m/W
Thermal resistance of the insulation screen	T_{1_is}	0.015772	0,01701	K·m/W
Thermal resistance between conductor and screen	T_1	0.41987	0.42033	K·m/W

Table 8 Results of the intermediate calculations and result of the thermal resistance between the conductor and the screen.

Due to the different thicknesses of the conductor and insulation layers specified in the CIGRE case, small deviations emerge in T_1.

2.6 Thermal resistance between screen and armor (T_2)

Because there is no armoring or outer metal sheath layers present, $T_2 = 0$ applies to both the CIGRE report and VCA results.

2.7 Thermal resistance of the external layer (T_3)

$$T_3 = \frac{\rho_e}{2 \cdot \pi} ln\left[1 + \frac{2 \cdot t_3}{d_s}\right]$$

Equation 16. The thermal resistance according to IEC 60287-2-1: 4.1.4.1, which is also used in VCA. Where t_3 is the thickness of the outer sheath and d_s is the diameter of the screen. ρ is the resistivity of the outer sheath. See also Table 2.

Due to the triangle formation with cables with a metal screen touching each other (IEC 60287-4.2.4.3.2), a factor of 1.6 is added.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Corrected thermal resistance of the outer sheath	T3	0.08672	0.08672	K·m/W

Table 9 Results of the intermediate calculations of the thermal resistance of the outer sheath.

2.8 External thermal resistance (T_4)

$$u = \frac{2 \cdot L}{d_e}$$

Equation 17. Relationship between installation depth (L) and diameter of the cable (de).

$$T_4 = \frac{1.5}{\pi} \cdot \rho \cdot [ln(2 \cdot u) - 0.630]$$

Equation 18. External thermal resistance. Where ρ is the thermal resistance of the soil.

$$T_4 = \frac{1}{2 \cdot \pi} \cdot \rho \cdot ln\left(u + \sqrt{u^2 - 1}\right)$$

Equation 19. Calculation of thermal resistance of the environment as implemented in VCA.

External thermal resistance is obtained from burial depth and cable diameter, together with the soil thermal resistivity. VCA evaluates T_4 as part of its iterative rating process, including mutual heating from neighboring cables. That general iterative treatment can differ from the hand calculation in the CIGRE brochure even when the final current remains close.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Ratio of installation depth of triangle (circuit) and diameter of single cable	u	26.490	26.490	
External thermal resistance	T_4	1.5947	1.5947	K·m/W

Table 10 Result of the thermal resistance of the environment, both from the CIGRE report and from VCA.

2.9 Maximum allowed current

$$I = \sqrt{\frac{\Delta\theta \ - W_d \cdot [0.5 \cdot T_1 + n \cdot (T_2 + T_3 + T_4)]}{R \cdot T_1 + n \cdot R \cdot (1 + \lambda_1) \cdot T_2 + n \cdot R \cdot (1 + \lambda_1 + \lambda_2) \cdot (T_3 + T_4)}}$$

Equation 20. Calculation of the maximum allowable current by an iteration process (IEC 60287-1-1 clause 1.4.1.1).

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.38514	0.38344	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.42033	K·m/W
Thermal resistance between sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.08672	0.08672	K·m/W
Thermal resistance environment	T_4	1.5947	1.5947	K·m/W
Losses in metal sheath	λ_1	0.2939	0.2939	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	3.9522×10^{-5}	3.9522×10^{-5}	Ω/m
Number of cores	n	1	1	
Maximum current	I	821.77	821.77	A

Table 11 Summary of results needed for current calculation.

The maximum current is obtained iteratively from IEC 60287-1-1. For the base Case 0 installation, CIGRE and VCA both give I = 821.77 A (when rounded off to two decimals)

2.10 Losses and temperatures

$$W_g = R \cdot I^2$$

Equation 21. Losses of the conductor.

$$W_s = \lambda_1 \cdot R \cdot I^2$$

Equation 22. Screen losses.

$$\theta_e = \theta_a + n \cdot (W_c + W_s + W_d) \cdot T_4$$

Equation 23. Temperature of the outer jacket.

$$\theta_s = \theta_e + n \cdot (W_c + W_s + W_d) \cdot T_3$$

Equation 24. Temperature of the screen.

$$\theta_c = \theta_s + \left(W_c + \frac{W_d}{2}\right) \cdot T_1$$

Equation 25. Temperature of the conductor.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	W_g	26.690	26.685	W/m
Screen losses	W_s	7.8442	7.843	W/m
Temperature of the conductor	θ_g	90	90	°C
Screen temperature	Θ_s	78.713	78.709	°C
Temperature of outer jacket	Θ_e	75.685	75.683	°C

Table 12 Comparing the values for conductor and screen losses from the CIGRE report and VCA. The highest values are shown for the VCA values. The values of the three different cables can be found in Figure 3.

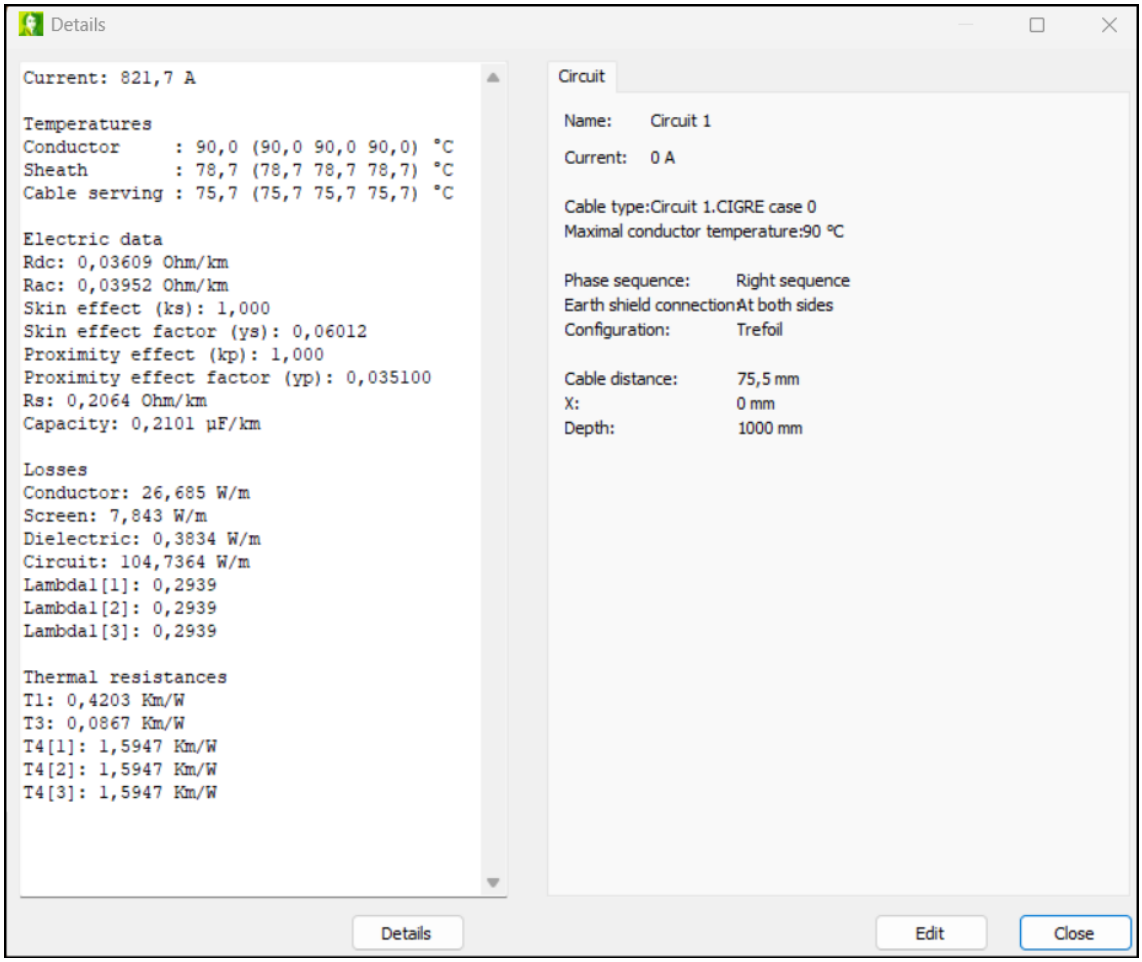


Figure 3 Results of VCA for the base case.

Conductor and screen losses and the associated temperatures are compared after the rating calculation. VCA reports phase-resolved values; the tabulated comparison uses the highest phase values.

Because the CIGRE examples are calculated by hand, geometric exceptions and cable positions are treated case by case. In VCA, component temperatures are updated during iteration by adjusting an effective ambient temperature that starts from the specified ambient value θa and accounts for heating from neighboring cables.

The CIGRE report also argues that neglecting eddy-current losses with a both-side earth-screen connection underestimates the required derating (about 2.4% for the base case, corresponding to I ≈ 803.16 A). IEC 60287-1-1 clause 2.3.1 does not require those eddy-current losses for a both-side bonded screen, and VCA therefore omits them in that bonding arrangement.

2.11 Situation of a one-sided earth screen

When there is an earth screen connection on one side (single point bonding), the Eddy current losses must be taken into account. These losses are calculated using Equation 26, the intermediate calculations (Equation 27-Equation 32), and the parameters from Table 2, Table 5 and Table 7. These equations correspond to the formulas in VCA.

$$\lambda''_1 = \frac{R_s}{R} \cdot \left[g_s \cdot \lambda_0 \cdot (1 + \Delta_1 + \Delta_2) + \frac{(\beta_1 \cdot t_s)^4}{12 \cdot 10^{12}} \right]$$

Equation 26. Eddy current losses. The intermediate calculations can be found in Equation 27-Equation 32.

where:

$$\beta_1 = \sqrt{\frac{4 \cdot \pi \cdot \omega}{10^7 \cdot \rho_s}}$$

Equation 27. Interim calculation for the parameter β_1 from Equation 26.

$$m = \frac{\omega}{R_s} 10^{-7}$$

Equation 28. Interim calculation for the parameter m from Equation 26.

$$g_s = 1 + \left(\frac{t_s}{d_s}\right)^{1.74} \cdot (\beta_1 \cdot d_s \cdot 10^{-3} - 1.6)$$

Equation 29. Interim calculation for the parameter g_s from Equation 26.

$$\lambda_0 = 3 \cdot \frac{m^2}{1 + m^2} \cdot \left(\frac{d_{gem}}{2 \cdot s}\right)^2$$

Equation 30. Interim calculation for the parameter λ_0 from Equation 26.

$$\Delta_1 = (1.14 \cdot m^{2.45} + 0.33) \cdot \left(\frac{d_{gem}}{2 \cdot s}\right)^{0.92m+1.66}$$

Equation 31. Interim calculation for the parameter Δ_1 from Equation 26.

$$\Delta_2 = 2$$

Equation 32. Interim calculation for the parameter Δ_2 from Equation 26.

In Table 13 a comparison is made between the outcome of the CIGRE report with the results from VCA in the case of an earth screen connection on one side. The other results remain the same

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Losses in metal sheath	λ_1	0.07770	0.07770	
Maximum current	I	886.17	886.09	A

Table 13 Current intensity results from the CIGRE report and VCA in the case of a one-sided earth screen.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	W_g	31.036	31.032	W/m
Screen losses	W_s	2.4117	2.4117	W/m
Temperature of the conductor	θ_g	90	90	°C
Screen temperature	Θ_s	76.887	76.9	°C

Table 14 Comparing the values for losses of the conductor and the screen from the CIGRE report and VCA in the case of a one-sided earth screen.

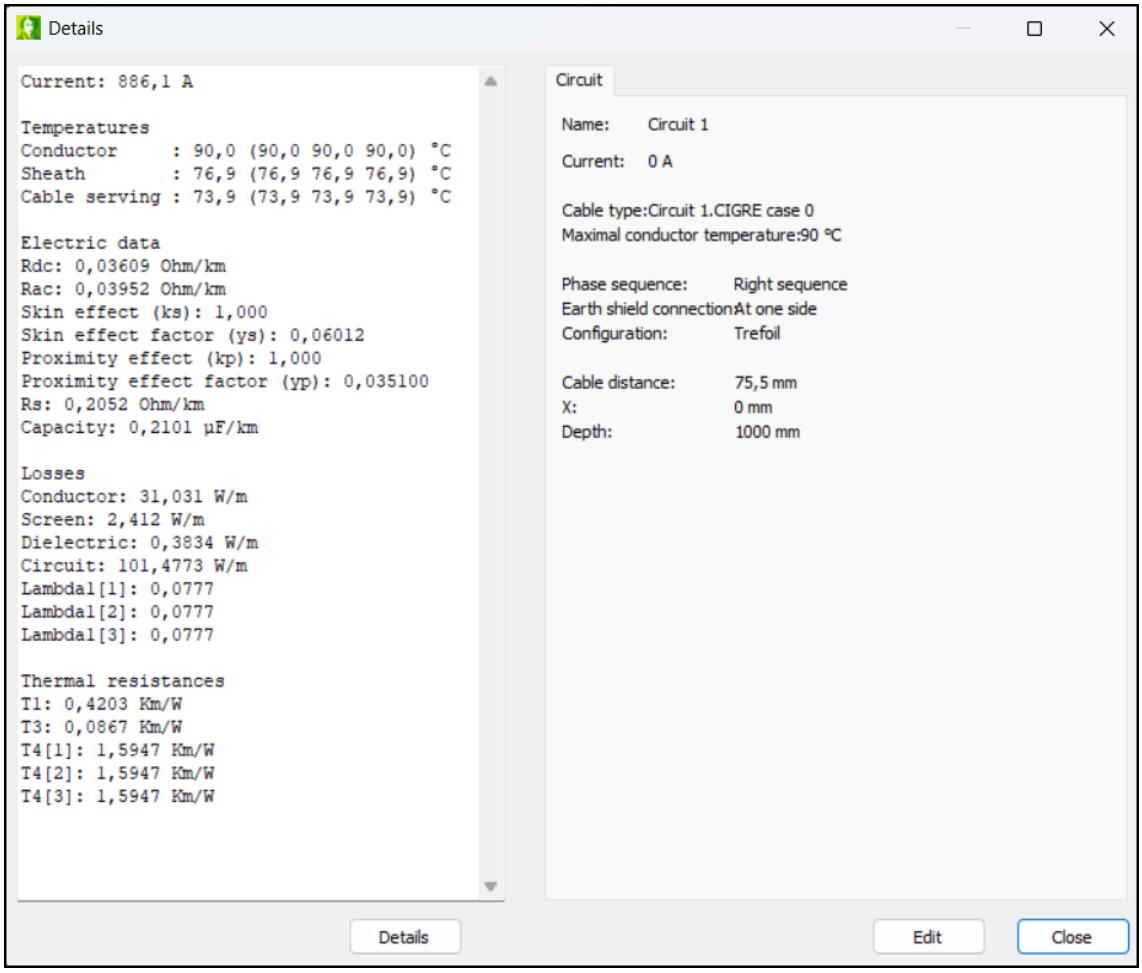


Figure 4 Results of VCA in the case of single point bonding

The resulting currents are essentially identical: CIGRE 886.17 A and VCA 886.09 A. Conductor and screen losses likewise agree closely.

