DOI: 10.1049/gtd2.12092



Enhancement of the thermal analysis of power cables installed in polyvinyl chloride (PVC) ducts under continuous and cyclic current loading conditions

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Abstract

A study of the performance of power cables installed inside non-metallic ducts is presented here. Cable capacity calculations for this type of installation are done. The thermal analysis of cables inside ducts which are installed in air as riser or buried in soils is presented. According to IEC 60287 cables can be installed in fibre ducts in concrete layer surrounded by the soil, in this article it is proposed to install the cables in PVC ducts directly buried in the soil. Based on IEC 60287-1-3 and IEC 60853-2 standards proposed models in steady state and dynamic cable loadings are constructed. The proposed equivalent thermal models are used in the calculations of the cable components temperature for cables installed in ducts. It is concluded that very high increase in cable conductor temperature is observed when the cable is installed in duct and used as riser or even when it is installed in duct buried in soil. Significant decrease in the temperature of the cable conductor can be noticed when the cable is directly buried in the soil compared with that installed in ducts.

1 | INTRODUCTION

The use of underground power cables for electrical energy transmission and distribution in towns and compactly populated zones is growing every year. Thermal analysis of underground power cables in steady state and dynamic loading is a subject, which has received extensive investigation in current years [1-10]. The cable installation in non-metallic protective ducts was abbreviated back in 1957 by Neher and McGrath [11]. The advantages of such this installation is to protect the power cables and cable risers from mechanical damage and to prevent human accidents. The calculations of the maximum continuous current loading capacity of cable installed in duct have been standardized by IEC 60287-1-3 family [12]. Hartline and Black carried out work to rate the cable risers current capacity, by the calculation of an average Nusselt number applicable for parallel flat plates and cylinders [13–15]. Anders modified Hartline and Black method of calculations of cable rating in risers, in trays, in tunnels and shafts by using mathematical model [16], which is implemented by CYMCAP [17]. Cables installed into cable tunes are typically used on projects where the cable duct is

buried into the ground, up to 1200 mm depth. This includes low voltage, medium voltage and high voltage ducted power cables [18]. Guidelines for the minimum depths of the underground power cables installation are specified by the IEC [12], IEEE [13] and DNO (distribution network operators in the UK) [19] depending on whether cables are directly buried into soil or installed in suitable cable ducts depending on ground location types. Unfortunately, these standards lack methods deal with cable risers in ducts. Installations of underground power cables in ducts are road crossings and cable risers. For complex cable arrangements, such as cables on riser ducts, cables in covered trays and cables in ducts, heat transfer mechanisms and heat transfer rates are greatly impacted by the installation geometries and environmental conditions. The thermal performance of cables installed in ducts is greatly dependent on the duct thickness, the cable laying method, and the surface coefficient of solar absorption in case of riser installation [20-26]. Overhead transmission line sections are usually connected with electrical components through a riser ensured on a pole and covered by a guard plastic duct to provide protection to the cables from mechanical damage. Usually, the capacity of the composite cable

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transmission line system is limited by the thermal performance of the cable riser. The reason is that the heat transfer from the cable surface to the ambient is severely obstructed by the protective cable plastic duct. Therefore the cable components temperatures increase and resulting in the limitation of the system current carrying capacity. New technique to install power cables into ducts is suggested by [27].

In this paper, various cable rating and their risers installed in PVC ducts are thermally investigated. The performance of cables installed in ducts buried in different soil types is studied. The effect of protective duct thickness on the cable components temperature is presented. It is noticed that the dry zone in the soil surrounding the cable duct is not formed. Calculations are done by employing the thermal models of cables used as risers in ducts and that installed in ducts and buried in soils. Computed temperatures of cable conductors are carried out in steady state and dynamic loading cases.

2 | THERMAL ANALYSIS OF POWER CABLES IN PVC DUCTS

The analysis done in this paper includes the thermal performance of cables installed in ducts under continuous and cyclic current loading conditions

2.1 | Mathematical modelling of cables installed in PVC duct loaded by steady state current (100% load factor)

Figure 1(a) shows three phase cable in flat formation, that is installed in duct and buried in a soil at a depth *L*. The equivalent thermal circuit of one phase is given in Figure 1(b). In this case the maximum current carrying capacity can be calculated by using IEC 60287-1-3 formula [12].

$$I = \sqrt{\left[\frac{\Delta\theta - W_{d} \left[0.5 \ T_{1} + n \left(T_{2} + T_{3} + T_{4}\right)\right]}{R_{ac} T_{1} + n R_{ac} \left(1 + \lambda_{1}\right) T_{2} + n R_{ac} \left(1 + \lambda_{1} + \lambda_{2}\right) \left(T_{3} + T_{4}\right)}\right]}$$
(1)

Where, *I* is the cable current in Amp., $\Delta\theta$ is the conductor temperature rise above ambient temperature in °C, W_c , W_s , W_a and W_d are the power losses in $W \text{ m} < \text{sp} > -1 < /\text{sp} > \text{of the conductor, screen, armouring and insulation respectively and <math>n$ is the number of conductors in the cable. T_1 , T_2 , T_3 and T_4 are defined as the thermal resistances of the insulation, armour, jacket and surrounding medium respectively in °C/W and R_{ac} is the electrical resistance of the conductor in $\Omega \text{ m} < \text{sp} > -1 < /\text{,sp} > \lambda_1 \text{ and } \lambda_2$ are the screen and armor loss factors. It has to be noted that the armour thermal resistance is ignored because it is usually made of metals. The thermal resistances of the cable different layers and the surrounding medium in °C/W can be calculated using the following equations [12]:

$$T_1 = \frac{\rho_{\rm i}}{2\pi} \ln\left(\frac{D_{\rm i}}{d_{\rm c}}\right) \tag{2}$$



