Report

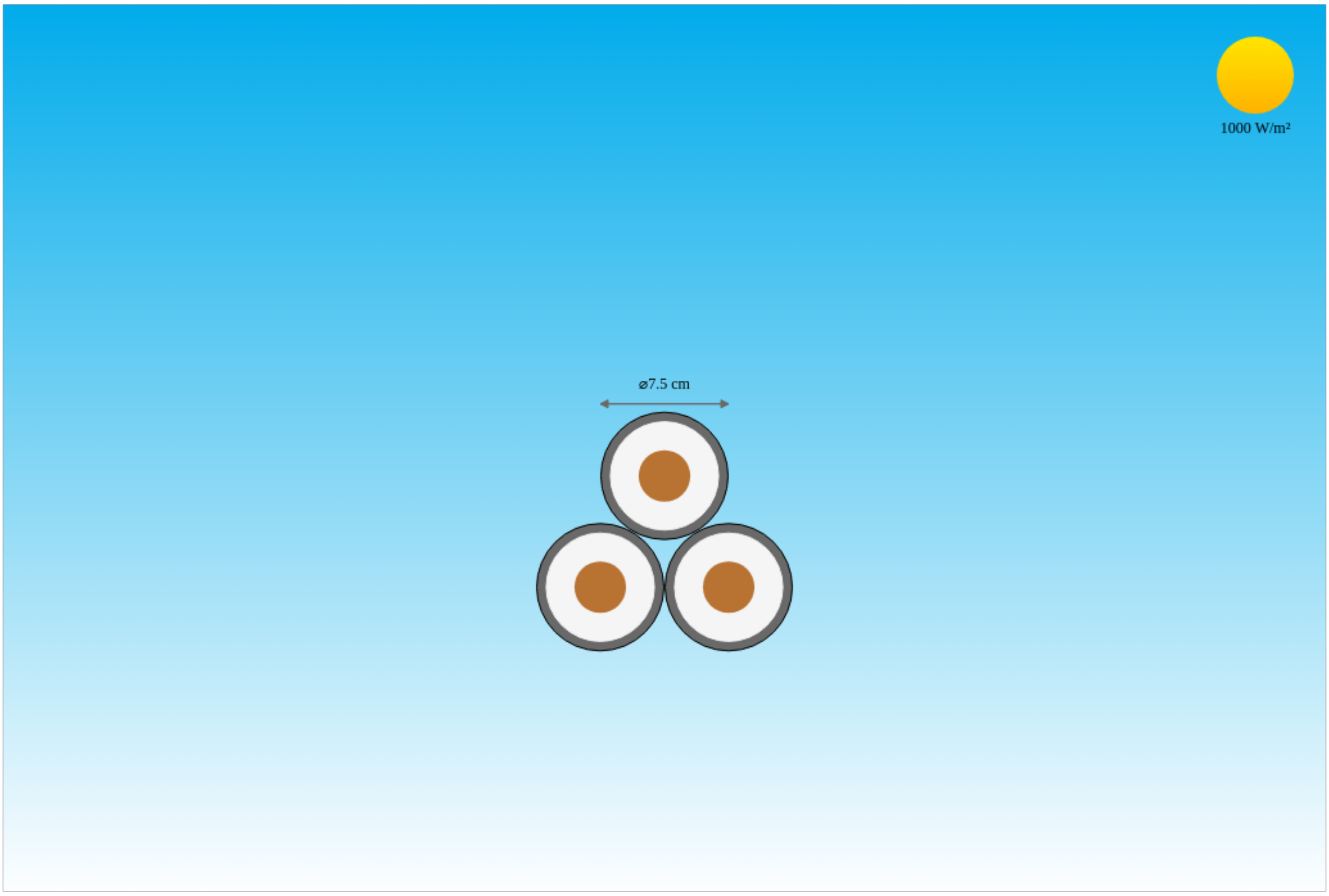
Title	Case study 0-4: Introductory (in air)
Project	Verification CIGRE TB 880
Description	Sub-case study with cables laid in free air directly exposed to solar radiation
Created	Date: 2025-05-14 Time: 21:27 Software version: 51cac (2025-05-14)