2.12 Cables in HDPE pipes

This variant places the three cables in separate touching HDPE pipes. Most rating inputs remain as in the base case (see Figure 5).

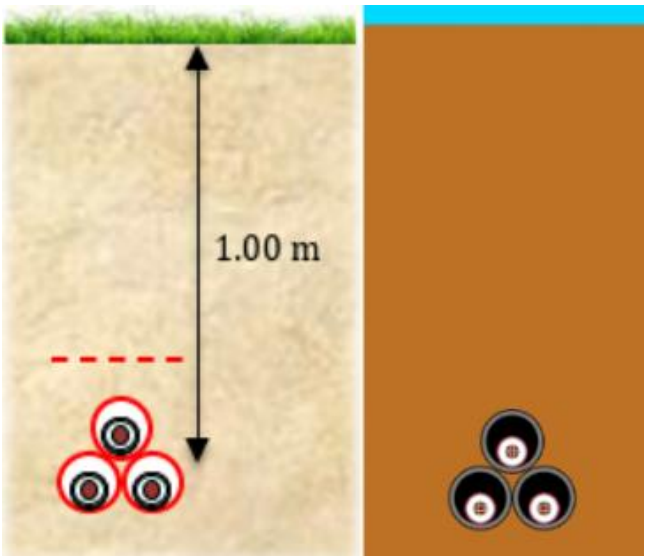


Figure 5 The situation from the CIGRE report and the comparable situation in VCA. Here the cables are placed in separate HDPE pipes.

Many of the parameters from section 2.9 that are required for the calculation of the maximum current remain the same. For these parameters, refer to the previous paragraphs. The parameters that change due to the adapted situation (i.e. placing the cables in separate tubes) are the reactance (X), the thermal resistance of the outer sheath (T_3), the thermal resistance of the environment (T_4) and the losses in the sheath (λ_1).2.9

Because the distance between the cables is increased, the reactance changes (see Table 15) and because the cables do not touch each other, the thermal resistance of the outer sheath changes (1.6 factor no longer applies). The adjusted values of the above parameters are summarized in Table 15.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
External diameter of the pipe	D_o	140	140	mm
Internal diameter of the tube	D_i	119.4	119.4	mm
Reactance per unit length of screen	X	8.9203×10^{-5}	8.9203×10^{-5}	Ω/m
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W

Table 15 Additional parameters for the situation where the cables are laid in pipes.

The results of the reactance, the thermal resistance of the outer sheath and the losses in the sheath are similar when we compare the CIGRE report with VCA.

To determine the thermal resistance of the environment (T_4), the intermediate results of Equation 33- Equation 35 are needed. Finally, Equation 36 gives the thermal resistance of the environment (T_4).

$$T_4' = \frac{U}{1 + 0.1 \cdot (V + Y \cdot \theta_m) \cdot d_e}$$

Equation 33. The thermal resistance between the cable and the tube. θ_m is the average temperature of the medium between the cable and the pipe.

The values of U, V and Y for a plastic tube can be found in Table 16. Because θ_m is not known, this is calculated through an iteration process. In the CIGRE report, 70°C is chosen as the starting value for θ_m (maximum operating temperature - 20°C). In VCA the starting value is set to 0°C.

Parameters	Result CIGRE	Result VCA	Unit
U	1.87	1.87	-
V	0.312	0.312	-
Y	0.0037	0.0037	-
θ_m start value	70	0	°C
θ_m end value	74.743	74.180	°C
ρ_{PE}	3.5	3.5	K·m/W

Table 16 Parameters associated with Equation 33 for a plastic tube.

$$T_4'' = \frac{1}{2 \cdot \pi} \cdot \rho_{PE} \cdot ln\left(\frac{D_o}{D_i}\right)$$

Equation 34. The thermal resistance of the tube.

$$T_4''' = \frac{1}{2 \cdot \pi} \cdot \rho \cdot [ln(2u) + 2ln(u)]$$

Equation 35. The thermal resistance of the area surrounding the pipe.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Ratio of installation depth of triangle and diameter of single pipe	u	14.285	14.285	-

Table 17 The ratio of the installation depth triangle and diameter of the pipe.

$$T_4 = T'_4 + T''_4 + T'''_4$$

Equation 36. The structure of the thermal resistance of the environment

Breaking down into the components relating to the different resistance layers. T'_4 = thermal resistance between the cable and the pipe, T''_4 = thermal resistance of the pipe and T'''_4 = thermal resistance of the area surrounding the pipe. See Table 18 for the calculated values and the comparison.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Thermal resistance between cable and tube	T'_4	0.3434	0.3434	K·m/W
Thermal resistance of the tube	T''_4	0.0887	0.0887	K·m/W
Thermal resistance environment tube	T'''_4	1.38	1.38	K·m/W
Thermal resistance environment	T_4	1.8121	1.8121	K·m/W

Table 18 Overview of the components of the thermal resistance of the environment (T_4) .

Table 19 provides an overview of the parameters required for the calculation of the maximum current. This shows that the maximum current intensity of the CIGRE report is quite similar to the results of VCA.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.38514	0.3834	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.4203	K·m/W
Thermal resistance between sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W
Thermal resistance environment	T_4	1.8121	1.8121	K·m/W
Losses in metal sheath	λ_1	0.83431	0.8343	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	3.8620×10^{-5}	3.8620×10^{-5}	Ω/m
Number of cores	N	1	1	
Maximum current	I	682.81	682.80	A

Table 19 Results of the CIGRE report and VCA when the cables are placed separately in conduits.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	W_g	18.006	18.004	W/m
Screen losses	W_s	15.022	15.021	W/m
Temperature of the conductor	θ_g	90	90	°C
Screen temperature	Θ_s	82.359	82.36	°C

Table 20 Comparing the values for conductor and screen losses from the CIGRE report and VCA.

The highest values are shown for the VCA values. The values of the three different cables can be found in Figure 6.

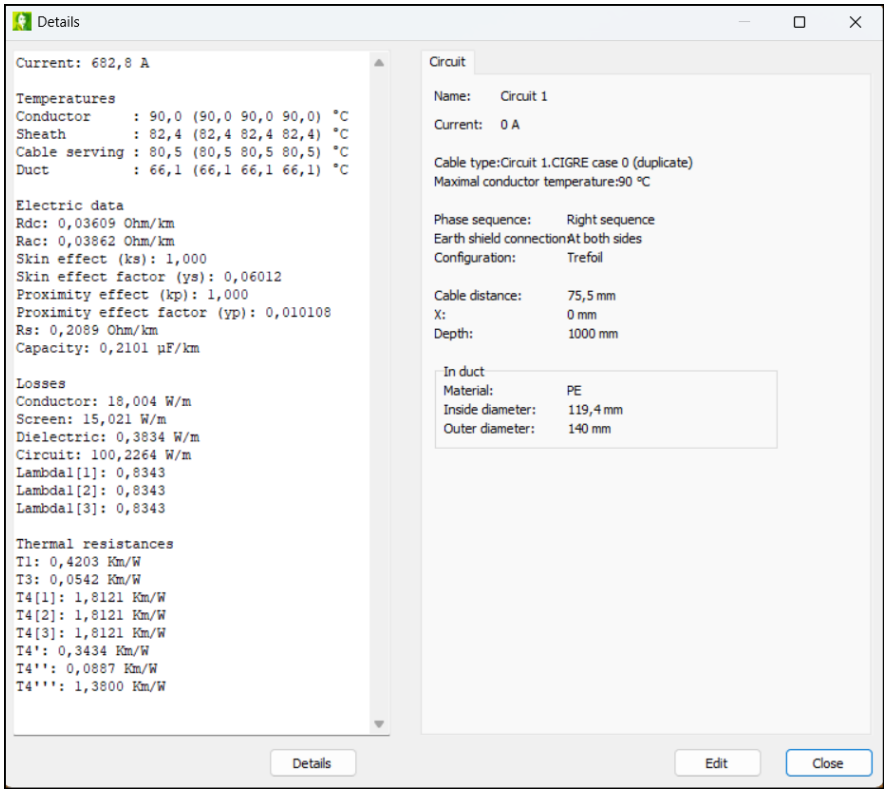


Figure 6 VCA results for cables placed in separate conduits.

The CIGRE report also gives the results in the case of not neglecting the eddy current losses. As a result, a derating factor of 0.5% is overlooked (I = 679.84 A). That effect is not implemented in VCA because it is not required by the IEC standard.

2.13 Cables in PVC pipes embedded in cement in flat configuration

Case 0 is expanded in this section with the placement of the cables underground in a flat-plane configuration. The cables are placed in separate PVC pipes that are symmetrically spaced apart and embedded in cement (Figure 7).

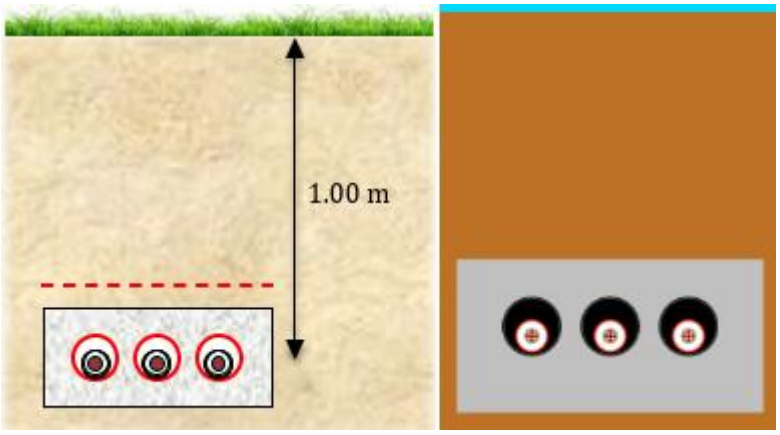


Figure 7 The situation from the CIGRE report and the comparable situation in VCA. Here the cables are placed in separate HDPE pipes and placed in a pipe bank.

Many of the parameters from section 2.9 that are required for the calculation of the maximum current remain the same. For these parameters we refer to the previous paragraphs. The parameters that change due to the adapted situation (i.e. placing the cables in separate tubes) are the proximity factor (y_p), the reactance (X), the thermal resistance of the outer sheath (T_3), the thermal resistance of the environment (T_4) and the losses in the sheath (λ_1).

Table 21 provides an overview of the dimensions of the pipes and the pipe bank.

Parameters	Symbol	Values	Unit
External diameter of the pipe	D_o	125	mm
Internal diameter of the tube	D_i	118.6	mm
Space between tubes	-	40	mm
Width of duct bank	x	325	mm
Duct bank height	y	655	mm
Axial distance between tubes	D_a	165	mm
Bottom of the tube bench	-	1162.5	mm
Thermal resistance of the cement	ρ_c	0.8	K·m/W

Table 21 Properties of the tubes and tube bank.

Due to the change in the distance of the axial distance between the conductors, the proximity factor must be recalculated (Equation 5). By replacing the parameter s with D_a we obtain the proximity factor for the current situation (see Table 22). The calculations and results of the CIGRE report compared to those from VCA are similar. The calculations for the AC resistance of the conductor are also similar.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Proximity factor	y_p	7.2685×10^{-3}	7.2685×10^{-3}	
AC resistance of the conductor	R_{AC}	3.8517×10^{-5}	3.8517×10^{-5}	Ω/m

Table 22 Overview of the parameters from the CIGRE report and from VCA.

For the flat configuration, two separate calculations for the reactance (X) are required. The other parameters can be found in Table 2 and Table 6.

$$X = 2 \cdot \omega \cdot 10^{-7} \cdot ln\left(\frac{2D_a}{d_{gem}}\right)$$

Equation 37. Screen reactance per unit cable length for two adjacent 1-core cables.

The following applies here: d_{gem} = average diameter of the screen (d_{is}+t_s).

$$X_m = 2 \cdot \omega \cdot 10^{-7} \cdot ln(2)$$

Equation 38. Joint reactance per unit length of cable between shield of the outer cable and the conductors of the other two cables.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Screen reactance per unit cable length for two adjacent 1-core cables	X	9.9526 x 10^{-5}	9.9526 x 10^{-5}	Ω/m
Joint reactance per unit length of the cable between the screen of the outer cable and the conductors of the other two cables	X_m	4.3552 x 10^{-5}	4.3552 x 10^{-5}	Ω/m

Table 23 Overview of the reactance results from the CIGRE report and from VCA.

The calculations and results for the reactance from the CIGRE report are identical to the results from VCA.

To calculate the losses (Table 24), Equation 39-Equation 42 and the value for R_s from Table 7 are needed. If we compare the results of the CIGRE report with those of VCA, we notice a small difference. Small differences in the loss factors follow from the small difference already present in T_1(Section 2.3).

$$P = X - X_m \ , \qquad Q = X - \frac{X_m}{3}$$

Equation 39

$$\lambda'_{1m} = \frac{R_s}{R} \cdot \frac{Q^2}{{R_s}^2 + Q^2}$$

Equation 40. Loss factor for center cable.

$$\lambda'_{11} = \frac{R_s}{R} \cdot \left[\frac{0.75 \cdot P^2}{{R_s}^2 + P^2} + \frac{0.25 \cdot Q^2}{{R_s}^2 + Q^2} + \frac{2 \cdot R_s \cdot P \cdot X_m}{\sqrt{3} \cdot \left({R_s}^2 + P^2\right) \cdot \left({R_s}^2 + Q^2\right)}\right]$$

Equation 41. Loss factor of the cable with the highest losses.

$$\lambda'_{12} = \frac{R_s}{R} \cdot \left[\frac{0.75 \cdot P^2}{{R_s}^2 + P^2} + \frac{0.25 \cdot Q^2}{{R_s}^2 + Q^2} - \frac{2 \cdot R_s \cdot P \cdot X_m}{\sqrt{3} \cdot \left({R_s}^2 + P^2\right) \cdot \left({R_s}^2 + Q^2\right)}\right]$$

Equation 42. Loss factor of the outer cable.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Intermediate parameter	P	14.308 x 10^{-5}	14.308 x 10^{-5}	Ω/m
Intermediate parameter	Q	8.5009 x 10^{-5}	8.5009 x 10^{-5}	Ω/m
Loss factor for center cable	λ_{1m}'	0.77484	0.7688	-
Loss factor of the cable with the highest losses	λ_{11}'	1.7105	1.72989	-
Loss factor of the outer cable	λ_{12}'	1.2819	1.2905	-
	λ_1'	1.7013	1.7013	

Table 24 Overview of the results of the CIGRE report and VCA regarding the loss factor of the cables.

In Table 24, the CIGRE result values are the initialized values and VCA results are from the final iteration (excluding λ_1'). The final iteration values are not known from the TB880 brochure in the CIGRE case.