FIGURE 1 Cable and riser configurations buried in ducts and their equivalent circuits at steady state, (a) cable arrangement, (b) cable equivalent circuit, (c) riser arrangement and (d) riser equivalent circuit

$$T_3 = \frac{\rho_j}{2\pi} \ln\left(\frac{D_c}{D_s}\right) \tag{3}$$

$$T_4 = T_4' + T_4'' + T_4''' \tag{4}$$

$$T_{4}' = \frac{U}{1 + 0.1 \left(V + Y \theta_{\rm m} \right) D_{\rm e}} \tag{5}$$

$$T_{4}^{\prime\prime} = \frac{\rho_{d}}{2\pi} \ln\left(\frac{D_{do}}{D_{di}}\right)$$
(6)
$$T_{4}^{\prime\prime\prime} = \frac{\rho_{soil}}{2\pi} \left\{ \ln\left(\frac{4L}{D_{do}}\right) + \ln\left(1 + \left(\frac{2L}{S}\right)^{2}\right) \right\}$$
(7)

(7)

where
$$T'_4$$
 is the thermal resistance of the air between the cable
jacket and the inner surface of the duct in °C/W, T''_4 is the ther-
mal resistance of the PVC duct in °C/W and T''_4 is the thermal
resistance of the soil surrounding the PVC duct in °C/W, ρ_i ,
 ρ_j , ρ_d and ρ_{soil} are the thermal resistivity in (°C m/W) of the
insulation, jacket, duct and the surrounding soil respectively. *L*
is the cable laying depth in meter, *S* is the distance between each
cable centre and its neighbour, d_c , D_i , D_s , D_c , D_{di} and D_{do} are
the diameters of the conductor, insulation, screen, jacket, inner
PVC duct and its outer diameter in meters respectively. *U*, *V*
and *Y* are constants which are defined by IEC 60287, and θ_m is
the mean temperature of the PVC duct medium in. Figure 1(c)
shows three phases cable riser in flat formation installed in PVC
duct and used as a riser with air as surrounding medium. Its
equivalent circuit is given in Figure 1(d). The maximum current
capacity of cables in vertical riser can be calculated using IEC
60287-1-3 formula [12]:

$$I = \sqrt{\left[\frac{\Delta\theta - W_{\rm d}\left[0.5\ T_1 + n\left(T_2 + T_3 + \ T_4^*\right)\right] - \sigma\ D_{\rm ro}H\ T_4^*}{R_{\rm ac}T_1 + nR_{\rm ac}\left(1 + \lambda_1\right)T_2 + nR_{\rm ac}\left(1 + \lambda_1 + \lambda_2\right)\left(T_3 + \ T_4^*\right)}\right]}$$
(8)

Where, σ is the absorption coefficient of solar radiation for the riser surface depending on the material of the riser duct, its value is considered to be 0.6 for PVC material, H is the intensity of solar radiation which is taken as 1000 W/m² for most spaces as an average value [28], and T_4^* is the surrounding thermal resistance in °C/W.

$$T_4^* = T_4^{*'} + T_4^{*''} + T_4^{*'''}$$
(9)

$$T_4^{*'} = \frac{U}{1 + 0.1 \left(V + Y \theta_{\rm r} \right) D_e} \tag{10}$$

$$T_4^{*''} = \frac{\rho_{\rm r}}{2\pi} \ln\left(\frac{D_{\rm ro}}{D_{\rm ri}}\right) \tag{11}$$

$$T_4^{*'''} = T_{\rm air-con} // T_{\rm air-rad}$$
(12)

where $T_4^{*'}$ is the thermal resistance of the air between the cable jacket and the inner surface of the riser in °C/W, $T_4^{*^{\prime\prime\prime}}$ and $T_4^{*^{\prime\prime\prime}}$ are the thermal resistances in °C/W of the riser PVC duct and the air surrounding the riser duct respectively, ρ_r is the thermal resistivity of the PVC duct in °C m/W, D_{ri} and D_{ro} are the diameters in meters of inner and outer PVC duct respectively. and θ_r is the mean temperature of the riser inner surface in °C. The thermal resistance of the air surrounding the PVC duct of the rised, $T_4^{*'''}$ is calculated as the following

$$T_4^{*'''} = T_{\text{air-conv}} //T_{\text{air-rad}}$$
(13)

$$T_{\rm air-conv} = \frac{1}{b_{\rm conv} A_{\rm s}} \tag{14}$$

$$T_{\rm air-rad} = \frac{1}{b_{\rm rad} A_{\rm s}} \tag{15}$$

$$b_{\rm conv} = \frac{N_{\rm u} \ K_{\rm amb}}{D_{\rm ro}} \tag{16}$$

$$b_{\rm rad} = \varepsilon \sigma_{\rm b} \left(\theta_{\rm r} + \theta_{\rm amb} \right) \left(\theta_{\rm r}^2 + \theta_{\rm amb}^2 \right)$$
(17)

$$N_{\rm u} = \left[0.6 + \frac{0.387 R a_D^{1/6}}{\left[1 + \left(\frac{0.559}{P_{\rm r}} \right)^{9/16} \right]^{8/27}} \right]^2$$
(18)

$$Ra_D = \frac{g P_r \beta D_{ro} (\theta_r - \theta_{amb})}{v^2}$$
(19)

where $T_{air-conv}$ and $T_{air-rad}$ are the surrounding air thermal resistances in °C/W of the convection and radiation respectively, $b_{\rm rad}$ and $b_{\rm conv}$ are the radiation and convection heat transfer dissipation coefficients respectively. A_s is the total exposed area of the cable duct to the air in m², ε is emissivity in W/m² of the PVC duct riser surface, σ_b is Stefan–Boltzmann constant, $\theta_{\rm r}$ and $\theta_{\rm amb}$ are the temperatures in of the PVC duct surface and ambient temperature respectively. $N_{\rm u}$ is the Nusselt number, $K_{\rm amb}$ is the thermal conductivity of the air at ambient temperature in W/ °C m and is the outer diameter of the PVC duct riser in meters, Ra_D is the Reynolds number, P_r is Prandtl number for air which changes with air temperature and can be obtained by using the tables of air physical properties [29], β is constant equals $3.2 \times 10^{-3} \text{ °C}^{-1}$, g is the gravity acceleration which its value is 9.8 m/s² and v is the kinematic viscosity of the air at ambient which is considered $18.5 \times 10^{-6} \text{ m}^2/\text{s}$ [29].