Arrangement

Arrangement	**in air project** (#3934)
Options	None
CIGRE TB 880, guidance points	02, 06, 26, 31
Systems	A

Statistics

Number of iterations of the solver	N_{calc}	16
Sum of currents from all systems	I_{sum}	974.28 A
Sum of average conductor temperatures from all systems	θ_{sum}	90 °C
Number of overheated electrical systems		0
Sum of losses from all systems	W_{sum}	155.526 W/m



Systems

Following systems are active in the arrangement:

#	Object	Current [A]	Temp. [°C]	Losses [W/m]	Load
		I_c	θ_c | θ_e	W_{sys}	LF
A	16173 CIGRE TB 880 Case 0 XLPE insulated ca...	974.3	90.0 | 71.4	155.5	1.00

Objects

Following objects are used:

16173 CIGRE TB 880 Case 0 XLPE insulated cable 132 kV

Ambient

Ambient temperature	θ_a	25 °C
Intensity of solar radiation	H_{sun}	1000 W/m^2

Constants

Standard acceleration of gravity	g	9.80665 m/s^2
Archimedes' constant π	π	3.141592653589793
Absolute temperature	θ_{abs}	273.15 K
Stefan Boltzmann constant	σ	5.67036713e-8 W/m^{2}K^4
Vacuum permeability	μ_0	1.2566370614359173e-6 H/m
Vacuum permittivity	ϵ_0	8.854187817620389e-12 F/m

System A (High voltage cable)

Ampacity

Cable		CIGRE TB 880 Case 0 XLPE insulated cable 132 kV
Rounded value, CIGRE TB 880	I_c	970 A
Conductor current	I_c	974.28 A

$$\sqrt{\frac{\theta_c - \theta_a - \Delta\theta_d - \Delta\theta_{sun}}{R_c\left(T_1 + n_{ph}\left(1+\lambda_1\right)T_2 + \left(1+\lambda_1+\lambda_2+\lambda_3\right)\left(n_{ph}T_3 + n_{cc}\left(T_{4i}+T_{4ii}+T_{4iii}\right)\right) + n_{cc}\lambda_4\left(\frac{T_{4ii}}{2}+T_{4iii}\right)\right)}}$$

Operating voltage	U_o	132 kV
Angular frequency	ω	314.2 rad/s

$2\pi f$

Number of sources in system	N_c	3
Number of conductors combined	n_{cc}	1

Load

System frequency	f	50 Hz
Continuous load	LF	1 p.u.

Arrangement

Arrangement		trefoil
Position cable 1	$x_1 \vert y_1$	0.0 | -43.6 mm
Position cable 2	$x_2 \vert y_2$	-37.7 | 21.8 mm
Position cable 3	$x_3 \vert y_3$	37.7 | 21.8 mm
Separation of conductors in a system	s_c	75.5 mm
Mean distance between the phases	a_m	95.124 mm
Geometric mean distance between phases of the same system	GMD	95.12404 m
Outer diameter	D_o	0.0755 m

Temperature

Temperature conductor	θ_c	90 °C

$\theta_a + \Delta\theta_c + \Delta\theta_{sun}$

Temperature screen/sheath	θ_s	74.17 °C
Temperature sheath	θ_{sh}	74.17 °C

$$\theta_c - T_1\left(W_c + \frac{W_d}{2}\right)$$

External temperature object	θ_e	71.36 °C

$$\theta_c - T_1\left(W_c + \frac{W_d}{2}\right) - n_{ph}T_2\left(W_c\left(1+\lambda_1\right)+W_d\right) - n_{ph}T_3\left(W_I + W_d\right)$$

Temperature rise

Temperature rise conductor	$\Delta\theta_c$	47.9355 K

$$n_{ph}\left(W_cT_{int} + W_dT_d\right) + n_{cc}\left(\left(W_c+W_s+W_{ar}+W_{sp}+W_d\right)\left(T_{4i}+T_{4ii}+T_{4iii}\right) + W_{duct}\left(\frac{T_{4ii}}{2}+T_{4iii}\right)\right)$$