T_4' remains equal to the value calculated in Table 18. T_4'' is recalculated via Equation 47 with the parameters from Table 21. This value (see Table 25) corresponds to the value from VCA. To calculate T_4''', Equation 43 is used. This is also the formula used in VCA. To calculate the correction factor, Equation 44-

Equation 46 and the parameters from Table 21 are required. In the CIGRE report, a correction factor is calculated for the difference between the thermal resistance of the cement and the soil. These calculations are identically present in VCA.

$$T_4''' = \frac{1}{2 \cdot \pi} \cdot \rho_c \cdot ln\left(u + \sqrt{u^2 - 1}\right)$$

Equation 43. External thermal resistance of the tube.

$$\ln(r_b) = \frac{1}{2} \cdot \frac{x}{y} \cdot \left(\frac{4}{\pi} - \frac{x}{y}\right) \cdot ln\left(1 + \frac{y^2}{x^2}\right) + ln\left(\frac{x}{2}\right)$$

Equation 44. Equivalent radius of the tube bench.

$$u = \frac{L}{r_b}$$

Equation 45. Adjusted location depth.

$$T_{4,corr}''' = \frac{N}{2 \cdot \pi} \cdot (\rho_e - \rho_c) \cdot ln\left(u + \sqrt{u^2 - 1}\right)$$

Equation 46. Correction to the thermal resistance for embedding in cement.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Equivalent radius of the tube bank	r_b	222.14	222.14	mm
Adjusted depth	u	4.5016	4.5016	
Number of cables in the duct bank	N	3	3	-
Correction factor on external thermal resistance of the tube	$T_{4,corr}'''$	0.20865	0.20865	K·m/W

Table 25 Overview of the parameters associated with the calculation of the correction factor $T_{4,corr}'''$.

To get the total external thermal resistance, Equation 47 is needed. The summary of all individual components and the result of the CIGRE report, compared to the results of VCA, are shown in Table 26.

$$T_4 = T'_4 + T''_4 + T'''_4 + T_{4,corr}'''$$

Equation 47. Calculation of the thermal resistance of the environment.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Thermal resistance between cable and tube	T'_4	0.35210	0.34625	K·m/W
Thermal resistance of the tube	T''_4	0.050188	0.050188	K·m/W
Thermal resistance environment tube	T'''_4	0.44115	0.44115	K·m/W
Correction factor for difference in thermal resistance of cement and soil	T_4, corr	0.20865	0.20865	K·m/W
Thermal resistance environment	T4	1.0521	1.0540	K·m/W

Table 26 Overview of the thermal resistance parameters of the environment.

It should be noted that the T'_4 value is temperature dependent. The value reported by CIGRE corresponds to the first iteration. Because VCA and CIGRE used different initial values for the average temperature, their first T'_4 values cannot be identical and given that CIGRE didn't record the final value for T'_4, direct comparison is not possible.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.38514	0.3834	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.4203	K·m/W
Thermal resistance between sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W

Thermal resistance environment	T_4	1.0521	1.0527	K·m/W
Losses in metal sheath	λ_1	1.7013	1.7013	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	3.8517×10^{-5}	3.8517×10^{-5}	Ω/m
Number of cores	N	1	1	
Maximum current	I	634.07	633.74	A

Table 27 Results of the CIGRE report and VCA when the cables are placed individually in pipes and embedded in cement.

The rated currents remain very close (See Table 27): CIGRE 634.07 A and VCA 633.74 A (difference ≈ 0.05%). Remaining differences in phase losses and temperatures are consistent with that small current difference and with the dielectric loss / T_1 modelling effects noted earlier.

Parameters	Symbol	Result	λ_{11}	λ_{1m}	λ_{12}	Unit
Conductor losses	W_g	CIGRE	15.486	15.142	15.248	W/m
		VCA	15.469	-	-	
Screen losses	W_s	CIGRE	26.346	12.128	19.891	W/m
		VCA	26.319	-	-	
Temperature difference above ambient temperature	$\Delta\Theta_P$	CIGRE	17.008	24.730	18.554	°C
		VCA	17.010	24.700	18.454	
Temperature of the conductor	θ_g	CIGRE	90	81.815	84.359	°C
		VCA	90	81.797	84.338	
Screen temperature	Θ_s	CIGRE	83.417	75.376	77.875	°C
		VCA	83.415	75.358	77.854	
Temperature of the outer sheath	Θ_j	CIGRE	81.129	73.877	75.950	°C
		VCA	81.118	73.860	75.930	

Table 28 Comparison of the values from the CIGRE report and VCA. The losses and temperatures of the individual components are broken down per cable.

The individual temperatures and losses are almost similar also considering the different ducts in this particular configuration. The conductor and screen losses are calculated only for the hottest cables in VCA

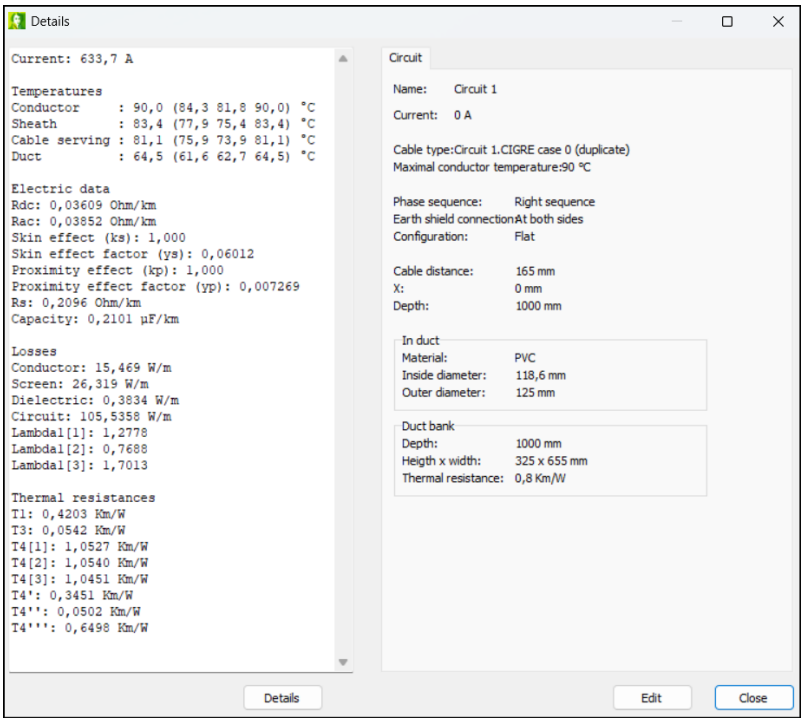


Figure 8 Results from VCA.

CIGRE states that omitting eddy-current losses under both-side bonding would miss about 0.22% derating (I ≈ 633.04 A).

2.14 Cables in PVC pipes embedded in cement in flat formation with one-sided earth screen

For this situation in the case of a one-sided earth screen (single point bonding), the eddy current losses must be taken into account.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.38514	0.3834	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.4203	K·m/W
Thermal resistance between sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W
Thermal resistance environment	T_4	1.0538	1.0538	K·m/W
Losses in metal sheath	λ_1	0.03095	0.0316	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	3.8517×10^{-5}	3.8517×10^{-5}	Ω/m
Number of cores	N	1	1	
Maximum current	I	904.55	904.64	A

Table 29 Results of the CIGRE report and VCA.

With single-point bonding, eddy-current losses are included. CIGRE and VCA currents are consistent: 904.55 A and 904.64 A respectively.

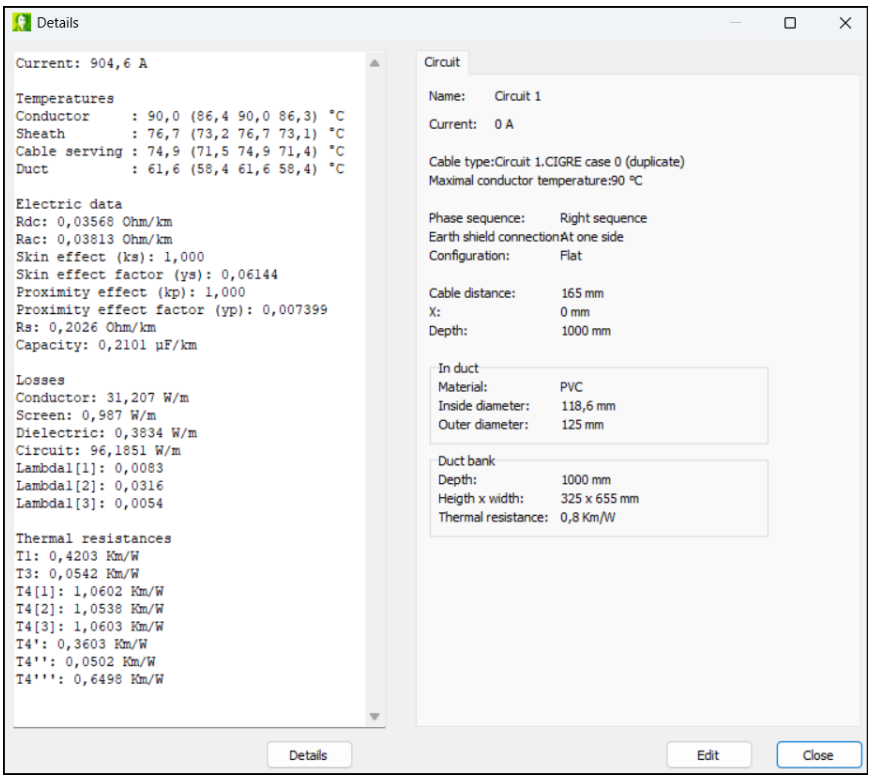


Figure 9 Results of VCA in the case of a one-sided earth shield.

2.15 Cables above ground exposed directly to sunlight

In this section the case is modified. Here the cables are exposed to sunlight in a triangle configuration in the open air (Figure 10).

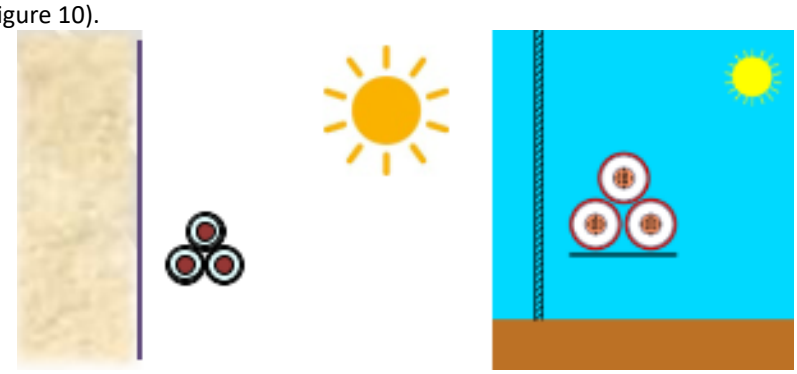


Figure 10 The cables in triangle configuration where the cables are exposed to direct sunlight.

The cable parameters are the same as in section 2.1. The adjusted environmental parameters can be found in Table 30. Many parameters from Table 11 remain unchanged, with the exception of T_4. This will be recalculated later in the section. The value of T_3 also deviates somewhat. The calculation is the same as Equation 16, except that a multiplication factor of 1.6 is not applied since the cables are not buried. The value of T_3 is therefore equal to the value from Table 17.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Intermediate parameter	Z	0.98	0.98	
Intermediate parameter	E	1.25	1.25	
Intermediate parameter	g	0.20	0.20	
Ambient temperature	θ_a	25	25	°C
Intensity of sunlight	H	1000	1000	W/m^2
Absorption coefficient of solar radiation for cable surfaces	σ	0.4	0.4	

Table 30 Parameters associated with the case where the cables are placed in direct sunlight

The parameters from Table 2, Table 11 and Table 17 are required for the calculations below. The calculations below correspond to the calculations in VCA.

$$h = \frac{Z}{(d_e)^g} + E$$

Equation 48. Heat dissipation coefficient.

$$\Delta\theta_d = W_d \cdot \left(\frac{1}{1+\lambda_1+\lambda_2} - \frac{1}{2}\right) \cdot T_2 - \frac{n \cdot \lambda_2 \cdot T_2}{1+\lambda_1+\lambda_2}$$

Equation 49. Heating caused by dielectric losses.

$$K_A = \frac{\pi \cdot d_e \cdot h}{1+\lambda_1+\lambda_2} \cdot \left[\frac{T_1}{n} + T_2 \cdot (1+\lambda_1) + T_3 \cdot (1+\lambda_1+\lambda_2)\right]$$

Equation 50

$$\Delta\theta_{ds} = \frac{\sigma \cdot d_e \cdot h}{1+\lambda_1+\lambda_2} \cdot \left[\frac{T_1}{n} + T_2 \cdot (1+\lambda_1) + T_3 \cdot (1+\lambda_1+\lambda_2)\right]$$

Equation 51. Temperature change due to exposure to direct sunlight.

$$(\Delta\theta_s)^{1/4}{}_{n+1} = \left[\frac{\Delta\theta + \Delta\theta_d + \Delta\theta_{ds}}{1 + K_A \cdot (\Delta\theta_s)^{1/4}{}_n}\right]^{\frac{1}{4}}, \quad (\Delta\theta_s)^{\frac{1}{4}}{}_{n+1} - (\Delta\theta_s)^{\frac{1}{4}}{}_n \leq 0.001$$

Equation 52. Recursion equation to calculate the surface temperature of the cable above ambient temperature.

The following applies: Δθ = 90 - 25 = 65 °C.

$$T_4 = \frac{1}{\pi \cdot D^*_e \cdot h \cdot (\Delta\theta_s)^{\frac{1}{4}}}$$

Equation 53. External thermal resistance.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Heat dissipation coefficient	h	2.8595	2.8595	$W/(m^2 \cdot K^{5/4})$
Intermediate parameter	K_A	0.25703	0.26721	K
External thermal resistance	T_4	0.56665	0.56650	K·m/W

Table 31 Results of the CIGRE report compared to the results of VCA.

The value of $\Delta\theta_d$ is set to 0 because the dielectric losses are neglected. Due to a small difference in T_1, there is a difference between the K_A, $\Delta\theta_{ds}$, $(\Delta\theta_s)^{1/4}$ and the T_4 value from the CIGRE report and the value from VCA.

$$I = \sqrt{\frac{\Delta\theta\ - W_d \cdot [0.5 \cdot T_1 + n \cdot (T_2 + T_3 + T_4)] - \sigma \cdot d_e \cdot H \cdot T_4}{R \cdot T_1 + n \cdot R \cdot (1 + \lambda_1) \cdot T_2 + n \cdot R \cdot (1 + \lambda_1 + \lambda_2) \cdot (T_3 + T_4)}}$$

Equation 54. Adjusted formula for the maximum current in case of cables above ground exposed to direct solar radiation.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Absorption coefficient of solar radiation for cable surfaces	σ	0.4	0.4	
External diameter of the cable	d_e	0.0755	0.0755	m
Intensity of sunlight	H	1000	1000	W/m2
Maximum allowable temperature rise of the conductor above ambient temperature	Δθ	65	65	°C
Dielectric losses per unit length per phase	W_d	0.38514	0.3834	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.4203	K·m/W
Thermal resistance between metal sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W
Thermal resistance environment	T_4	0.56665	0.5665	K·m/W
Losses in metal sheath	λ_1	0.29829	0.2982	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	3.9522×10^{-5}	3.9522×10^{-5}	Ω/m
Number of cores	N	1	1	
Maximum current	I	990.94	990.72	A

Table 32 Summary of results needed for current calculation.