2.2 | Results and discussion of steady state cable loading

Five soil samples are tested to be used as back-fill materials surrounding the PVC duct of the underground power cable. Each soil sample is contained in a cylinder of plastic material with a diameter of 100 mm. and height of 120 mm; a heat flux is introduced by heater in a downward direction. This flux is measured by using heat flux's meter. Soil moisture sensor probe is used for measuring the soil moisture content. The cylinder containing the soil sample has been sealed. By this arrangement, the moisture tension and thus water content can be adjusted. A number of thermo-couples are placed within the walls along the soil's sample, for measuring the temperature distribution at different points along the soil tested sample. Figure 2(a) shows the experimental testing arrangement, contains soil testing device; autotransformer for delivering the required current, power supply to give the required DC voltage to the moisture sensor and programmable logic controller (PLC) device. The purpose of this experimental work is to measure the soil thermal resistivity of



FIGURE 2 The experimental testing system arrangement and example of measurement, (a) testing system arrangement, (b) temperature versus distance for silty sand soil when $Pf = \infty$ and $Qh = 728 \text{ w/m}^2$

each soil sample and its volumetric specific heat. The determination of the soil sample specific heat at each moisture content amount is done according to the relation given in [30, 31]:

$$C_{\text{psoil}} = C_{\text{d}} \gamma_{\text{d}} + C_{\text{w}} \gamma_{\text{w}} G_1 \tag{20}$$

where C_{psoil} is the volumetric specific heat in (J/m^{3o}C), C_{d} is the dry soil specific heat in (J/kg °C), C_{w} is specific heat of water in (J/kg °C), γ_{d} is dry density of the tested soil, γ_{w} is water density and G_1 is the tested soil moisture content.

The temperature distribution at different points in each investigated soil sample against distance is measured, one example is shown in Figure 2(b) for silty sand soil contains 8% gravel, 60% sand and 32% silt. As it is noticed in this figure there are two slopes for the temperature distance relationship with respect to time, i.e. there are two zones, the first one is formed near the heat source and represents the cable, it is defined as the drying zone. The second one which is usually starts at the end of first zone is known as the wet zone. The discontinuity in the curves indicates the separation between dry zone and moist zone. The slope of each zone indicates to the variation in the soil thermal resistivity that can be calculated using Equation (21) [2,32]:

$$\sigma = \frac{\left(\frac{dT}{dZ}\right)}{Q_{\rm h}} \tag{21}$$

 $\frac{dT}{dZ}$ is the temperature variation with the distance in °C/m, σ is the tested soil resistivity in °C m/W and $Q_{\rm h}$ is the heat flux in W/m^2 . It has to be noted that the heat flux distribution in the soil at actual condition is different from that given in arrangement of Figure 1, but the purpose of the soil testing is to obtain the soil characteristics such as its wet and dry thermal resistivity, the temperature at which dry zone is formed and the specific heat of each tested soil sample. All these parameters have to be obtained under uniform heat flux density in the soil. This is done by the test arrangement given in Figure 1. The experimental results of the tested soil samples are given in Table 1. In this table the specifications of soils used in the study as backfill materials are given. Different soils decomposition samples contain percent of sand, clay and moisture are presented. The critical temperature given in Table 1 can be defined as the temperature at which the dry zone is formed. Details of the 0.4, 11, 33 kV cables specifications used in the study are given in Table 2. The calculations are done to study 0.4, 11 and 33 kV cables performances that are installed in guard PVC ducts and buried in soil and as risers in air. The calculations are done by using the thermal models given in Figure 1(b,d) and their corresponding equations. Approximation is done in case of cable installed in PVC duct and buried in the soil by considering the PVC duct and the coaxial cable as consentric. Unfortunately, in the field installations they are inconsentric as shown in Figure 1(a).

Table 3 shows the relation between the guard PVC duct thickness and the cable current capacity when the cable is buried in soil type (1), in which its characteristic is given in Table 1 and also when the cable is used as riser. The results given in this table are done for 0.4, 11 and 33 kV cables considering the conductor temperature in each case is 90 °C according to IEC60287 specifications. The thermal properties of cable elements are considered as follows: for copper the thermal resistivity in (°C m/W) is 2.5×10^{-3} and its thermal specific heat in $(J/m^3 \circ C)$ is 3.45×10^6 , for Aluminium the thermal resistivity in (°C m/W) is 4.545×10^{-3} and its thermal specific heat in $(J/m^3.^{\circ}C)$ is 2.5×10⁶, for XLPE the thermal resistivity in (°C m/W) is 3.5 and its thermal specific heat in $(I/m^3 °C)$ is 2.4×10^6 , the PVC thermal resistivity in (°C m/W) is 6 and its thermal specific heat in $(I/m^3 \circ C)$ is 1.7×10^6 . Finally the thermal conductivity at 70 °C of air is considered to be 0.02881 in $(W/^{\circ}C m)$ and its thermal specific heat in $(kJ/m^{3} \circ C)$ is 1.007.