Temperature rise dielectric losses	$\Delta\theta_d$	0.3194 K

$W_d\left(n_{ph}T_d + n_{cc}\left(T_{4i}+T_{4ii}+T_{4iii}\right)\right)$

Temperature difference surface—ambient	$\Delta\theta_s$	46.3578 K

$$\frac{\Delta\theta_s + T_{4iii}n_{cc}W_t + \Delta\theta_{sun}}{2}$$

Temperature difference solar radiation $\sigma_{sun} D_o H_{sun} T_{4iii}$	$\Delta\theta_{sun}$	17.0645 K

Losses

Ohmic

Conductor losses (phase) ${I_c}^2 R_c$	W_c	37.515 W/m
Screen/sheath losses (phase) $\lambda_1 W_c$	W_s	13.942 W/m
Duct losses	W_{duct}	0 W/m
Ohmic losses (phase) $W_c(1+\lambda_1+\lambda_2+\lambda_3+\lambda_4)$	W_I	51.457 W/m

Dielectric

Dielectric losses (phase) $\omega C_b \left(1000\frac{U_o}{\sqrt{3}}\right)^2 \tan\delta_i$	W_d	0.385 W/m

Total

Total losses (phase) $W_I + W_d$	W_t	51.842 W/m
Total losses (object) $n_{ph} W_t$	W_{tot}	51.842 W/m
Total losses (system)	W_{sys}	155.526 W/m

Thermal resistance

Thermal resistance ambient $\frac{1}{\pi D_o h_{bs} {\Delta\theta_s}^{\frac{1}{4}}}$	T_{4iii}	0.5651 K.m/W
Intensity of solar radiation	H_{sun}	1000 W/m^2
Heat dissipation coefficient for black surfaces in free air $\frac{Z_{bs}}{{D_o}^{g_{bs}}} + E_{bs}$	h_{bs}	2.859 W/m^2/K$^{5/4}$
Installation constant E	E_{bs}	1.25
Installation constant g	g_{bs}	0.2
Installation constant Z	Z_{bs}	0.96

Cable

Internal thermal resistance for current losses $\frac{T_1}{n_{ph}} + (1+\lambda_1) T_2 + (1+\lambda_1+\lambda_2+\lambda_3) T_3$	T_{int}	0.4942 K.m/W
Internal thermal resistance for dielectric losses $\frac{T_1}{2n_c} + T_2 + T_3$	T_d	0.26414 K.m/W

Other characteristics

Earthing

earthing screen/sheath		both-side bonding
Variation of spacing		No variation

Loss factor

Loss factor shield (screen/sheath) $\lambda_{11} + F_e\lambda_{12}$	λ_1	0.3717
Loss factor shield, circulating currents $\frac{\frac{R_e}{R_c}}{1+\left(\frac{R_e}{X_e}\right)^2}$	λ_{11}	0.2978
Loss factor shield, eddy currents $\frac{R_{sh}}{R_c}\left(g_s\lambda_0\left(1+\Delta_1+\Delta_2\right)+\frac{\left(\beta_1 t_{sh}\right)^4}{12{\cdot}10^{12}}\right)$	λ_{12}	0.0784
Electrical resistance shield/armour	R_e	2.0335e-1 Ω/km
Substitution coefficient λ_0 for eddy-currents $3\frac{{m_0}^2}{1+{m_0}^2}\left(\frac{d_e}{2s_c}\right)^2$	λ_0	0.0141
Substitution coefficient Δ_1 for eddy-currents $\left(1.14{m_0}^{2.45}+0.33\right)\left(\frac{d_e}{2s_c}\right)^{0.92m_0+1.66}$	Δ_1	0.0805
Substitution coefficient Δ_2 for eddy-currents	Δ_2	0
Substitution coefficient m_0 for eddy-currents $10^{-7}\frac{\omega}{R_{sh}}$	m_0	0.1545 Hz.m/Ω
Substitution coefficient β_1 for eddy-currents $\sqrt{\frac{4\pi\omega}{10^7\rho_{sh}\left(1+\alpha_{sh}\left(\theta_{sh}-20\right)\right)}}$	β_1	106.8179
Substitution coefficient g_s for eddy-currents $1+\left(\frac{t_{sh}}{D_{sh}}\right)^{1.74}\left(10^{-3}\beta_1 D_{sh}-1.6\right)$	g_s	1.00248
Factor F_e eddy-current losses $\frac{4{M_e}^2{N_e}^2+\left(M_e+N_e\right)^2}{4\left({M_e}^2+1\right)\left({N_e}^2+1\right)}$	F_e	0.9421
Substitution coefficient M_e to calculate factor F_e $\frac{R_e}{X_e}$	M_e	4.0344
Substitution coefficient N_e to calculate factor F_e $\frac{R_e}{X_e}$	N_e	4.0344
Loss factor armour	λ_2	0