The resulting currents are CIGRE 990.94 A and VCA 990.72 A (Table 32). Losses and temperatures remain similar.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	W_g	38.809	38.797	W/m
Screen losses	W_s	11.576	11.570	W/m
Temperature of the conductor	θ_g	90	90	°C
Screen temperature	Θ_s	73.624	73.7	°C

Table 33 Comparison of the losses and temperatures from the CIGRE report and VCA.

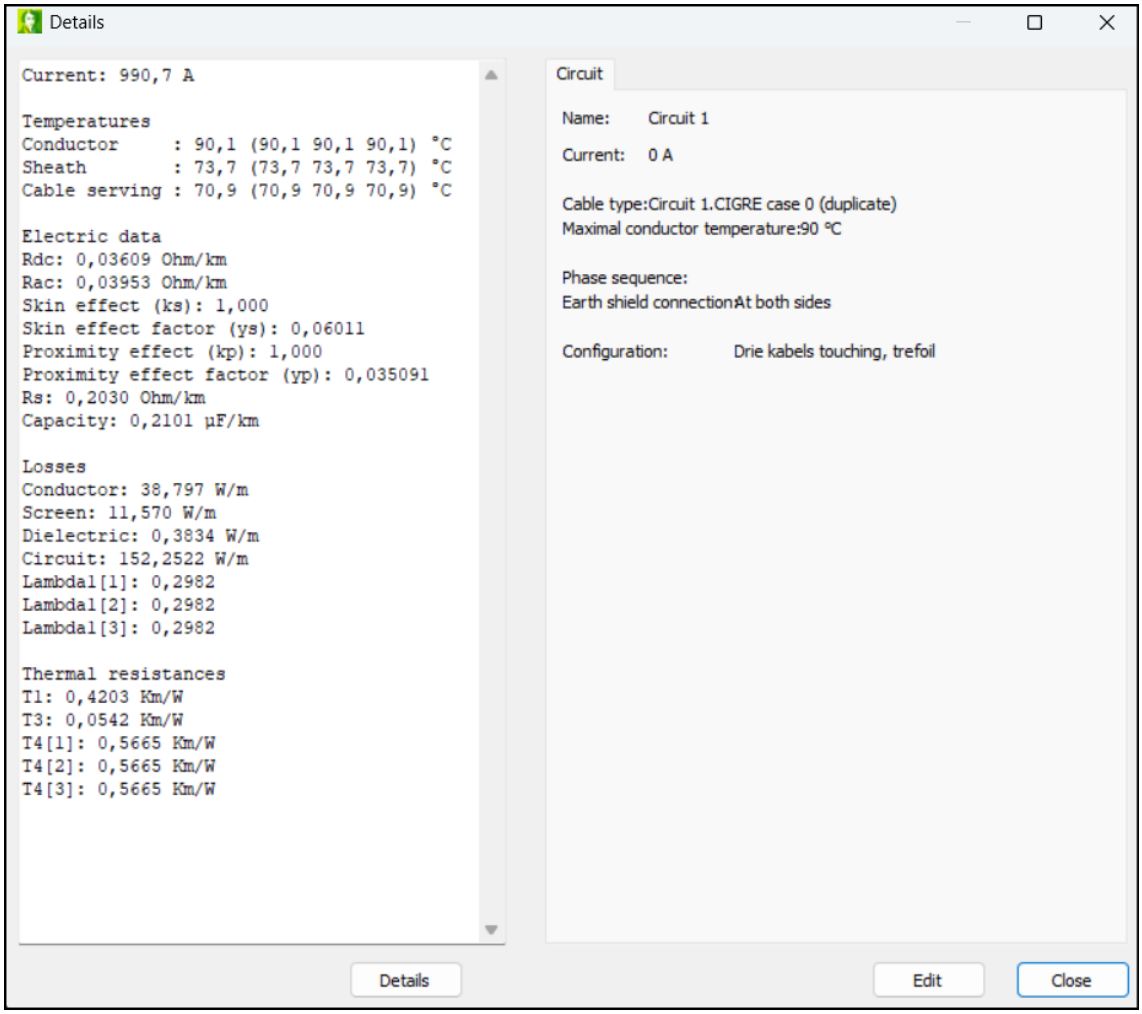


Figure 11 Results of VCA for cables exposed to direct sunlight.

For the above situation, the eddy current losses have been neglected, because the earth screen connection is present on both sides. This is according to the IEC standard. Eddy-current losses are again omitted for both-side bonding, in line with IEC. CIGRE estimates that including them would reduce the rating by about 1.66% (I ≈ 974.28 A).

2.16 Cables above the ground that are not directly exposed to solar radiation

For the situation above, with the exception that the cables are not exposed to direct sunlight, the results are shown in Table 34 and Table 35.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.38514	0.3834	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.4203	K·m/W
Thermal resistance between metal sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W
Thermal resistance environment	T_4	0.5876	0.5875	K·m/W
Losses in metal sheath	λ_1	0.30301	0.3029	
Losses in armouring	λ_2	0	0	

AC resistance conductor	R	3.9522×10^{-5}	3.9522×10^{-5}	Ω/m
Number of cores	n	1	1	
Maximum current	I	1141.36	1141.25	A

Table 34 Maximum current for overhead cables not directly exposed to solar radiation.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	W_g	51.485	51.477	W/m
Screen losses	W_s	15.601	15.582	W/m
Temperature of the conductor	θ_g	90	90	°C
Screen temperature	Θ_s	68.302	68.3	°C

Table 35 The associated losses and temperatures of the cables.

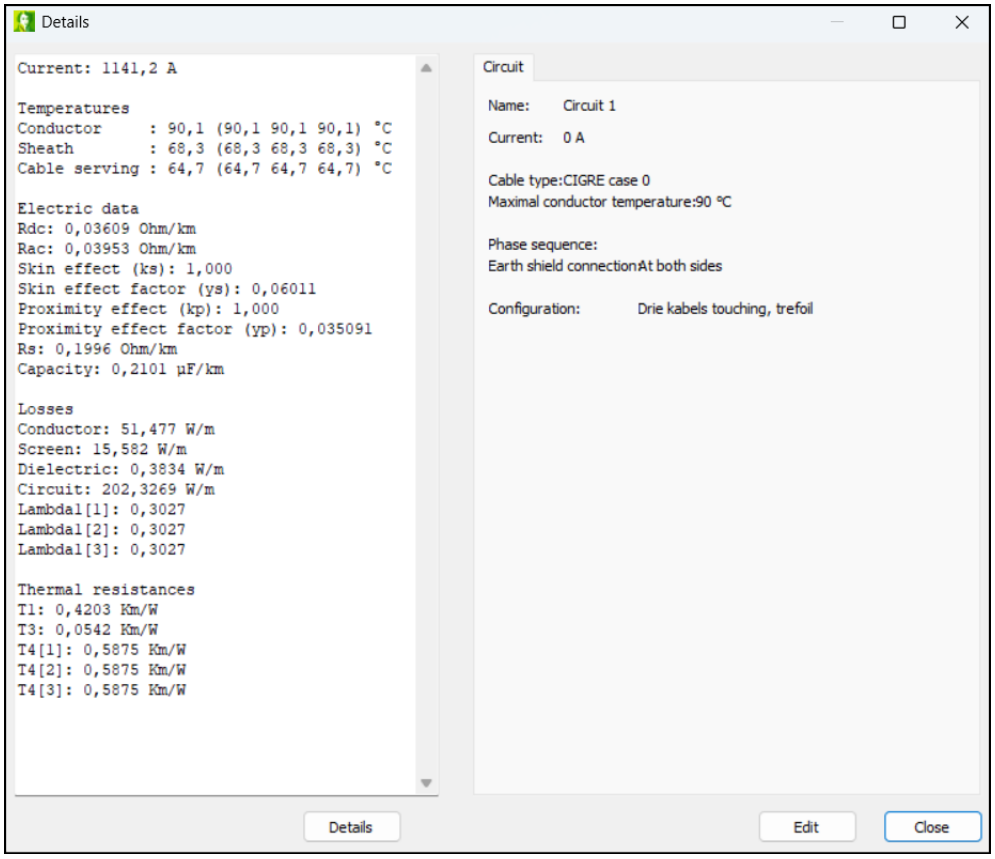


Figure 12 Results of VCA for cables not directly exposed to solar radiation.

Here too, there is a small difference between the calculated current intensity from the CIGRE report and VCA. This also comes from the difference in T_1.

2.17 Cables above the ground directly exposed to sunlight with a one-sided earth screen

For the situation of the cables above ground directly exposed to solar radiation with a one-sided earth shield, there are a few parameters that need to be recalculated (see Table 36). These are λ_1 and the intermediate parameters necessary for the calculation of T_4. These depend on λ_1.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Losses in metal sheath	λ_1	0.0790	0.0790	
Heat dissipation coefficient	h	2.8595	2.8595	$W/(m^2 \cdot K^{5/4})$
External thermal resistance	T_4	0.5718	0.5718	K·m/W

Table 36 The comparison of the results of λ1, T4 and the associated intermediate parameters from the CIGRE report and from VCA.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Absorption coefficient of solar radiation for cable surfaces	σ	0.4	0.4	
External diameter of the cable	d_e	0.0755	0.0755	m
Intensity of sunlight	H	1000	1000	W/m2
Maximum allowable temperature rise of the conductor above ambient temperature	$\Delta\theta$	65	65	°C
Dielectric losses per unit length per phase	W_d	0.38514	0	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.4203	K·m/W
Thermal resistance between metal sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W
Thermal resistance environment	T_4	0.5718	0.5718	K·m/W
Losses in metal sheath	λ_1	0.0790	0.0790	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	3.9522×10^{-5}	3.9522×10^{-5}	Ω/m
Number of cores	N	1	1	
Maximum current	I	1046.5	1046.23	A

Table 37 The results of the CIGRE report and VCA.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	W_g	43.281	43.266	W/m
Screen losses	W_s	3.4181	3.416	W/m
Temperature of the conductor	θ_g	90	90	°C
Screen temperature	Θ_s	71.747	71.8	°C

Table 38 Losses and temperatures of the cable components. The values of the CIGRE report are quite similar to the results of VCA.

With single-point bonding, λ_1 and the T_4 intermediate parameters that depend on λ_1 are recalculated. Currents agree closely: CIGRE 1046.5 A and VCA 1046.23 A (Table 37). The largest intermediate difference remains T_1; other differences are negligible for practical purposes. The losses fall also in the same range as in the CIGRE case (See Table 38)

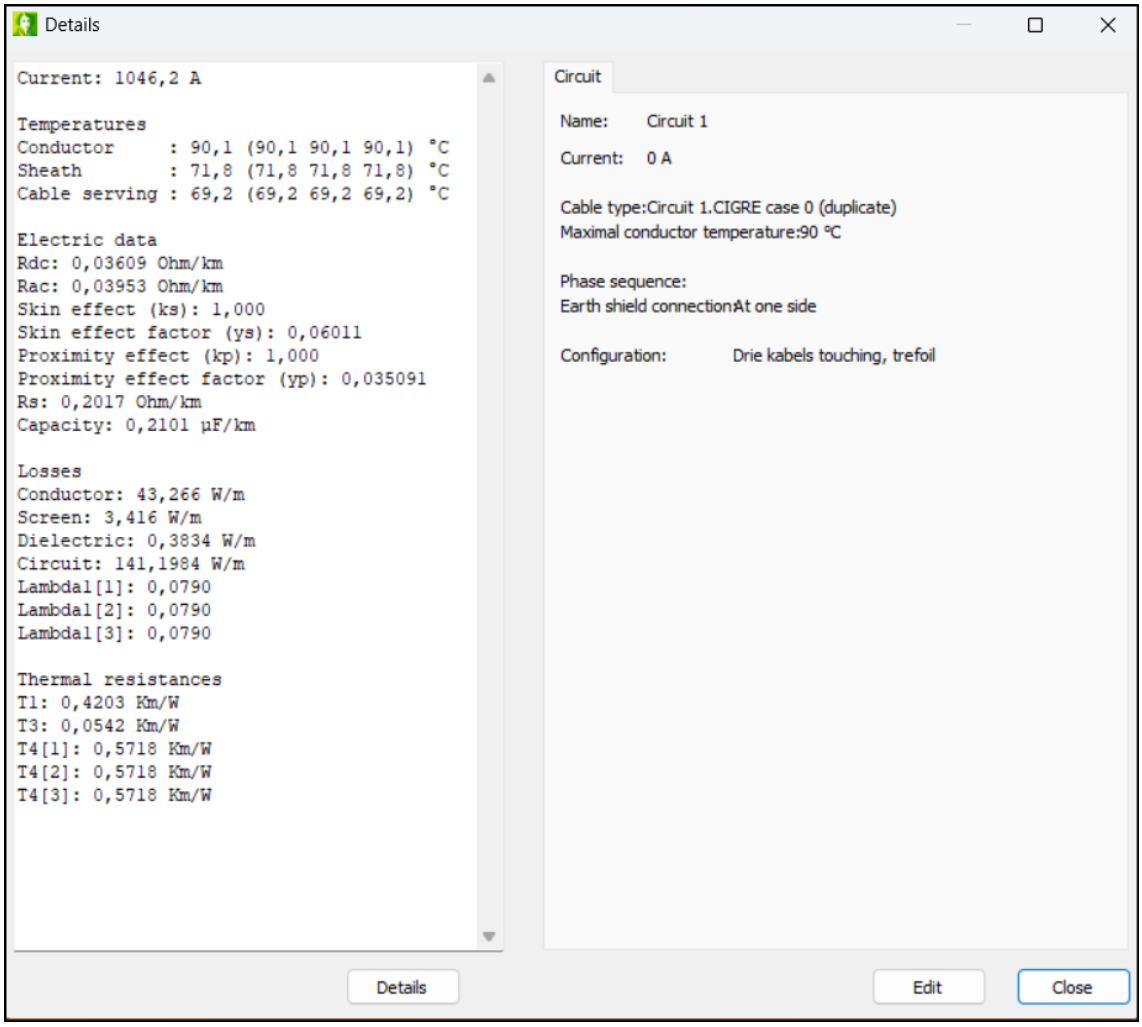


Figure 13 Results of VCA for single point bonding

2.18 Cables in an unfilled trench

This section looks at cables touching each other in a flat-plane formation placed in an unfilled trench (Figure 14). This situation is comparable to the situation where the cables are placed above the ground. Here there is no exposure to direct solar radiation due to the trench. The environmental parameters are shown in Table 39. The perimeter of the channel is set to 1.27 m.