Table 3 gives the PVC duct thickness versus cable conductor temperature of 0.4 and 33 kV cables for different load currents. From this table it is noticed that when keeping the conductor temperature at 90 $^{\circ}$ C, the 0.4 kV cable current capacity that is installed in duct and buried in soil type (1) is reduced to 89.3% of its value when the duct thickness is increased from 1.5 to 15 mm. When the same cable is used as riser installed in PVC

TABLE 1 The soils specifications used in the study

Soil composition	Critical temperature [°C]	Wet thermal resistivity [°C m/W]	Dry thermal resistivity [°C m/W]	Specific heat [J/m ³ °C]
(1) 90% sand + 10% clay+0.032 moisture	58	0.91	2.63	1.55
(2) 70% sand + 30% clay+0.05 moisture	55.5	0.821	3.5	1.6
(3) 50% sand + 50% clay+0.071 moisture	52	0.805	3.75	1.63
(4) 30% sand + 70% clay+0.13 moisture content	50	0.773	4.1	2.1
(5)15% sand + 85% clay+0.2 moisture	49	0.746	4.5	2.7

 TABLE 2
 Cables data used in the study

Cables Details	0.4 kV-three core	11 kV-single core	33 kV-single core
Conductor material	Copper	Copper	Copper
Conductor diameter [mm]	12.4	40.2	40.2
Insulation type	PVC	XLPE	XLPE
Insulation diameter [mm]	14.8	54.3	59.5
Screen type	_	Aluminium	Aluminium
Screen Diameter [mm]	_	58.8	64
Cover type	PVC	PVC	PVC
Overall cable diameter [mm]	36.1	65.4	71
guard tubes material	PVC	PVC	PVC
Duct inner diameter [mm]	50	180	100
Riser inner diameter [mm]	50	180	100
Riser length [mm]	1000	1000	1000
Burial depth [mm]	600	800	800
Configuration	Three core	Trefoil	Flat
Bonding method	_	Two ends bonding	Two ends bonding
Spacing between cables [mm]	-	-	142

duct, the cable current capacity is reduced to 90.7 % as the duct thickness is increased by ten times of its initial value (1.5 mm). Similar results are noticed for 11 kV cable, its capacity is reduced to 91.5% when the duct thickness is increased ten times while the cable is installed in duct and buried in soil type (1). By using the same cable as riser in PVC duct its capacity is reduced to 86.59%. For 33 kV cable similar values are 91.2% and 87.2% respectively. From Table 4, it is observed that a rise in the conductor temperature was happened with the increase of the PVC duct thickness. As example an increase in cable conductor temperature by about 15 °C is noticed when the cable is installed in duct and buried in soil type (1) and also when it is installed as riser in duct for 33 kV loaded by 375 A. This is happened when the duct thickness is increased from 3 to 25 mm. The reason of course is the increase of the thermal resistance of the PVC duct. Similar observations are noticed in Table 4 for 0.4 kV cable conductor when it is loaded by 120 and 150 A. The results given in Tables 3 and 4 are in agreement with that reported by ref. [21].

As given in Table 3 it is noticed also that for the same cable rating the cable current capacity installed in riser is much lower when it is installed in duct and buried in soil. This is achieved with the existing results given in Table 4. The ratio given in Table 3 can be defined as the ratio between the current of cable riser and the cable current in duct buried in soil type (1).

As it is seen in Table 3, this ratio is between 0.68 and 0.676 for three core cable, 0.650 and 0.61 for trefoil cables, while it is in the range of 0.97–0.93 in flat cables. Figure 3 gives samples of heat maps of different cable components for cables installed in ducts buried in soil type (1) and risers in ducts. Figure 3(a) shows the heat map of vertical riser when the duct thickness of 0.4 kV riser was 18 mm and buried in soil type 1, the cable current was 150 A.

PVC duct thickness [mm]	Cables installation type	0.4 kV three core cable current [A]	11 kV trefoil cable current [A]	33 kV flat cable current [A]
1.5	In duct buried in soil type 1	272	802	657
	Vertical riser	184	522	641
	Ratio	0.676	0.650	097
2.5	in duct buried in soil type 1	269	796	634
	Vertical riser	182	516	620
	Ratio	0.676	0.648	0.97
4	in duct buried in soil type 1	265	787	629
	Vertical riser	180	506	615
	Ratio	0.679	0.642	0.97
6	in duct buried in soil type 1	260	776	623
	Vertical riser	177	495	603
	Ratio	0.68	0.637	0.96
9	in duct buried in soil type 1	253	761	614
	Vertical riser	174	479	587
	Ratio	0.687	0.629	0.956
12.5	in duct buried in soil type 1	247	745	605
	Vertical riser	170	463	570
	Ratio	0.68.	0.621	0.94
15	in duct buried in soil type 1	243	734	599
	Vertical riser	167	452	559
	Ratio	0.68	0.61	0.93

TABLE 3 PVC duct thickness versus cable current of 0.4, 11 and 33 kV cables at conductor temperature 90 °C

TABLE 4 PVC duct thickness versus cable conductor temperature of 0.4 and 33 kV cables for different load currents

PVC duct thickness [mm]	Cables installation type	0.4 kV cable conductor temperature [°C] at 120 A	0.4 kV cable conductor temperature [°C] at 150 A	33 kV cable conductor temperature [°C] at 375 A
3	In duct buried in soil type 1	41.8	51.2	71.5
	Vertical riser	59.9	81	89.2
5	in duct buried in soil type 1	42.4	52.2	73.4
	Vertical riser	61.1	82.9	93
8	in duct buried in soil type 1	43.3	53.4	75.8
	Vertical riser	62.7	85.3	95
12	in tube buried in soil type 1	44.2	54.9	78.6
	Vertical riser	64.6	88.2	97.5
18	in duct buried in soil type 1	45.3	56.6	82.4
	Vertical riser	67	91.8	100
25	in duct buried in soil type 1	46.5	58.2	86.5
	Vertical riser	69.7	95.9	104