Electrical parameters

System

System length	L_{sys}	1000 m
Power factor	$\cos\varphi$	1

Resistance

Electrical resistance conductor $R_{cDC}\left(1+y_s+y_p\right)$	R_c	3.9522e-5 Ω/m → 0.0395 Ω
Electrical resistance DC conductor $R_{c20}\left(1+\alpha_c\left(\theta_c-20\right)\right)$	R_{cDC}	3.6085e-5 Ω/m → 0.0361 Ω
Skin effect factor conductor $\frac{{x_s}^4}{192+0.8{x_s}^4}$	y_s	0.06012
Factor for skin effect on conductor $\sqrt{10^{-7}\frac{8\pi f}{R_{cDC}}k_s}$	x_s	1.86612
Proximity effect factor conductor $\frac{{x_p}^4}{192+0.8{x_p}^4}\left(\frac{d_c}{s_c}\right)^2\left(0.312\left(\frac{d_c}{s_c}\right)^2+\frac{1.18}{\frac{{x_p}^4}{192+0.8{x_p}^4}+0.27}\right)$	y_p	0.0351
Factor for proximity effect of conductors $\sqrt{10^{-7}\frac{8\pi f}{R_{cDC}}k_p}$	x_p	1.86612
Electrical resistance sheath $R_{sh}\left(1+\alpha_{sh}\left(\theta_{sh}-20\right)\right)$	R_{sh}	2.0335e-4 Ω/m → 0.2033 Ω
Electrical resistance shield	R_s	2.0335e-4 Ω/m → 0.2033 Ω
Reduction factor $\frac{R_s}{\sqrt{{R_s}^2+{X_s}^2}}$	RF	0.3019

Electrical field strength, capacitive load current

Electrical field strength insulation inner/outer $\frac{U_e}{1000}\frac{1}{r_x\ln\left(\frac{r_{osc}}{r_{isc}}\right)}$	E_i	6.956 | 3.603 kV/mm
Radius to point x in insulation	r_x	16.65 | 32.15 mm
Line-to-ground voltage $\frac{1000U_o}{\sqrt{3}}$	U_e	76210.24 V
Capacitance insulation $\frac{1}{2\pi\epsilon_0}\frac{10^{-9}}{18}C_b$	C_b	2.111e-10 F/m → 0.2111 μF
Capacitive load current $U_e\omega C_b$	I_C	5.054e-3 A/m → 5.0536 A
Charging capacity $n_{ph}{U_e}^2\omega C_b$	P_C	385.1382 var/m → 385.1382 kvar
Capacitive earth short-circuit current $U_e\omega C_E$	I_{Ce}	5.054e-3 A/m

Reactance

Self reactance conductor $\omega\frac{\mu_0}{2\pi}\ln\left(\frac{D_E}{GMR_c}\right)$	X_a	7.088e-4 Ω/m → 0.7088 Ω

Self reactance screen/sheath $\omega \frac{\mu_0}{2\pi} \ln\left(\frac{2s_c}{d_s}\right)$	X_e	5.040e-5 Ω/m → 0.0504 Ω

Induced current (approximate)

Induced circulating current shield $\max\left(I_c\sqrt{\frac{\lambda_{11,sb}R_c}{R_s}}\right)$	I_s	234.397+0.000j A
Loss factor shield, circulating currents	$\lambda_{11,sb}$	0.2978+0.0000j