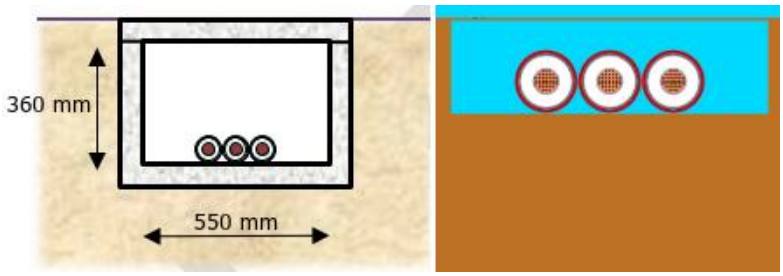


Figure 14 The representation from the CIGRE report and from VCA of cables in flat formation placed in an unfilled trench.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Intermediate parameter	Z	0.62	0.62	
Intermediate parameter	E	1.95	1.95	
Intermediate parameter	g	0.25	0.25	
Ambient temperature	θ_a	25		°C
Outline of the trench	p	1.27	1.27	

Table 39 The environmental parameters of the unfilled channel.

Many of the parameters are comparable to the values from section 2.16. The parameters that need to be recalculated are the reactance, heat dissipation coefficient, the losses of the screen and the thermal resistance of the environment. These are shown in Table 40 and Table 41. In Table 40, the CIGRE result values for the λ's are the initialized values and VCA results are from the final iteration (excluding λ_1'). The final iteration values are not known from the TB880 brochure in the CIGRE case.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Screen reactance per unit cable length for two adjacent 1-core cables	X	5.0403×10^{-5}	5.0403×10^{-5}	Ω/m
Joint reactance per unit length of the cable between the shield of the outer cable and the conductors of the other two cables	Xm	4.3552×10^{-5}	4.3552×10^{-5}	Ω/m
Loss factor for center cable	λ_{1m}'	0.15263	0.15506	-
Loss factor of the cable with the highest losses	λ_{11}'	0.78904	0.79920	-
Loss factor of the outer cable	λ_{12}'	0.62818	0.63399	-
Loss factor of the cable with the highest losses (final iteration)	λ_1'	0.7886	0.7886	

Table 40 Overview of the updated parameters for cable losses.

K_A in Table 41 has a small deviation in the calculation. This can be traced back to the T_1 calculation as discussed in section 2.3.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Heat dissipation coefficient	h	3.1328	3.1328	$W/(m^2 \cdot K^{5/4})$
Heating caused by dielectric losses	$\Delta\theta_d$	9.5341 x 10-3	0	°C
Intermediate parameter	K_A	0.21466	0.2136	$K^{-1/4}$

Temperature change due to air in the trench	$\Delta\theta_{tr}$	27.878	27.89	°C
External thermal resistance	T_4	0.6014	0.6017	K·m/W

Table 41 Overview of the recalculated parameters necessary for the calculation of the thermal resistance of the environment.

The final results of the maximum current are shown in Table 42. This table shows the values for the cable with the highest temperature. Table 43 shows the individual losses and temperatures of the cable components. Further data from VCA can be found in Figure 15.

$$I = \sqrt{\frac{\Delta\theta \ - W_d \cdot [0.5 \cdot T_1 + n \cdot (T_2 + T_3 + T_4)] - \Delta\theta_{tr}}{R \cdot T_1 + n \cdot R \cdot (1 + \lambda_1) \cdot T_2 + n \cdot R \cdot (1 + \lambda_1 + \lambda_2) \cdot (T_3 + T_4)}}$$

Equation 55. Adjusted formula for the maximum current in case of cables in an unfilled trench according to the CIGRE report.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.38514	0	W/m
Thermal resistance between conductor and insulation	T_1	0.41987	0.4203	K·m/W
Thermal resistance between metal sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.054200	0.054200	K·m/W
Thermal resistance environment	T_4	0.6014	0.6017	K·m/W
Losses in metal sheath	λ_1	0.78861	0.7886	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	3.9522×10^{-5}	3.9522×10^{-5}	Ω/m
Number of cores	N	1	1	
Maximum current	I	764.56	763.70	A

Table 42 Results of the maximum current and cable parameters from the CIGRE report and VCA.

For completeness, the losses and temperatures of the conductor and the screen from the CIGRE report have been compared and shown in Table 43 which are in line with expectations (minor deviations).

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	W_g	23.103	23,049	W/m
Screen losses	W_s	18.219	18.22	W/m
Temperature difference due to air in the trench	$\Delta\theta_{tr}$	27.878	27.89	°C
Temperature of the conductor	θ_g	90	90	°C
Screen temperature	Θ_s	80.219	80.2	°C

Table 43 A comparison of the values for losses and temperatures of the conductor and the screen from the CIGRE report and VCA.

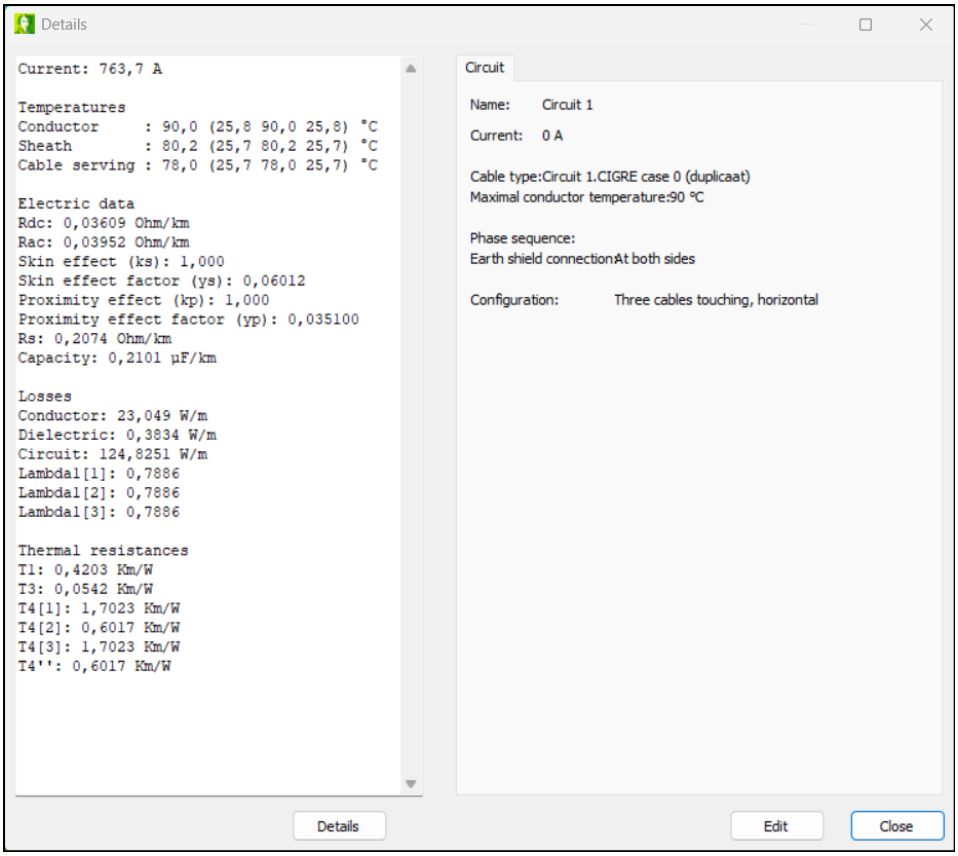


Figure 15 Results of VCA for cable in a trench

By neglecting the eddy current losses (according to the CIGRE report), the derating factor is underestimated by 1.43% (I = 754.86 A).

2.19 Conclusions

Across all Case 0 installations examined in this chapter, the maximum currents from CIGRE and VCA agree to well within 0.2%. Representative values are:

In these five variants under Case 0, the phase voltage (U_0) is not stated and this input value is calculated by dividing the line to line voltage by $\sqrt{3}$. As a result, there are no differences between the CIGRE report and VCA.

The main modelling differences that do appear in intermediate parameters are:

- Equal conductor and insulation screen thicknesses in VCA, which shift capacitance and dielectric losses relative to the unequal thicknesses used by CIGRE.
- Layer-by-layer T_1 in CIGRE versus the aggregated IEC formulation in VCA. Those differences remain visible in some intermediate quantities but do not materially change the rated current in these Case 0 examples.
- Eddy-current losses with both-side bonding, which CIGRE discusses as an additional derating but which IEC 60287-1-1 does not require and which VCA therefore omits.

Overall, for Case 0 the VCA ratings are consistent with the CIGRE brochure. Intermediate methodological differences are real and worth documenting, but they do not undermine the agreement on maximum current for the situations studied.

3 COMPARISON CIGRE CASE 4 WITH VCA

3.1 Cable properties and environmental parameters

For case 4, an underground 1-core cable of 33 kV with partial covering of screen wires was used (Figure 16 and Figure 17). This coverage is less than 50% of the screen and has been chosen as an example to demonstrate the application of the multiplication factors relating to T_1 and T_3 from IEC 60287.2.1 clause 4.2.4.3.3.

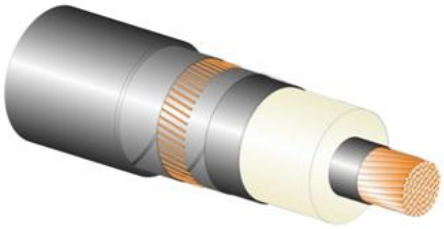


Figure 16 1-core XLPE cable with less than 50% screen coverage taken from the CIGRE report



Figure 17 XLPE cable simulated in the VCA cable type editor based on the values from Table 44 and Table 45.

Here d_g = diameter of the conductor, d_e = external diameter of the cable, t_i = thickness of the insulation, t_s = thickness of the screen, t_{gs} = thickness of the conductor screen and t_{is} = thickness of the insulation screen

Construction	Value	Unit	Symbol
Voltage Phase to phase (U)	33	kV	
Conductor, Surface area	240	mm^2	
Conductor, material	Copper	Material	
Conductor, type	Round compacted, stranded	Type	
Conductor, DC resistance at 20 °C	75.4×10^{-6}	Ω/m	R_0
Tape over conductor type/material	No	Type	
Insulation, type	XLPE unfilled	Type	
Maximum conductor temperature	90	°C	θ_g
Insulation permittivity	2.5		ε
Losing insulation	0.004		tan(δ)
Tape under metal screen/jacket type	Semiconductor	Type	
Wire screen, material	Copper	Material	
Wire screen, nominal cross-section	35	mm^2	
Wire screen, diameter wire	0.9	mm	Rev
Wire screen, laying length	240	mm	Ls
Wire screen, actual number of wires	56	Number	ns
Wire screen actual cross section (used)	35.63	mm^2	Ash
Counter helix	No	Yes/no	
Outer sheath, material	HDPE with semiconductor layer	Material	

Table 44 Cable specifications of case 4 taken from the CIGRE report.

Table 44 shows the structure of the cable. Here the insulation losses (tan(δ)) are set equal to 0.004, same as VCA. A further complication is that CIGRE states a phase-to-phase voltage, whereas VCA's rated voltage input is handled as a phase-related quantity; conversion follows the usual U / $\sqrt{3}$ relationship. The phase voltage conversion can be performed using Equation 56.

$$U = \sqrt{3}U_0$$

Equation 56. Conversion of phase voltage (U_0) to coupled voltage (U)

Table 45 shows the cable dimensions. As far as possible, these are also drawn in Figure 17. Not all specific shells from the CIGRE case could be defined in the cable type editor. Tape 1 and wire shield are collectively defined in VCA as shield and the combination of the three external layers (from Tape 2 to the outside of the cable) are scaled under the outer jacket. The parameters in the cross-section of Figure 17 are also noted in brackets in Table 47 for clarity with the following abbreviations: d_g = diameter of the conductor, de = external diameter of the cable, t_i = thickness of the insulation, t_s = thickness of the screen, t_{gs} = thickness of the conductor screen and t_{is} = thickness of the insulation screen. In VCA, the thickness of the insulation is called "t_1" instead of "t_i" (see Figure 17). The thickness of the conductor and insulation shield is calculated indirectly in VCA using Equation 57. For this cable type it is assumed that the thickness of both screens is the same

Thickness and diameters	Thermal resistance (ρ)	Layer thickness (t)	Diameter (d)
Unit	K·m/W	mm	mm
Conductor (g)			18.4 (=d_g)
Conductor screen (g_s)	2.5	0.5 (=t_{gs})	19.4

Insulation (i)	3.5	7.7 (= t_i)	34.8	
Insulation screen (i_s)	2.5	0.5 (= t_{is})	35.8	
Tape 1 (semiconductor bedding) tape 1 (t_{oi})	6	0.5 (=t_s)	36.8 (=d_{toi})	screen
Wire screen (d_s)	N/A	0.9	38.6	
Tape 2 (tape 2) (t_{od})	6	0.3	39.2	
PE sheath (incl. laminate glue) (ec)	3.5	2.2 (=t_3)	43.6	outer sheath
Semiconducting outer layer sheath (e)	2.5	0.2	44 (= d_e)	

Table 45 Dimensions of the XLPE cable from the CIGRE report. The corresponding parameter from Figure 17 is stated in brackets. The right side shows which layers of the cable are combined in VCA.

$$t_{gs} = d_e - 2 \cdot t_s - 2 \cdot t_i - d_g, \text{where: } t_{gs} = t_{is}$$
$$d_i = d_g + 2 \cdot t_i + 2 \cdot t_{gs}$$

Equation 57. From the external diameter of the cable (d_e), the thickness of the screen (t_s) and the diameter of the conductor (d_g), both the thickness of the conductor screen (t_{gs}) and the insulation screen (t_{is}) are calculated. The diameter of the insulation layer (d_i) is then calculated from t_{gs}, t_i and d_g.

Parameters	Value	Unit	Symbol
Environment	Underground	Above ground/underground	
Configuration	Triangle	Triangle/flat	
Depth underground to center of triangle (circuit)	1000	mm	L
CC distance	Near	Near/mm	
Thermal resistance of the ground	1.0	K·m/W	ρ
Ambient temperature	20	°C	θa
Earth screen connection	Both sides		

Table 46 Properties of the installation and the environment.

The CC distance in Table 46 is the distance between the axes of the conductors. Since in case 4 it is set to "close" and lies in a triangle, this means that this distance is equal to the external diameter of the cable.