Figure 3(b) gives the heat map of 0.4 kV cable installed in duct has 8 mm thickness and buried in soil type (1), the cable is loaded by 120 A, Figure 3(c) shows the cable components temperature distribution of 33 kV installed in 18 mm duct thickness and buried in soil type (1) and loaded by 375 A. Finally Figure 3(d) shows the heat map for 33 kV cable components in

vertical riser when the duct thickness was 12 mm and load current 375 A. The results shown in Figure 3 confirm the tabulated results in Tables 3 and 4

Table 5 gives the steady state current of the cables under study at 30 °C ambient temperature when installed in PVC duct thickness 5 mm and buried in soil types given in Table 1, the

TABLE 5 steady state current of different cables at 30 °C ambient temperature and duct thickness 5 mm, at conductor temperat	ture 90	°C
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Soil type	Cables buried type	0.4 kV three core	11 kV single core	33 kV single core
(1) 90% sand + 10% clay+0.032	Cable in vertical riser	167 (A)	428 (A)	573 (A)
moisture content	Cable installed in duct and buried in soil	253 (A)	751 (A)	601 (A)
	Cable buried in soil directly	357 (A)	849 (A)	680 (A)
(2) 70% sand + 30% clay+0.05	Cable in vertical riser	167 (A)	428 (A)	573 (A)
moisture content	Cable installed in duct and buried in soil	257 (A)	773 (A)	622 (A)
	Cable directly buried in soil	372 (A)	888 (A)	712 (A)
(3) 50% sand + 50% clay+0.071	Cable in vertical riser	167 (A)	428 (A)	573 (A)
moisture content	Cable installed in duct and buried in soil	258 (A)	777 (A)	626 (A)
	Cable directly buried in soil	374 (A)	896 (A)	718 (A)
(4) 30% sand + 70% clay+0.13	Cable in vertical riser	167 (A)	428 (A)	573 (A)
moisture content	Cable installed in duct and buried in soil	259 (A)	785 (A)	634 (A)
	Cable directly buried in soil	380 (A)	912 (A)	731 (A)
(5) 15% sand + 85% clay+0.2	Cable in vertical riser	167 (A)	428 (A)	573 (A)
moisture content	Cable installed in duct and buried in soil	260 (A)	793 (A)	641 (A)
	Cable directly buried in soil	385 (A)	926 (A)	743 (A)

conductor temperature is considered 90 °C. It is noticed from this table that the soil composition has influence on the cable capacity when the cable is installed directly in the soil. This impact is reduced when the cable is installed in a duct and buried in the soil. The reason may be due to the preventing of the thermal resistances of the PVC duct and the air that fill the space between cable surface and duct inner surface the heat to be dissipate into the surrounding soil of the cable. It is noticed from this table that increasing the clay present in the soil leads to an increase of cables current capacity that are installed in soil either the cable is installed directly in the soil or buried in it with protective PVC duct.

Finally it is observed that the cable in riser has lower current capacity comparing with the cable directly buried in soil and the cable installed in PVC duct and buried in soil. From this table the derating factor can be calculated for each cable considering the method of cable installation and back-fill soil type.

3 | DYNAMIC THERMAL MODEL FOR CABLES INSTALLED IN DUCTS AND BURIED IN SOILS AND RISERS

Figure 4(a) shows the equivalent dynamic thermal model of cable installed in buried PVC duct, while Figure 4(b) gives similar thermal circuit for cable riser installed in PVC duct. Where, θ_c , θ_s , θ_j , θ_{air} and θ_{duct} are the conductor, sheath (screen), jacket, air and duct temperatures in °C above ambient respectively, T_1 , T_3 and T_4 are the insulation, jacket and surrounding soil thermal resistances in °C/w respectively. T'_4 is the thermal resistance of the duct in °C/w, T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is the thermal resistance of the duct and T''_4 is due duct and T''_4

thermal resistance of the soil surrounding the duct in °C/w. Q_c , Q_i , Q_s , Q_j , Q_{soil} , Q_{air} and Q_{duct} are the thermal capacitances of conductor, insulation, screen, jacket, surrounding soil, air and duct respectively and p is the van wormer coefficient [33].

As mentioned before the metallic screen thermal resistance T_2 is ignored. The copper losses in the conductor are defined as W_c , losses of the sheath W_s and dielectric losses of the insulation layers are W_{d1} and W_{d2} . The different cable element losses are calculated according to IEC 60287-1-3 [12].

3.1 | Dynamic thermal analysis model of cable installed in buried duct

The thermal analysis at each node of the thermal model given in Figure 4(a) can be represented by the following equations

$$\theta_{duct}' = \frac{1}{Q_4} \cdot \left(\frac{\theta_{air} - \theta_{duct}}{T_4''} - \frac{\theta_{duct} - \theta_a}{T_4''} \right)$$
(22)

$$\theta_{\rm air}' = \frac{1}{\mathcal{Q}_{\rm duct}} \cdot \left(\frac{\theta_{\rm j} - \theta_{\rm air}}{T_4'} - \frac{\theta_{\rm air} - \theta_{\rm duct}}{T_4''} \right)$$
(23)

$$\theta_{j}' = \frac{1}{\mathcal{Q}_{\text{air}}} \cdot \left(\frac{\theta_{\text{s}} - \theta_{\text{j}}}{T_{3}} - \frac{\theta_{\text{j}} - \theta_{\text{air}}}{T_{4}'} \right)$$
(24)

$$\theta'_{\rm s} = \frac{1}{Q_3} \cdot \left(W_{\rm s} + W_{\rm d2} + \frac{\theta_{\rm c} - \theta_{\rm s}}{T_1} - \frac{\theta_{\rm s} - \theta_{\rm j}}{T_3} \right) \quad (25)$$

$$\theta_{\rm c}' = \frac{1}{Q_1} \cdot \left(W_{\rm c} + W_{\rm d1} - \frac{\theta_{\rm c} - \theta_{\rm s}}{T_1} \right) \tag{26}$$