Load, Voltage drop

Apparent power generator-side $\sqrt{3}U_oI_c$	S_G	222.75 MVA
Voltage drop $\sqrt{3}\left(R_c\cos\varphi + \omega L_m \sin\varphi\right)$	V_{drop}	0.068 V/(A.km) → 66.7 V = 0.05%
Inductance (mean) $\frac{\mu_0}{2\pi} \ln\left(\frac{GMD}{GMR_c}\right)$	L_m	1.800e-6+0.000e0j H/m → 1.8002 mH

Telegrapher equation

Surge impedance $\sqrt{\frac{Z_1}{Y_1}}$	Z_C	92.4076-3.2248j Ω
Propagation constant $\sqrt{Z_1Y_1}$	γ_C	2.138e-7+6.128e-6j

Impedance valid up to 100 Hz without earth return

Positive sequence admittance $G + j\omega C_b$	Y_1	0.000e0+6.631e-8j S/m → 0.0000+0.0001j S
Positive sequence impedance $R_1 + jX_1$	Z_1	3.952e-5+5.656e-4j Ω/m → 0.0395+0.5656j Ω
Positive sequence reactance $\omega \frac{\mu_0}{2\pi} \ln\left(\frac{GMD}{GMR_c}\right)$	X_1	5.656e-4 Ω/m → 0.5656 Ω

Cable datasheet

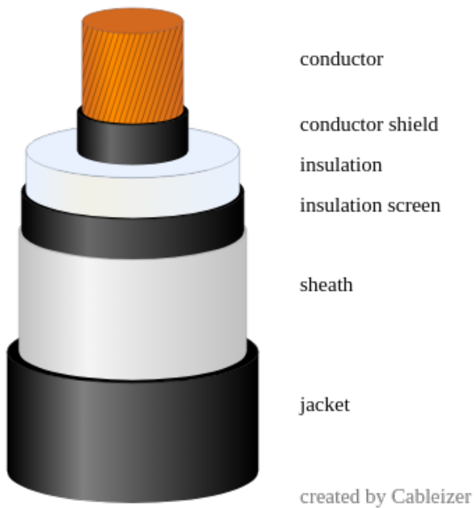
Title CIGRE TB 880 Case 0 XLPE insulated cable 132 kV (#16173)

Cable is used in following systems: AIR

CIGRE TB 880, guidance points 15, 20, 23, 25, 30, 32, 33, 34, 38, 39, 42, 44, 45

General Data

Rated line-to-line voltage	U_n	132 kV
Base voltage for tests	U_0	76 kV
Highest voltage for equipment	U_m	145 kV
Nominal system frequency	f	50 Hz
Number of conductors cable	n_c	1
Number of phases in a cable	n_{ph}	1



Cable elements

Conductor

Cross-sectional area conductor	A_c	1 x 630 mm^2
Conductor material	M_c	Copper, round stranded
External diameter conductor	d_c	30.3 mm
Radius conductor	r_c	15.15 mm

$$\frac{d_c}{2}$$

Insulation

Insulation material	M_i	Crosslinked polyethylene (XLPE)
Thickness conductor shield	t_{cs}	1.5 mm
Thickness insulation	t_{ins}	15.5 mm
Thickness insulation screen	t_{is}	1.3 mm
Thickness insulation	t_i	18.3 mm

$$t_{ct} + t_{cs} + t_{ins} + t_{is}$$

Sheath

Sheath material	M_{sh}	Aluminium
Thickness sheath	t_{sh}	0.8 mm
corrugated		No

Jacket

Jacket material	M_j	High density polyethylene (HDPE, ST7)
Thickness jacket	t_j	3.5 mm

Overall

External diameter object	D_e	75.5 mm
Absorption coefficient solar radiation	σ_{sun}	0.4
Emissivity cable	ϵ_e	0.9
Reflectivity cable $1 - \epsilon_e$	η_e	0.1
Mass cable $m_{hollow} + m_{metal}$	m_{tot}	9.418 kg/m