Parameters	Value (from CIGRE and VCA)	Unit	Symbol
Conductor, temperature coefficient per K at 20°C	3.93×10^{-3}		α_{20}
Skin effect factor	1		k_s
Proximity effect factor	1		k_p
System frequency	50	Hz	f
Distance between axes of guide	44	mm	s (= d_e)
Relative permittivity of the insulation	2.5		ε
Thermal resistance of sheath at 20°C	1.7241×10^{-8}	Ωm	ρ_s

Table 47. Other parameters needed for further calculations. These are derivatives of the cable arrangement.

In Table 47, the distance between conductors (s) is equal to the external diameter of the cable (d_e), because the configuration is in triangle with minimum distance between the cables. To keep a distinction between the two parameters for other cases, we keep the extra parameter "s". The table contains the parameters that are largely derived from the cable properties and that, together with the data from Table 44, Table 45 and Table 46, are discussed in the following paragraphs during the (interim) calculations to ultimately calculate the maximum current. We will show this step by step in the following paragraphs.

3.2 Calculation of AC resistance of the cable at operating temperature

In this section the AC resistance of the cable is calculated. The parameters from Table 45 and Table 47 are required for this.

$$R' = R_0 \cdot \left[1 + \alpha_{20} \cdot (\theta_g - 20)\right]$$

Equation 58. DC resistance of the conductor at operating temperature.

$$x_s{}^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_s$$

Equation 59. Argument of Bessel function, necessary to calculate skin effect factor y_s.

$$y_s = \frac{x_s{}^4}{192 + 0.8 \cdot x_s{}^4}, \text{voor: } 0 < x_s \leq 2.8$$

Equation 60. Skin effect factor.

$$x_p{}^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_p$$

Equation 61. Argument of Bessel function, necessary to calculate proximity effect factor y_p.

$$y_p = \frac{x_p{}^4}{192 + 0.8 \cdot x_p{}^4} \cdot \left(\frac{d_g}{s}\right)^2 \cdot \left[0.312 \cdot \left(\frac{d_g}{s}\right)^2 + \frac{1.18}{\frac{x_p{}^4}{192 + 0.8 \cdot x_p{}^4} + 0.27}\right]$$

Equation 62. Proximity effect factor.

$$R = R' \cdot (1 + y_s + y_p)$$

Equation 63. AC resistance of the conductor.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
DC resistance of the conductor at 20 °C	R’	9.6143×10^{-5}	9.6143×10^{-5}	Ω/m
Argument of Bessel function - skin effect	x_s^2	1.3071	1.3071	
Skin effect factor	y_s	8.8350×10^{-3}	8.8350×10^{-3}	
Argument of Bessel function – proximity effect factor	x_p^2	1.3071	1.3071	
Proximity effect factor	y_p	6.6227×10^{-3}	6.6227×10^{-3}	
AC resistance of the conductor	R	9.7629×10^{-5}	9.7629×10^{-5}	Ω/m

Table 48 Results of the intermediate calculations to determine the AC resistance of the conductor.

The results of the AC resistance calculations in the CIGRE report correspond exactly with the values from VCA.

3.3 Dielectric losses

To calculate the dielectric losses, the parameters from Table 44, Table 45 and Table 47 are used.

$$C = \frac{\varepsilon}{18 \cdot ln\left(\frac{d_i}{d_{c_sc_}}\right)} \cdot 10^{-9}$$

Equation 64. Capacitance.

In Equation 64. Capacitance. $d_{c\ sc}$ represents the diameter of the conductor and the conductor screen together.

$$\omega = 2\pi f$$

Equation 65. Angular frequency of the system.

$$W_d = \omega \cdot C \cdot {U_0}^2 \cdot tan(\delta)$$

Equation 66. Dielectric losses per unit length per phase.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Capacitance	c	2.3768 x 10^{-10}	2.3768 x 10^{-10}	F/m
Angular frequency of the system	ω	314.16	314.16	rad/s
Dielectric losses per unit length in each phase	W_d	0.1084	0.1084	W/m

Table 49 Results of the intermediate calculations to determine the dielectric losses. The values of the CIGRE report have been compared with results in VCA

In VCA, the U_0 (Equation 56) is given as a parameter (Figure 17: U_{nom}) and stored as an integer. This means there is minimal deviation from the CIGRE calculation.

3.4 Losses in metal sheath (λ_1)

To solve the equations below, the parameters from Table 44, Table 45 and Table 47 are used. The calculations of the CIGRE report are shown below.

$$A_s = n_s \cdot \pi \cdot \frac{{d_s}^2}{4}$$

Equation 67. Cross section of the wires of the screen.

Note, in Equation 67, “ds” is not the diameter of the screen, but the diameter of the wire itself. In VCA this calculation is skipped because it is currently not possible to calculate the lay factor when no reinforcement has been selected (see also the lack of this in Figure 16). As a result, the component regarding the lay factor is omitted and no comparison of Equation 67 to Equation 68 in VCA is possible. Instead, the nominal cross-sectional area of the wire screen is given (in Table 44). This is also located under the screen under surface component (see Figure 16).

$$LF_s = \sqrt{1 + \frac{[\pi \cdot (d_{toi} + d_s)]^2}{{L_s}^2}}$$

Equation 68. Lay factor of the wires in the screen.

Here d_{toi} is the diameter of tape 1 from Table 47.

$$R_{sc} = LF_s \cdot \frac{\rho_s}{A_s}$$

Equation 69. AC resistance of the screen at 20°C per unit length.

$$\theta_s = \theta - (I^2 \cdot R + 0.5 \cdot W_d) \cdot T_1$$

Equation 70. Maximum display operating temperature .

Please note that this calculation is calculated iteratively.

$$R_{sh} = R_{sc} \cdot [1 + \alpha_{20} \cdot (\theta_s - 20)]$$

Equation 71. Sheath resistance at operating temperature.

$$d_{gem} = d_{toi} + d_s$$

Equation 72. Average diameter of the mantle.

In Equation 72 the average diameter of the jacket is calculated. This is the diameter of the semiconducting bed (tape 1) and the thickness of the wire screen. In VCA this is currently not possible in terms of input parameters. By taking the thickness of the semiconductor bed together with the thickness of the wire screen (see Figure 17 and Table 45), it is possible to determine the correct thickness of the conductor screen/insulation screen, but this is at the expense of the precision of this calculation.

$$X = 2 \cdot \omega \cdot 10^{-7} \cdot ln\left(\frac{2s}{d_{gem}}\right)$$

Equation 73. Reactance per unit length of screen.

$$\lambda'_{1,s} = \frac{R_{sh}}{R} \cdot \frac{1}{1 + \left(\frac{R_{sh}}{X}\right)^2}$$

Equation 74. Loss factor due to currents induced in the screen.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Cross section of the wires of the screen.	A_s	35.626 x 10^{-6}	35.63 x 10^{-6}	m^2
Layfactor of the wires in the screen	LF_s	1.1151	-	
AC resistance of the screen at 20°C	R_{sc}	5.3967 x 10^{-4}	6.000 x 10^{-4}	Ω/m
Resistance of the jacket to the operating temperature	R_{sh}	6.6350 x 10^{-4}	5.8373 x 10^{-4}	Ω/m
Average diameter of the mantle	d_{gem}	37.7 x 10^{-3}	37.2 x 10^{-3}	m
Reactance per unit length of screen	X	5.3261 x 10^{-5}	5.4100 x 10^{-5}	Ω/m
Loss factor due to currents induced in the screen	$\lambda'_{1_s} = \lambda_1$	0.043512	0.0490	

Table 50 Results of the intermediate calculations to determine the loss factor in the screen.

Because the lay factor from the CIGRE report is not included in VCA, there is a difference in Equation 69 for determining the value of the AC resistance of the screen. (R_{sc}) This also affects Equation 71, in which the sheath resistance (R_{sh}) is calculated. Due to the more precise way of splitting off layers in the mantle in the CIGRE report, there is also a difference in the average diameter of the mantle (d_{gem}), shown in Equation 72. This has a limited effect on the result of Equation 73: the reactance (X). These previously mentioned differences ultimately also result in a difference in the loss factor in the screen (Equation 72).

Since there are no eddy current losses, $\lambda''_1 = 0$. This applies to the calculation of the CIGRE report and VCA results.

3.5 Thermal resistance between conductor and screen (T_1)

Below are the calculations performed in the CIGRE report. Each layer of different material (and therefore a different specific resistance) is calculated separately. Finally, the thermal resistance components are added together and multiplied by a correction factor, which is determined by the amount of coverage of the wire screen. The input parameters can be found in Table 45 and Table 46.

$$T_{1_gs} = \frac{\rho_{gs}}{2\pi} \cdot ln\left(\frac{d_{gs}}{d_g}\right)$$

Equation 75. Thermal resistance of the conductor screen.

$$T_{1_i} = \frac{\rho_i}{2\pi} \cdot ln\left(\frac{d_i}{d_{gs}}\right)$$

Equation 76. Thermal resistance of the insulation.

$$T_{1_is} = \frac{\rho_{gs}}{2\pi} \cdot ln\left(\frac{d_{is}}{d_i}\right)$$

Equation 77. Thermal resistance of the insulator screen.

$$T_{1_toi} = \frac{\rho_{toi}}{2\pi} \cdot ln\left(\frac{d_{toi}}{d_{is}}\right)$$

Equation 78. Thermal resistance of the semiconducting bed.

$$T'_1 = T_{1_gs} + T_{1_i} + T_{1_is} + T_{1_toi}$$

Equation 79. Thermal resistance of between conductor and screen.

$$Coverage\ percentage = \frac{d_s \cdot n_s}{\pi \cdot (d_{toi} + d_s)} \cdot LF_s$$

Equation 80. Percentage coverage by the wire screen.

$$T_1 = 1.07 \cdot T'_1$$

Equation 81. The corrected thermal resistance.

Because there is coverage between 20% and 50%, a correction factor is needed for both T_1 and T_3. The IEC standard 60287-4.2.4.3.3 contains an additional requirement, namely that the length of the lay (L_s) must be at least 15 x d_{toi}. This does not apply in this case (Ls = 6.2 x d_{toi}). Nevertheless, this correction factor was chosen in the CIGRE report because no other option is indicated in the IEC standard to include the degree of coverage as a correction factor for the T_1.

For VCA, the resistivity of the insulation is used and the t_1 in VCA is defined as purely the thickness of the insulation, excluding the conductor screen and insulation (see Equation 82). In the IEC standard, t_1 is defined as the thickness of the insulation between conductor and sheath. Although this calculation is correct in VCA, it is worth considering renaming the label "t_1" so that this does not cause confusion with the definition of the IEC standard.

$$T_1 = \frac{\rho}{2 \cdot \pi} ln\left[1 + \frac{2 \cdot t_1}{d_g}\right]$$

Equation 82. The formula from IEC 60287-2-1: 4.1.2.1, which is applied in VCA.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Thermal resistance of the conductor screen	T_{1_sc}	0.021057	-	K·m/W
Thermal resistance of insulation	T_{1_i}	0.32550	-	K·m/W
Thermal resistance of the insulation screen	T_{1_si}	0.011272	-	K·m/W
Thermal resistance of the semiconducting bed	T_{1_tuws}	0.026308	-	K·m/W
Thermal resistance between conductor and screen	T'_1	0.38414	-	K·m/W
Percentage coverage by the wire screen		47.5%	-	
Thermal resistance between conductor and screen	T_1	0.41103	0.3578	K·m/W

Table 51 Results of the intermediate calculations to determine the thermal resistance between conductor and screen in the screen.

In VCA the calculations of the different layers are not divided. This follows the current IEC standard (IEC 60287-2-1: 4.1.2.1). This creates a difference between the calculated value in the manner of the CIGRE report and the current VCA method, which is based on the current IEC standard. The exclusion of lay factor in VCA causes this difference.

3.6 Thermal resistance between screen and armor (T_2)

Because there are no armoring or outer metal layers present, $T_2 = 0$ applies to both the CIGRE report and VCA results.

3.7 Thermal resistance of the external layer (T_3)

Only the data from Table 45 are required in this section. CIGRE again evaluates outer layers separately and applies the coverage correction. More flexible layer input in VCA would allow a closer reproduction of the CIGRE build-up.

$$T_{3_tod} = \frac{\rho_{tod}}{2\pi} \cdot ln\left(\frac{D_{tod}}{D_{ds}}\right)$$

Equation 83. Thermal resistance between tape and wire screen.

$$T_{3_ec} = \frac{\rho_{ec}}{2\pi} \cdot ln\left(\frac{D_{ec}}{D_{tod}}\right)$$

Equation 84. Thermal resistance of outer layer.

$$T_{3_e} = \frac{\rho_e}{2\pi} \cdot ln\left(\frac{D_e}{D_{ec}}\right)$$

Equation 85. Thermal resistance of the semiconducting outer layer.

$$T'_3 = T_{3_tod} + T_{3_ec} + T_{3_e}$$

Equation 86. Thermal resistance of outer sheath.

$$T_3 = 1.6 \cdot T'_3$$

Equation 87. Corrected thermal resistance of the outer sheath.

The correction factor was determined using the same method as the correction factor for T_1 (see section 3.5).

$$T_3 = \frac{\rho_{ec}}{2 \cdot \pi} ln\left[1 + \frac{2 \cdot t_3}{d_{ds}}\right]$$

Equation 88. The formula from IEC 60287-2-1: 4.1.4.1, which is applied in VCA. t_3 are the thicknesses of the outer 3 layers taken together, d_{ds} is the external diameter of the armouring. ρ_{ec} is taken here as resistivity. See also Table 45.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Thermal resistance between tape and wire screen	T_{3_tod}	0.014729		K·m/W
Thermal resistance of outer layer	T_{3_ec}	0.059258		K·m/W
Thermal resistance of the semiconducting outer layer	T_{3_e}	0.0036337		K·m/W
Thermal resistance of outer sheath	T'_3	0.077621		K·m/W
Correction factor (see section 3.5)		1.6		
Corrected thermal resistance of the outer sheath	T_3	0.12419	0.1167	K·m/W

Table 52 Results of the intermediate calculations of the thermal resistance of the outer sheath. The results from the CIGRE report and from VCA are presented side by side.

As is also the case when calculating the thermal resistance between conductor and screen, the CIGRE method also carried out much more specific calculations. This is not yet recorded in a standard and has therefore not been implemented in VCA.

3.8 External thermal resistance (T_4)

The following calculations require the data from Table 45 and Table 46.

$$u = \frac{2 \cdot L}{d_e}$$

Equation 89. Ratio between laying depth (L) and diameter of the cable (d_e).

$$T_4 = \frac{1.5}{\pi} \cdot \rho \cdot [ln(2 \cdot u) - 0.630]$$

Equation 90. External thermal resistance. Where ρ is the thermal resistance of the soil.