FIGURE 3 Heat maps of different cable components for cables, (a) vertical riser of 0.4 kV when the duct thickness is 18 mm and load current 150 A, (b) cable installed in tube when duct thickness 8 mm and load current 120 A, (c) 33 kV cable components in buried duct when duct thickness 18 mm and load current 375 A and (d) heat map for different 33 kV cable components in vertical riser when the tube thickness is 12 mm and load current 375 A



FIGURE 4 Dynamic thermal model, (a) for cables installed in tube and buried in soil, (b) for cables in vertical riser

The three thermal capacitances of the model Q_1 , Q_3 and Q_4 are calculated according to IEC 60853-2 standards as [33].

$$Q_1 = Q_c + p Q_i \tag{27}$$

$$Q_3 = (1-p) \cdot Q_i + Q_s + Q_j \tag{28}$$

$$Q_4 = Q_{\text{soil}} \tag{29}$$

The cable nodes equations can be solved by using the following equation:

$$\begin{bmatrix} \theta_{\text{duct}}(t) \\ \theta_{\text{air}}(t) \\ \theta_{j}(t) \\ \theta_{c}(t) \end{bmatrix} = \begin{bmatrix} c_{1}v_{1}^{-} \cdot e^{\lambda_{1}t} + c_{2}v_{2}^{-} \cdot e^{\lambda_{2}t} + c_{3}v_{3}^{-} \cdot e^{\lambda_{3}t} + c_{4}v_{4}^{-} \cdot e^{\lambda_{4}t} \\ \theta_{c}(t) \end{bmatrix} + c_{5}v_{5}^{-} \cdot e^{\lambda_{5}t} \end{bmatrix} + \begin{bmatrix} \theta_{\text{duct}}(\infty) \\ \theta_{\text{air}}(\infty) \\ \theta_{j}(\infty) \\ \theta_{s}(\infty) \\ \theta_{c}(\infty) \end{bmatrix}$$
(30)

Here v_1^-, v_2^- and v_3^- are meant as Eigen vector and λ_1, λ_2 and λ_3 are denoted as Eigen value. Equation (31) is used to calculate the value of constants c_1, c_2 and c_3 by the determination of the value of the initial temperature (0) at each load cycle and calculating the temperature at steady state condition (∞), the thermal

capacitances given in Figure 4(a) are ignored at steady state.

$$\begin{bmatrix} v_1^- & v_2^- & v_3^- & v_4^- & v_5^- \end{bmatrix} \begin{bmatrix} c_1\\ c_2\\ c_3\\ c_4\\ c_5 \end{bmatrix} = \begin{bmatrix} \theta_{duct}(0)\\ \theta_{air}(0)\\ \theta_j(0)\\ \theta_s(0)\\ \theta_c(0) \end{bmatrix} - \begin{bmatrix} \theta_{duct}(\infty)\\ \theta_{air}(\infty)\\ \theta_j(\infty)\\ \theta_j(\infty)\\ \theta_s(\infty)\\ \theta_c(\infty) \end{bmatrix}$$
(31)

The thermal resistance and capacitance of each cable layer of single core cable that is installed in duct and its surrounding soil can be calculated using the following equations [12,33].

$$T_1 = \frac{\rho_i}{2\pi} \ln\left(\frac{D_i}{d_c}\right) \tag{32}$$

$$T_3 = \frac{\rho_j}{2\pi} \ln\left(\frac{D_e}{D_s}\right) \tag{33}$$

$$T_{4} = T_{4}' + T_{4}'' + T_{4}'''$$

$$T_{4}' = \frac{U}{1 + 0.1/(L + N^{2} - N^{2})}$$
(34)

$$T_4'' = \frac{\rho_{\rm d}}{2\pi} \ln\left(\frac{D_{\rm do}}{D_{\rm di}}\right) \tag{35}$$

$$T_4^{\prime\prime\prime} = \frac{\rho_{\text{soil}}}{2\pi} \left\{ \ln\left(\frac{4L}{D_{\text{do}}}\right) + \ln\left(1 + \left(\frac{2L}{S}\right)^2\right) \right\} \quad (36)$$

$$Q_{\rm c} = C_{\rm pc} \mathcal{A}_{\rm c} \tag{37}$$

$$Q_{\rm i} = \frac{\pi}{4} \left(D_{\rm i}^2 - d_{\rm c}^2 \right) C_{\rm pi}$$
(38)

$$Q_{\rm s} = \frac{\pi}{4} \left(D_{\rm s}^2 - D_{\rm i}^2 \right) C_{\rm ps}$$
(39)

$$Q_{\rm j} = \frac{\pi}{4} \left(D_{\rm c}^2 - D_{\rm s}^2 \right) C_{\rm pj} \tag{40}$$

$$Q_{\rm air} = \frac{\pi}{4} \left(D_{\rm di}^2 - D_{\rm e}^2 \right) C_{\rm pair} \tag{41}$$

$$Q_{\rm duct} = \frac{\pi}{4} \left(D_{\rm do}^2 - D_{\rm di}^2 \right) C_{\rm pduct}$$
(42)

$$Q_{\rm soil} = \pi \left(L^2 - \left(\frac{D_{\rm e}}{2} \right)^2 \right) C_{\rm psoil}$$
 (43)

$$p = \frac{1}{2\ln\left(\frac{D_{i}}{d_{c}}\right)} - \frac{1}{\left(\frac{D_{i}}{d_{c}}\right)^{2} - 1}$$
(44)

where ρ_i, ρ_j, ρ_d and ρ_{soil} are the thermal resistivity of the insulation, jacket, PVC duct and the surrounding soil material respectively. $C_{pc}, C_{pi}, C_{ps}, C_{pj}, C_{psoil}, C_{pair}$ and C_{pduct} are the volumetric specific heat of each cable layer material, the surrounding soil, air and duct respectively. Therefore, $d_c, D_i, D_s, D_c, D_{di}$ and D_{do} are the diameter of the conductor, insulation, screen, jacket, inner PVC duct and outer duct respectively. The U, V and Y are constants given in IEC 60287 [12] in case of cables installed in buried duct, θ_{duct} is the mean temperature of the duct medium, S and L are the distance between the cables in case of flat formation and the cable burial depth in meters respectively, and A_c is the conductor area in m².