Electrical

Conductor

Electrical resistance DC conductor 20°C	R_{c20}	2.8300e-5 Ω/m
Standard DC resistance of conductor	R_{co}	0.0283 Ω/km
Coating of wires		plain
Skin effect coefficient	k_s	1
Proximity effect coefficient	k_p	1
Geometric mean radius conductor $K_{GMR} r_{z1}$	GMR_c	0.01173 m
Factor geometric mean radius	K_{GMR}	0.774
Constant relating to conductor formation	K_{BICC}	0.0512
Number of wires conductor	n_{cw}	91
Diameter of wires conductor (average)	d_{cw}	2.97 mm

Insulation

Capacitance, with approximation (CIGRE TB 880) $\frac{1}{2\pi\epsilon_0}\frac{10^{-9}}{18} C_b$	C_b	2.111e-10 F/m
Capacitance (exact) $\frac{2\pi\epsilon_0\epsilon_i}{\ln\left(\frac{r_{osc}}{r_{isc}}\right)}$	C_b	2.114e-10 F/m
Capacitance to earth C_b	C_E	2.111e-10 F/m
Vacuum permittivity	ϵ_0	8.854187817620389e-12 F/m
Radius above the inner semi-conducting layer $\frac{d_c}{2} + t_{ct} + t_{cs}$	r_{isc}	16.65 mm
Radius over capacitive insulation layers $\frac{D_{ins}}{2}$	r_{osc}	32.15 mm

Velocity of propagation $\frac{1}{1000\sqrt{\mu_0\epsilon_0\epsilon_i}}$	v_{prop}	189605.4 km/s

Screen + Sheath

Electrical resistance sheath $10^6\frac{\rho_{sh}}{A_{sh}}$	R_{sh}	1.6691e-4 Ω/m
Electrical resistance screen/sheath 20°C	R_{so}	1.669e-1 Ω/km

Radius

Radius conductor	r_{z1}	0.01515 m
Radius shield (inner)	r_{z2}	0.03305 m
Radius shield (outer)	r_{z3}	0.03305 m
Radius sheath (inner)	$r_{z2,sh}$	0.03305 m
Radius sheath (outer)	$r_{z3,sh}$	0.03465 m
Radius outersheath	r_{z6}	0.03775 m

Material parameters

Conductor

Electrical resistivity conductor material	ρ_c	1.724e-8 Ω.m
Temperature coefficient conductor material	α_c	3.93e-3 1/K
Reciprocal of temperature coefficient conductor material	β_c	2.345e2 K
Volumetric heat capacity conductor material	σ_c	3.45e6 J/(K.m^3)
Thermal conductivity conductor material	k_c	384.62 W/(m.K)
Density conductor material	ζ_c	8.94 g/cm^3

Insulation

Relative permittivity insulation material	ϵ_i	2.5
Loss factor insulation material	$\tan\delta_i$	0.001
Thermal resistivity insulation material	ρ_i	3.5 K.m/W
Volumetric heat capacity insulation material	σ_i	2.40e6 J/(K.m^3)
Density insulation material	ζ_i	0.923 g/cm^3
Max. temperature conductor	θ_{cmax}	90 °C
Max. temperature conductor, emergency overload	θ_{cmaxeo}	105 °C
Max. temperature conductor, short-circuit	θ_{cmaxsc}	250 °C
Conductor shield		
Thermal resistivity conductor shield	ρ_{cs}	2.5 K.m/W
Insulation screen		
Thermal resistivity insulation screen	ρ_{is}	2.5 K.m/W

Sheath

Specific electrical resistivity sheath material	ρ_{sh}	2.840e-8 Ω.m
Temperature coefficient sheath material	α_{sh}	4.03e-3 1/K
Reciprocal of temperature coefficient sheath material	β_{sh}	2.281e2 K
Volumetric heat capacity sheath material	σ_{sh}	2.50e6 J/(K.m^3)
Thermal conductivity sheath material	k_{sh}	208.3 W/(m.K)
Density sheath material	ζ_{sh}	2.712 g/cm^3