The formula of the CIGRE report (Equation 90) is based on cables partially covered with metal. Because the option to enter lays in VCA is currently limited, it is not possible to calculate this. In VCA the T4 is calculated in a different way. Here the formula from IEC 60287-2-1: 4.2.2 is used (see Equation 91). In this calculation, u is determined as described in Equation 89, with the exception that 0.25 x D_e is added to the location depth. This is due to the triangle formation and, as described in the standard, the depth to the center of the triangle is determined.

$$T_4 = \frac{1}{2 \cdot \pi} \cdot \rho \cdot ln\left(u + \sqrt{u^2 - 1}\right)$$

Equation 91. Calculation of thermal resistance of the environment as described in the IEC standard and implemented in VCA.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Ratio of installation depth of triangle and diameter of single cable	u	45.4545	45.9545	
External thermal resistance	T4	1.8525	1.8525	K·m/W

Table 53. Result of the thermal resistance of the environment, both from the CIGRE report and from VCA.

3.9 Maximum allowed current

$$I = \sqrt{\frac{\Delta\theta \ - W_d \cdot [0.5 \cdot T_1 + n \cdot (T_2 + T_3 + T_4)]}{R \cdot T_1 + n \cdot R \cdot (1 + \lambda_1) \cdot T_2 + n \cdot R \cdot (1 + \lambda_1 + \lambda_2) \cdot (T_3 + T_4)}}$$

Equation 92. Calculation of the maximum allowable current by an iteration process (IEC 60287-1-1 clause 1.4.1.1).

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.10842	0.1084	W/m
Thermal resistance between conductor and insulation	T_1	0.41103	0.3578	K·m/W
Thermal resistance between metal sheath and armouring	T_2	0	0	K·m/W
Thermal resistance outer sheath	T_3	0.12419	0.1167	K·m/W
Thermal resistance environment	T_4	1.8525	1.8525	K·m/W
Losses in metal sheath	λ_1	0.043512	0.0497	
Losses in armouring	λ_2	0	0	
AC resistance conductor	R	9.7629×10^{-5}	9.7629×10^{-5}	Ω/m
Number of cores	N	1	1	
Maximum current	I	537.46	542,84	A

Table 54 Summary of results needed for current calculation.

Despite the intermediate minor differences in λ_1, T_1, T_3 and T_4, the rated currents differ by only about 1%: CIGRE 537.46 A and VCA 542.84 A (Table 54).

3.10 Losses

Conductor and screen losses reflect the differences already present in λ1 and in the rated current. Screen losses therefore diverge more than conductor losses (See Table 55)

$$w_g = R \ \cdot I^2$$

Equation 93. Losses of the conductor.

$$w_s = \lambda_1 \cdot R \ \cdot I^2$$

Equation 94. Screen losses.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Conductor losses	w_g	28.202	28.769	W/m
Screen losses	w_s	1.2271	1.432	W/m

Table 55. Comparing the values for conductor and screen losses from the CIGRE report and VCA.

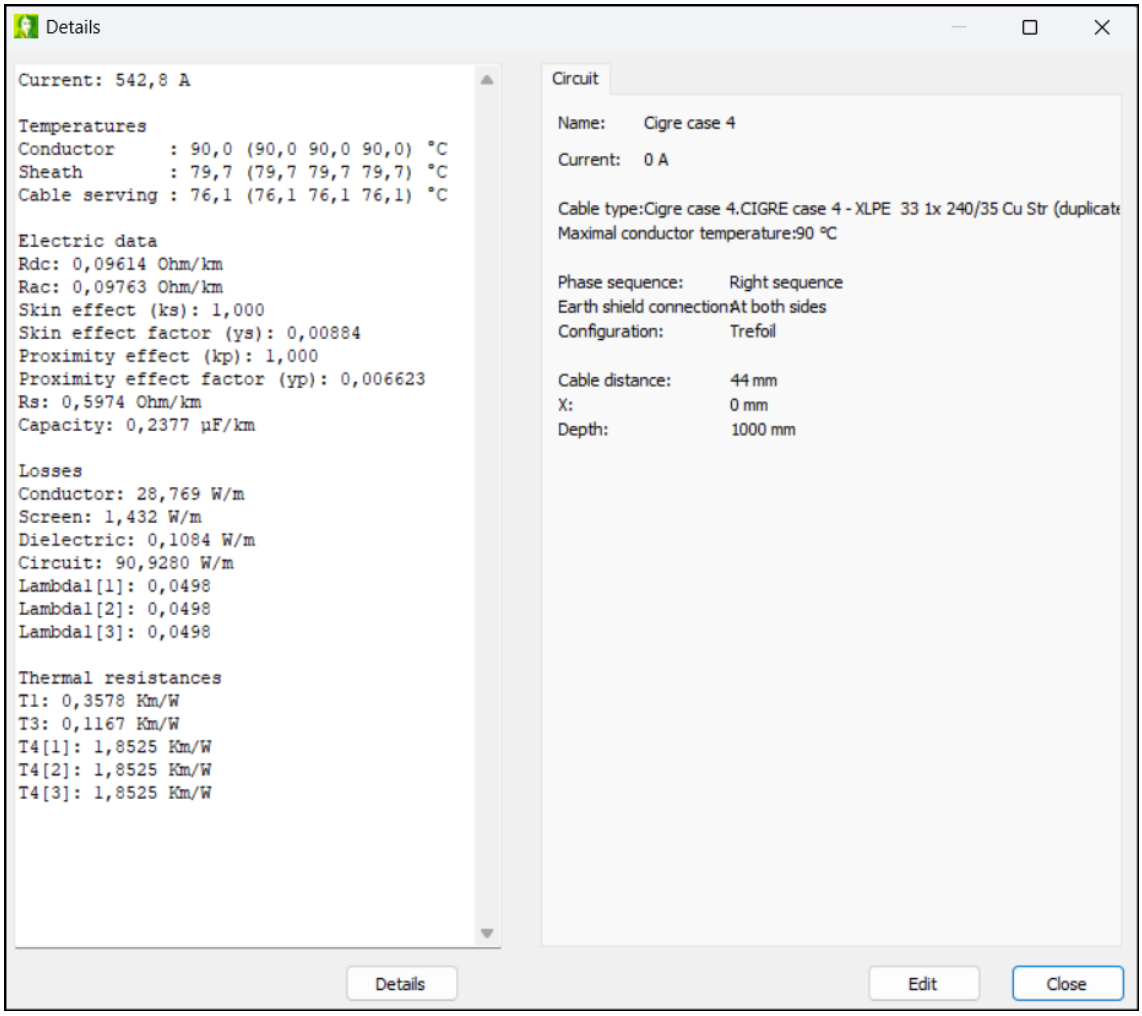


Figure 18 VCA results for case 4.

3.11 Conclusions

Case 4 is the most demanding of these three studies for VCA's present cable editor. Missing lay-factor handling and limited ability to enter individual bedding, tape and sheath layers cause differences in intermediate quantities—especially λ_1, T_1 and T_3.

Those intermediate gaps do not, however, translate into a large ampacity error: the maximum currents agree within about 1% (537.46 A CIGRE vs 542.84 A VCA). The inclusion or exclusion of Wd also has little practical effect on I for this case.

Priority improvements for VCA follow directly from this comparison: support for wire-screen lay factor without requiring armour, more flexible multi-layer screen/sheath definition, and alignment of the partial-coverage T4 path with the IEC options used in TB 880. Until those are available, Case 4 remains a useful regression check: intermediate parameters may differ slightly, but the rated current stays close.

4 COMPARISON CIGRE CASE 10 WITH VCA

4.1 Cable properties

For case 10, a 3-core cable was chosen (see Figure 19 and Figure 20) with an aluminum sector-shaped compact conductor. The insulation consists of mass impregnated paper (not shielded). The screen is a normal lead screen with steel tape armouring. The outer sheath is made of PVC.



Figure 19 3-core cable with paper insulation and aluminum sector-shaped compact conductor.



Figure 20 The 3-core cable simulated in the cable type editor of VCA based on the values from Table 56.

Here t_i = thickness of the insulation, t_s = thickness of the screen, t_b = thickness of the bedding, d_b = diameter of the bedding, d_a = diameter of the armor and d_e = external diameter of the cable.

Construction	Value	Unit	Symbol
Voltage	8/10 (12)	kV	
Conductor, Surface area	95	mm^2	A_g
Conductor, material	Aluminum	Material	
Conductor	Bundled, beaten, sector-shaped	Type	
Insulation, type	Impregnated paper	Type	
Construction	Bundled cores filled with paper	Type	
Belt	Impregnated paper	Material	
Metal screen	Lead	Material	
Bedding layer	Jute tapes	Material	
Armoring	Galvanized steel tapes	Material	
Armouring, width tape	50	mm	w_a
Armouring, thickness of tape	0.8	mm	t_{at}
Armouring, gap of the tape	25	mm	w_g
Armoring, number of tapes	2	mm	N
Outer sheath	PVC jacket	Material	
Conductor, DC resistance at 20 °C	3.2×10^{-4}	Ω/m	R_0
Maximum conductor temperature	50	°C	θ_g
Cable weight	6.3	kg/m	

Table 56 Cable specifications of case 10 taken from the CIGRE report.

Thickness and diameters	Thermal resistance (ρ)	Thickness layer	Diameter
Unit	K·m/W	mm	mm
Conductor (g)			9.5
Insulation between conductors (ig)		4.7	
Insulation between conductor and screen (i)	6.0	3.9 (= t_i)	
Metal screen(s)		2.0 (=t_s)	40.0
Bedding (b)	6.0		46.0 (=d_b)
Armor (a)		1.6	49.2 (= d_a)
Outer sheath (e)	5.0	2.8	55.0 (= d_e)

Table 57 The dimensions of the 3-wire cable.

Table 57 shows the dimensions of the cable. This also indicates which dimensions are drawn in Figure 20. The following applies: d_b = diameter of the bedding, d_a = diameter of the armouring, d_e = diameter of the outer jacket, t_i = thickness of the insulation between conductor and screen, t_s = thickness of the screen and t_b = thickness of the bedding.

4.2 Installation conditions

Parameters	Value	Unit	Symbol
Environment	Underground	Above ground/underground	
Depth underground to center of cable	1000	mm	L
Thermal resistance of the ground	1.0	K·m/W	ρ
Ambient temperature	15	°C	θ_a
Earth screen connection	On one side		

Table 58 Properties of the installation and environment.

The other parameters necessary for further calculations can be found in Table 47. Other parameters necessary for the intermediate calculations to calculate the maximum current.

Parameters	Value CIGRE	VCA	Unit	Symbol
Temperature coefficient of the conductor per K at 20°C	4.03 x 10^{-3}	4.03 x 10^{-3}		α_{20}
Skin effect factor	1	1		k_s
Proximity effect factor	0.8	0.8		k_p
System frequency	50	50	Hz	f
Relative permittivity of the insulation	4.0	4.0		ε
Thermal resistance of lead screen at 20°C	2.14 x 10^{-7}	2.14 x 10^{-7}	Ωm	ρ_s
Permeability of steel tape in reinforcement	300	300		μ

Table 59 Other parameters necessary for the intermediate calculations to calculate the maximum current.

4.3 Calculation of AC resistance of the cable at operating temperature

In this section the AC resistance of the cable is calculated. The necessary parameters for the calculations below can be found in Table 56, Table 57 and Table 59.

$$R' = R_0 \cdot \left[1 + \alpha_{20} \cdot (\theta_g - 20)\right]$$

Equation 95. DC resistance of the conductor at operating temperature.

$$x_s{}^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_s$$

Equation 96. Argument of Bessel function, necessary to calculate skin effect factor y_s.

$$y_s = \frac{x_s{}^4}{192 + 0.8 \cdot x_s{}^4}, \text{voor: } 0 < x_s \leq 2.8$$

Equation 97. Skin effect factor.

The results of VCA are similar in terms of skin effect factor. In the following steps you will find differences between the two methods.

$$s = d_x + t, waarbij\ d_x = d_g$$

Equation 98. Distance between axes of conductor.

Here d_x is defined according to the IEC standard 60228: table 2 and is calculated in a different way in VCA (see Equation 99).

$$d_g = 1.1 \cdot \sqrt{\frac{A_g}{0.25 \cdot \pi}}, \qquad t = 2 \cdot t_i - d_s - 2 \cdot t_s - D_{oga}$$

Equation 99. Equations used in the current VCA for calculating dg and s. D_{oga} = diameter over stranded cores.

$$x_p{}^2 = \frac{8\pi f}{R'} \cdot 10^{-7} \cdot k_p$$

Equation 100. Argument of Bessel function, necessary to calculate proximity effect factor y_p.

$$y_p = \frac{{x_p}^4}{192 + 0.8 \cdot {x_p}^4} \cdot \left(\frac{d_g}{s}\right)^2 \cdot \left[0.312 \cdot \left(\frac{d_g}{s}\right)^2 + \frac{1.18}{\frac{{x_p}^4}{192 + 0.8 \cdot {x_p}^4} + 0.27}\right] \cdot \frac{2}{3}$$

Equation 101. Proximity effect factor.

$$R = R' \cdot \left[1 + 1.5(y_s + y_p)\right]$$

Equation 102. AC resistance of the conductor.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
DC resistance of the conductor at operating temperature	R'	3.5869 x 10^{-4}	3.5869 x 10^{-4}	Ω/m
Argument of Bessel function - skin effect	x_s^2	0.35034	0.35034	
Skin effect factor	y_s	6.3894 x 10^{-4}	6.3894 x 10^{-4}	
Diameter of equivalent circular conductor with the same cross-section and compactness	d_g	11.0	11	mm
Axial distance between conductors	s	15.7	15.7	mm
Argument of Bessel function – proximity effect factor	x_p^2	0.28027	0.28027	
Proximity effect factor	y_p	6.0459 x 10^{-4}	6.0459 x 10^{-4}	
AC resistance of the conductor at operating temperature	R	3.5936 x 10^{-4}	3.5932 x 10^{-4}	Ω/m

Table 60 Results of the intermediate calculations to determine the AC resistance of the conductor.

4.4 Dielectric losses

The parameters from Table 57 were used for the following calculations.

$$r_1 = \frac{d_s - 2 \cdot t_s - 2 \cdot t_i}{2}$$

Equation 103. Enclosing radius of the three sector-shaped conductors. Here d_s is the diameter of the metal screen.

$$c = 0.55 \cdot r_1 + 0.29 \cdot t_{ig}$$

Equation 104. Distance between axes of the conductors and the axis of the cable. Here t_{ig} is the thickness of the insulation between conductors.

$$d_a = d_s - 2 \cdot t_s$$

Equation 105. Diameter across belt of insulation.

$$C = \frac{\varepsilon}{18 \cdot ln\left[\sqrt{\frac{3 \cdot c^2 \cdot \left(\left(\frac{d_a}{2}\right)^2 - c^2\right)^3}{\left(\frac{d_x}{2}\right)^2 \cdot \left[\left(\frac{d_a}{2}\right)^6 - c^6\right]}}\right]} \cdot 10^{-9}$$

Equation 106. Capacitance.

$$\omega = 2\pi f$$

Equation 107. Angular frequency of the system.

$$W_d = \omega \cdot C \cdot {U_0}^2 \cdot tan(\delta)$$

Equation 108. Dielectric losses per unit length per phase.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Overarching radius of the three sector-shaped conductors	r_1	14.1	-	mm
Distance between axes of the conductors and axis of the cable	c	9.118	-	mm
Diameter of umbrella insulation	d_a	36.0	-	mm
Capacitance	C	3.5926×10^{-10}	4.1457×10^{-10}	F/m
Angular frequency of the system	ω	314.16	314.16	rad/s
Dielectric losses per unit length in each phase	W_d	0.037622	0.0434	W/m

Table 61 Results of the intermediate calculations to determine the dielectric losses.