3.2 | Dynamic thermal model for cables in vertical riser

The different elements of a cable riser and the surrounding air medium is given in the thermal model shown in Figure 4(b). By considering the thermal analysis at each node, the equations representing the cable riser elements are.

$$\theta_{\text{air}}' = \frac{1}{\mathcal{Q}_{\text{riser}}} \cdot \left(W_{\text{sun}} + \frac{\theta_{\text{j}} - \theta_{\text{air}}}{T_4^{*'}} - \frac{\theta_{\text{air}} - \theta_{\text{a}}}{T_4^{*''} + T_4^{*'''}} \right) \quad (45)$$

$$\theta_{j}' = \frac{1}{Q_{\text{air}}} \cdot \left(\frac{\theta_{\text{s}} - \theta_{j}}{T_{3}} - \frac{\theta_{j} - \theta_{\text{air}}}{T_{4}^{*'}} \right)$$
(46)

$$\theta'_{\rm s} = \frac{1}{Q_3} \cdot \left(W_{\rm s} + W_{\rm d2} + \frac{\theta_{\rm c} - \theta_{\rm s}}{T_1} - \frac{\theta_{\rm s} - \theta_{\rm j}}{T_3} \right) \tag{47}$$

$$\theta_{\rm c}' = \frac{1}{Q_1} \cdot \left(W_{\rm c} + W_{\rm d1} - \frac{\theta_{\rm c} - \theta_{\rm s}}{T_1} \right) \tag{48}$$

The three capacitances of the model Q_1 , Q_3 and Q_4 are given as defined by IEC 60853-2 standards [33].

$$Q_1 = Q_c + p \cdot Q_i \tag{49}$$

$$\mathcal{Q}_3 = (1-p) \quad \mathcal{Q}_i + \mathcal{Q}_s + \mathcal{Q}_j \tag{50}$$

$$Q_4 = Q_{\text{soil}} \tag{51}$$

where θ_c , θ_s , θ_j and θ_{air} are the conductor, sheath (screen), jacket and air temperature above ambient temperature respectively and T_1 , T_3 and T_4 are the insulation, jacket and surrounding soil thermal resistances respectively. $T_4^{*'}$ is the thermal resistance of the air between the cable jacket and the inner surface of the riser, $T_4^{*''}$ is the thermal resistance of the riser and $T_4^{*'''}$ is the thermal resistance of the air surrounding the riser. Q_c , Q_i , Q_s , Q_j , Q_{air} and Q_{riser} are the thermal capacitances of conductor, insulation, screen, jacket, air and PVC duct riser respectively and p is the van wormer coefficient [33].

The thermal losses in the conductor are defined as W_c , losses of the sheath W_s , W_{sun} is the sun solar radiation and dielectric losses of the insulation layer are W_{d1} and W_{d2} . The different cable losses are calculated according to the formulas given in IEC 60287-1-3. The set of equations given above is solved by the same way that is explained in Section 3.1 as the following :

$$\begin{bmatrix} \theta_{air} (t) \\ \theta_{j} (t) \\ \theta_{s} (t) \\ \theta_{c} (t) \end{bmatrix} = \begin{bmatrix} c_{1}v_{1}^{-} \cdot e^{\lambda_{1}t} + c_{2}v_{2}^{-} \cdot e^{\lambda_{2}t} + c_{3}v_{3}^{-} \cdot e^{\lambda_{3}t} + c_{4}v_{4}^{-} \cdot e^{\lambda_{4}t} \end{bmatrix} + \begin{bmatrix} \theta_{air} (\infty) \\ \theta_{j} (\infty) \\ \theta_{s} (\infty) \\ \theta_{c} (\infty) \end{bmatrix}$$

$$(52)$$

Here, v_1^- , v_2^- and v_3^- are defined as Eigen vector and λ_1 , λ_2 and λ_3 are denoted as Eigen value. Equation (53) given below is used to calculate the value of constants c_1 , c_2 and c_3 by determining the value of the initial temperature (0) at each load cycle and calculating the temperature at steady state condition (∞), the thermal capacitances of the circuit given in Figure 4(b) are ignored at steady state condition.

$$\begin{bmatrix} v_1^- & v_2^- & v_3^- & v_4^- \end{bmatrix} \begin{bmatrix} c_1\\ c_2\\ c_3\\ c_4\\ c_5 \end{bmatrix} = \begin{bmatrix} \theta_{air}(0)\\ \theta_j(0)\\ \theta_s(0)\\ \theta_c(0) \end{bmatrix} - \begin{bmatrix} \theta_{air}(\infty)\\ \theta_j(\infty)\\ \theta_j(\infty)\\ \theta_c(\infty)\\ \theta_c(\infty) \end{bmatrix}$$
(53)

The thermal capacitance and resistance of each cable layer of single core cable laid in PVC duct as riser surrounded by air can be calculated using the following equations [12,33].