Jacket

Thermal resistivity jacket material	ρ_j	3.5 K.m/W
Thermal resistivity additional layer	ρ_{jj}	2.5 K.m/W
Volumetric heat capacity jacket material	σ_j	2.40e6 J/(K.m^3)
Electrical conductivity jacket material	κ_j	2.00e-15 S/m
Density jacket material	ζ_j	0.941 g/cm^3

Thermal resistance

Internal thermal resistances for rating calculation

Thermal resistance conductor—sheath T_1 0.4199 K.m/W

$$T_{ct} + T_{cs} + T_{ins} + T_{is} + T_{scb} + T_{scs} + T_{dsh}$$

Thermal resistance armour bedding T_2 0 K.m/W

Thermal resistance jacket T_3 0.0542 K.m/W

$$T_{ab} + T_j + T_{jj}$$

Thickness conductor—sheath t_1 18.3 mm

$$t_i + t_{scb} + t_{scs} + \frac{H_{sh} + \Delta H}{2}$$

Thickness sheath—armour t_2 0 mm

$$\frac{H_{sh} + \Delta H}{2} + t_{ab}$$

Thickness armour—surface t_3 3.5 mm

$$t_j + t_{jj}$$

Cable elements

Thermal resistance, transient T_{tot} 0.4741 K.m/W

$$T_1 + T_2 + T_3$$

Thermal resistance insulation T_i 0.41987 K.m/W

$$T_{ct} + T_{cs} + T_{ins} + T_{is}$$

Thermal resistance conductor shield T_{cs} 0.03756 K.m/W

$$\frac{\rho_{cs}}{2\pi} \ln\left(\frac{D_{cs}}{D_{cs} - 2t_{cs}}\right)$$

Thermal resistance insulation T_{ins} 0.36654 K.m/W

$$\frac{\rho_i}{2\pi} \ln\left(\frac{D_{ins}}{D_{ins} - 2t_{ins}}\right)$$

Thermal resistance insulation screen T_{is} 0.01577 K.m/W

$$\frac{\rho_{is}}{2\pi} \ln\left(\frac{D_{ins} + 2t_{is}}{D_{ins}}\right)$$

Thermal resistance jacket T_j 0.0542 K.m/W

$$\frac{\rho_j}{2\pi} \ln\left(\frac{D_j - 2t_{jj}}{D_j - 2\left(t_j + t_{jj}\right)}\right)$$

Dimensions

Diameter

External diameter conductor d_c 30.3 mm

Diameter over conductor shield D_{cs} 33.3 mm

$$d_c + 2\left(t_{ct} + t_{cs}\right)$$

Diameter over insulation D_{ins} 64.3 mm

$$d_c + 2\left(t_{ct} + t_{cs} + t_{ins}\right)$$

Diameter over insulation incl. insulation screen $d_c + 2\left(t_{ct} + t_{cs} + t_{ins} + t_{is}\right)$	D_i	66.9 mm
Diameter over insulation screen $d_c + 2t_i$	D_{is}	66.9 mm
Equivalent diameter of screen and sheath	d_s	67.7 mm
Mean diameter sheath $D_{shb} + t_{sh} + H_{sh} + \Delta H$	d_{sh}	67.7 mm
Diameter over sheath $D_{shb} + 2\left(t_{sh} + H_{sh} + \Delta H\right)$	D_{sh}	68.5 mm
Diameter over sheath jacket	D_{shj}	68.5 mm
Diameter over jacket $D_{ar} + 2\left(t_j + t_{jj}\right)$	D_j	75.5 mm

Area

Cross-sectional area conductor	A_c	630 mm^2
Cross-sectional area insulation $\frac{\pi}{4}\left({D_{is}}^2 - {d_c}^2\right)$	A_i	2794.1 mm^2
Cross-sectional area sheath $d_{sh} t_{sh} \pi$	A_{sh}	170.15 mm^2
Cross-sectional area jacket $\frac{\pi}{4}\left({D_j}^2 - \left(D_j - 2\left(t_j + t_{jj}\right)\right)^2\right)$	A_j	791.7 mm^2