In VCA the comparison of the IEC standard (60287-1-1: 2.2) is used. The capacitance varies for this reason and also the effect is seen in the different values obtained for the dielectric losses. The more detailed calculation of the actual center of the center of the cable performed in the CIGRE report is a point to take into account for next steps with VCA.

4.5 Losses in the lead sheath (λ_1)

The following comparisons use data from Table 56, Table 57 and Table 59.

$$S = \pi \cdot t_s \cdot (d_s - t_s)$$

Equation 109. Cross-section of the lead sheath.

$$R_{so} = \frac{\rho_s}{S}$$

Equation 110. Lead sheath resistance at 20 °C. ρs is the resistivity at 20°C.

$$\theta_s = \theta - (I^2 \cdot R + 0.5 \cdot W_d) \cdot T_1$$

Equation 111. Lead sheath operating temperature.

In Equation 111, the maximum temperature is calculated in an iterative manner.

$$R_s = R_{so} \cdot [1 + \alpha_s \cdot (\theta_{sc} - 20)]$$

Equation 112. Resistance of the lead sheath of the cable at operating temperature.

$$\lambda'_1 = 0$$

Equation 113. Loss factor for circulating losses in lead sheath.

$$d_{gem} = d_s - t_s$$

Equation 114. Average diameter of lead sheath.

$$\lambda''_1 = 0.94 \cdot \frac{R_s}{R} \cdot \left(\frac{2 \cdot r_1 + t_{ig}}{d_{gem}}\right)^2 \cdot \frac{1}{1 + \left(\frac{R_s}{\omega} \cdot 10^7\right)^2}$$

Equation 115. Loss factor of Eddy current losses in lead sheath.

$$A = \frac{w_a}{w_a + w_g} \cdot \pi \cdot t_a \cdot N \cdot [d_b + N t_a]$$

Equation 116. Cross section of steel tape armouring. Here: w_a = width of reinforcement, w_g = gap of reinforcement tape, ta = thickness of reinforcement, N = number of reinforcement tapes

$$\delta = \frac{A}{\pi \cdot d_a}$$

Equation 117. Equivalent thickness of reinforcement.

$$f_A = \left[1 + \left(\frac{d}{d_A}\right)^2 \cdot \frac{1}{1 + \frac{d_A}{\mu \cdot \delta}}\right]^2$$

Equation 118. Additional factor for the loss factor due to the steel tape reinforcement.

In the VCA calculation, the additional factor from Equation 118 has already been put into Equation 115.

$$\lambda_1 = \lambda'_1 + f_A \cdot \lambda''_1$$

Equation 119. Total loss factor for lead sheath.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Cross section of lead sheath	S	2.3876 x 10^2	2.3876 x 10^2	mm^2
Resistance of lead sheath at 20°C	R_{so}	8.9629 x 10^{-4}	8.9630 x 10^{-4}	Ω/m
Resistance of the lead sheath at the operating temperature	R_s	9.7532 x 10^{-4}	9.7532 x 10^{-4}	Ω/m
Average diameter of lead sheath	d_{gem}	38.0	38.0	mm
Cross section of steel tape armouring	A	159.51	159.51	mm^2
Equivalent thickness of armouring	δ	1.0667	1.0667	mm
Additional factor due to the steel tape armouring	f_A	2.4174	2.4174	
Total loss factor for lead sheath	λ_1	4.7915 x 10^{-3}	4.7915 x 10^{-3}	

Table 62 Results of the intermediate calculations to determine the loss factor in the lead screen.

4.6 Losses in armoring (λ_2)

The following comparisons require the parameters from the previous section and from Table 59 and Table 60.

$$k = \frac{1}{1 + \frac{d_A}{\mu \cdot \delta}}$$

Equation 120. Factor for calculating losses.

$$\lambda'_2 = \frac{s^2 \cdot k^2 \cdot 10^{-7}}{R \cdot d_A \cdot \delta}$$

Equation 121. Hysteresis loss of steel tape reinforcement.

$$\lambda''_2 = \frac{2.25 \cdot s^2 \cdot k^2 \cdot \delta \cdot 10^{-8}}{R \cdot d_A}$$

Equation 122. Eddy current losses for steel tape armouring.

$$\lambda_2 = \lambda'_2 + \lambda''_2$$

Equation 123. Total losses in armoring.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Factor k	k	0.87051	0.87264	-
Hysteresis loss of steel tape armouring	λ'_2	1.0237 x 10^{-3}	1.2487 x 10^{-3}	-
Eddy current losses for steel tape armouring	λ''_2	2.6208 x 10^{-4}	3.2476 x 10^{-4}	-
Total losses in armouring	λ_2	1.2858 x 10^{-3}	1.2986 x 10^{-3}	-

Table 63 Results of the interim calculations to determine the loss factor in the reinforcement.

Once again, the differences in the factor k in Table 63 can be explained by the difference in the equivalent thickness of the reinforcement (δ). For the difference in hysteresis loss of steel armoring, there is a difference in (δ) and the distance between the conductors (s). Little is written about this in the standard. The difference in the losses is limited, but present.

4.7 Thermal resistance between conductor and screen (T_1)

The data from Table 57 is required for the following calculations.

$$d_a = d_s - 2 \cdot t_s$$

Equation 124. Diameter of umbrella insulation.

$$r_1 = \frac{d_s - 2 \cdot t_s - 2 \cdot t_i}{2}$$

Equation 125. Radius of umbrella circle around conductors.

$$F_2 = 1 + \frac{3 \cdot t_{ig}}{2 \cdot \pi \cdot (d_x + t_{ig}) - t_{ig}}$$

Equation 126. Factor.

$$G = 3 \cdot F_2 \cdot ln\left(\frac{d_a}{2 \cdot r_1}\right)$$

Equation 127. Factor.

$$T_1 = \frac{\rho_i}{2\pi} \cdot G$$

Equation 128. Thermal resistance between conductor and metal screen.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Diameter of insulation	d_a	36.0	36.0	mm
Radius of the surrounding circle of the conductors	r_1	14.1	14.1	mm

Factor F	F_2	1.1501	1.1501	
Factor G	G	0.84254	0.84255	
Thermal resistance between conductor and metal screen	T_1	0.80457	0.8046	K·m/W

Table 64 Results of the intermediate calculations to determine the thermal resistance between conductor and screen in the screen.

4.8 Thermal resistance between sheath and armor (T_2)

To calculate the value of the thermal resistance between sheathing and armouring, only Table 57 is required.

$$T_2 = \frac{\rho_b}{2\pi} \cdot ln\left(\frac{d_b}{d_s}\right)$$

Equation 129. Thermal resistance of the bedding layer.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Thermal resistance of bedding layer	T_2	0.13346	0.13346	K·m/W

Table 65 Result of the calculation of the thermal resistance of the bedding layer.

There is no difference between the values of T_2 from the CIGRE report and from VCA.

4.9 Thermal resistance of the external layer (T_3)

Once again, only Table 57 is required for the thermal resistance of the external layer.

$$T_{3oc} = \frac{\rho_e}{2\pi} \cdot ln\left(\frac{d_e}{d_a}\right)$$

Equation 130. Thermal resistance of outer covering.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Thermal resistance of outer layer	T_3	0.088681	0.0887	K·m/W

Table 66 Result of the calculation of the thermal resistance of the outer sheath.

4.10 External thermal resistance (T_4)

The data for the following formulas can be found in Table 57 and Table 58.

$$u = \frac{2L}{d_e}$$

Equation 131. Ratio between installation depth (L) and diameter of the cable (de).

$$T_4 = \frac{\rho}{2\pi} \cdot ln\left(u + \sqrt{u^2 - 1}\right)$$

Equation 132. External thermal resistance.

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Ratio between laying depth and diameter of the cable	u	36.364	36.364	
External thermal resistance	T_4	0.68222	0.6822	K·m/W

Table 67 Result of the thermal resistance of the environment, both from the CIGRE report and from VCA.

The calculations of the thermal resistance of the environment from the CIGRE report correspond with the results of VCA.

4.11 Maximum allowed current

$$I = \sqrt{\frac{\Delta\theta \ - W_d[0.5 \cdot T_1 + n(T_2 + T_3 + T_4)]}{R \cdot T_1 + nR(1 + \lambda_1)T_2 + nR(1 + \lambda_1 + \lambda_2)(T_3 + T_4)}}$$

Equation 133. Calculation of the maximum allowable current by an iteration process (IEC 60287-1-1 clause 1.4.1.1).

Parameters	Symbol	Result CIGRE	Result VCA	Unit
Dielectric losses per unit length per phase	W_d	0.037622	0.0434	W/m
Thermal resistance between conductor and insulation	T_1	0.80457	0.8046	K·m/W
Thermal resistance between metal sheath and armouring	T_2	0.13346	0.13346	K·m/W
Thermal resistance outer sheath	T_3	0.088681	0.0887	K·m/W
Thermal resistance environment	T_4	0.68222	0.68222	K·m/W
Losses in metal sheath	λ_1	4.7915×10^{-3}	4.8×10^{-3}	Ω/m
Losses in armoring	λ_2	1.2858×10^{-3}	1.285×10^{-3}	
AC resistance conductor	R	3.5936×10^{-4}	3.5935×10^{-4}	
Number of cores	N	3	3	
Maximum current	I	165.74	165.69	A

Table 68 Summary of results needed for current calculation.

The maximum current value is close to the CIGRE report result as shown in Table 68.

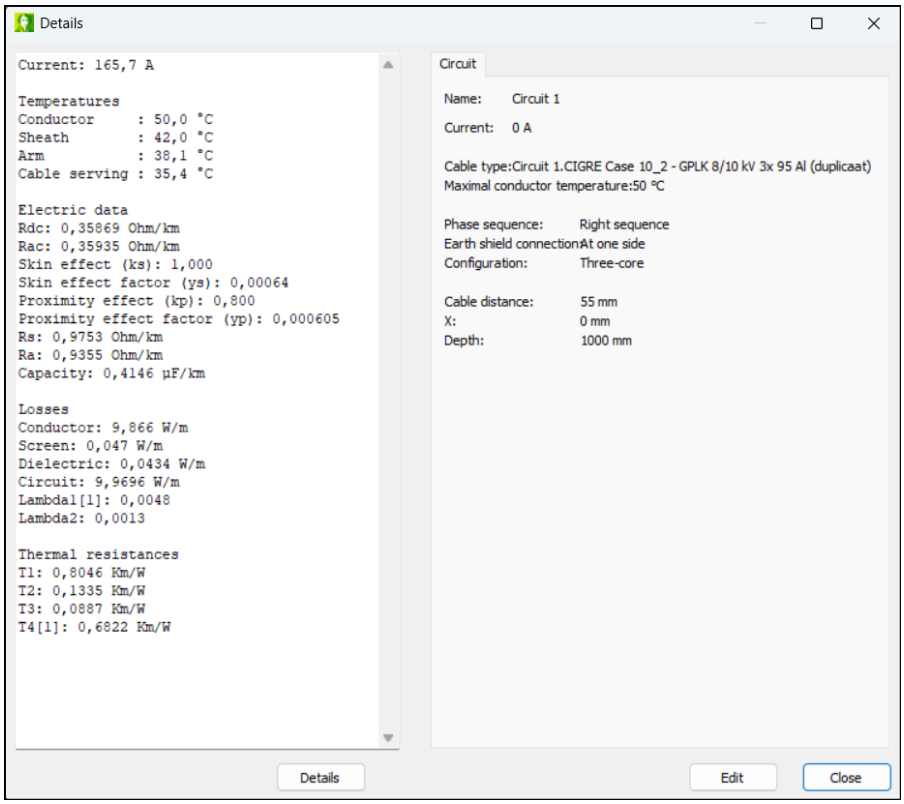


Figure 21 VCA results for case 10.

4.12 Conclusions

For Case 10 the final result that matters for rating, the maximum current agrees almost exactly (165.74 A CIGRE vs 165.69 A VCA).

Intermediate differences still deserve attention:

- Proximity-effect factor: IEC 60287-1-1 Table 2 supports the CIGRE value
- Voltage input: CIGRE mixes voltage usage in places; VCA should adopt a single, clearly documented convention.
- Sector-core geometry: CIGRE's more detailed center calculation changes capacitance and W_d relative to the IEC virtual-center formula used in VCA, without spoiling the final current in this case.

Case 10 therefore confirms VCA's rating for a three-core PILC construction, while highlighting geometry and factor choices that should be tightened so that intermediate parameters, track TB 880 more closely.

5 OVERALL CONCLUSIONS

The three case studies show that VCA reproduces CIGRE TB880 ampacities very closely as shown in the table 69.

Case / Situation	TB880 Chapter	CIGRE (A)	VCA (A)	Δ (A)	Δ (%)
Case 0-1: Base case	4	821,77	821,77	0	0
Case 0-1: Variant with single point bonding	4.6.3	886,17	886,09	-0,08	-0,01
Case 0-2: Sub-case study with touching HDPE ducts	4.7	682,81	682,8	-0,01	0
Case 0-3: Sub-case study with PVC ducts in flat formation embedded in concrete	4.8	634,07	633,74	-0,33	-0,05
Case 0-3: Variant with single point bonding	4.8.5	904,55	904,64	0,09	0,01
Case 0-4: Sub-case study with cables laid in free air directly exposed to solar radiation	4.9	990,94	990,72	-0,22	-0,02
Case 0-4: Variant with cables protected from direct solar radiation	4.9.5	1141,36	1141,25	-0,11	-0,01
Case 0-4: Variant with single point bonding	4.9.6	1046,5	1046,23	-0,27	-0,03
Case 0-5: Sub-case study with cables in an unfilled trough	4.10	764,56	763,7	-0,86	-0,11
Case 4: A 33kV land cable	8	537,46	542,84	5,38	1
Case 10: A 10kV three core PILC cable	14	165,74	165,69	-0,05	-0,03

Table 69 Summary of maximum current comparison of all the 3 cases

The causes for the differences have been explained per case. The main differences arise due to the difference in modelling of the conductor screen and the isolation thicknesses in VCA. The intermediate results deviate slightly due to this but the effect on the maximum current result is not significant in all the cases.

NEXT STEPS

- Validation of Case study 1: Direct buried 132kV cables
- Laying factor to be introduced in Vision Cable Analysis
- Flexibility to be introduced for different input thicknesses for isolation and conductor screen