$$T_1 = \frac{\rho_{\rm i}}{2\pi} \ln\left(\frac{D_{\rm i}}{d_{\rm c}}\right) \tag{54}$$

$$T_3 = \frac{\rho_{\rm j}}{2\pi} \ln\left(\frac{D_{\rm e}}{D_{\rm s}}\right) \tag{55}$$

$$T_4^* = T_4^{*'} + T_4^{*''} + T_4^{*''}$$
(56)

$$T_4^{*'} = \frac{U}{1 + 0.1 \left(V + Y \theta_{\rm r} \right) D_{\rm e}}$$
(57)

$$T_4^{*''} = \frac{\rho_{\rm r}}{2\pi} \ln\left(\frac{D_{\rm ro}}{D_{\rm ri}}\right) \tag{58}$$

$$T_4^{*'''} = T_{\text{air-con}} // T_{\text{air-rad}}$$
(59)

$$Q_{\rm c} = C_{\rm pc} \mathcal{A}_{\rm c} \tag{60}$$

$$Q_{\rm i} = \frac{\pi}{4} \left(D_{\rm i}^2 - d_{\rm c}^2 \right) C_{\rm pi}$$
 (61)

$$Q_{\rm s} = \frac{\pi}{4} \left(D_{\rm s}^2 - D_{\rm i}^2 \right) C_{\rm ps}$$
 (62)

$$Q_{\rm j} = \frac{\pi}{4} \left(D_{\rm e}^2 - D_{\rm s}^2 \right) C_{\rm pj}$$
 (63)

$$Q_{\rm air} = \frac{\pi}{4} \left(D_{\rm di}^2 - D_{\rm e}^2 \right) C_{\rm pair} \tag{64}$$

$$Q_{\rm riser} = \frac{\pi}{4} \left(D_{\rm ro}^2 - D_{\rm ri}^2 \right) C_{\rm priser}$$
(65)

where ρ_i , ρ_j and ρ_r are the thermal resistivity of the insulation, jacket and riser duct material respectively. C_{pc} , C_{pi} , C_{ps} , C_{pj} , C_{pair} and C_{priser} are the volumetric specific heat of each cable layer material, air and riser respectively. Therefore, d_c , D_i , D_s , D_c , D_{ri} and D_{ro} are the diameter of the conductor, insulation, screen, jacket, inner riser and outer riser respectively. The U, Vand Y are constants given in IEC 60287-1-3 [12], in case of cable riser and θ_r is the mean temperature of the riser medium, S is the distance between the cables in case of flat formation, and A_c is the conductor area.

$$T_{\rm air-conv} = \frac{1}{b_{\rm conv} \, \mathcal{A}_{\rm s}} \tag{66}$$

$$T_{\rm air-rad} = \frac{1}{b_{\rm rad} \, A_{\rm s}} \tag{67}$$

$$b_{\rm conv} = \frac{N_{\rm u} \ K_{\rm amb}}{D_{\rm ro}} \tag{68}$$

$$b_{\rm rad} = \varepsilon \sigma_{\rm b} \left(\theta_{\rm r} + \theta_{\rm amb} \right) \left(\theta_{\rm r}^2 + \theta_{\rm amb}^2 \right)$$
 (69)

$$N_{\rm u} = \left[0.6 + \frac{0.387 R a_D^{1/6}}{\left[1 + \left(\frac{0.559}{P_{\rm r}}\right)^{9/16} \right]^{8/27}} \right]^2 \tag{70}$$

$$Ra_D = \frac{g P_r \beta D_{\rm ro} (\theta_{\rm r} - \theta_{\rm amb})}{v^2}$$
(71)

Where, $T_{air-conv}$ and $T_{air-rad}$ are the surrounding air thermal resistances of the convection and radiation respectively, b_{rad} and b_{conv} are the radiation and convection heat transfer dissipation coefficients respectively. A_s is the total exposed area of the air, ε is emissivity of the riser surface, σ_b is Stefan–Boltzmann constant, θ_r and θ_{amb} are the temperature of the riser surface and ambient temperature respectively. N_u is the Nusselt number, K_{amb} is the thermal conductivity of the air at ambient temperature and D_{ro} is the outer diameter of the riser. Ra_D is the Reynolds number, P_r is Prandtl number for air, which changes with air temperature and can be attained by using air physical properties tables [24], β is the volumetric thermal expansion of air at ambient temperature, g is the gravity acceleration and v is the kinematic viscosity of the air at ambient temperature [24].

3.3 | Results and discussion of dynamic buried cable and riser loadings

3.3.1 | Load cycles of 0.4, 11 and 33 kV cables

The calculations are carried out when each cable is loaded by its load cycle given in Figure 5(a) [34].

3.3.2 | Results of cables installed in PVC ducts directly buried in the soil loaded by dynamic loading

The steps of the calculations of cable elements, PVC duct and surrounding medium temperatures in case of dynamic loading are explained in the flowchart given in Figure 5(b). The flowchart used the equations governed the cable installed in PVC duct and buried in soil and also the cable that is installed in riser which are given in items 3.1 and 3.2. Figure 6(a) gives cable riser components temperature of 0.4 kV, similar results for the



FIGURE 5 Load cycling of cables under study and the used flowchart, (a) load cycles, (b) used flow chart

same cable installed in PVC duct and buried in soil type (1) are given in Figure 6(b).

Comparison between the cable conductor temperature of the cable riser installed in PVC duct and the cable installed in the duct and buried in soil type (1) is given Figure 6(c). Figure 6(d) gives similar comparison when soil (3) is used as back-fill material. The duct thickness is considered to be 5 mm. From Figure 6(a), it is noticed that the maximum conductor temperature reached to about 119 °C after 60 h loading exceeding the allowable limit by about 29 °C.



FIGURE 6 0.4 kV cable temperature loaded by its cyclic loading, (a) cable in vertical riser, (b) cable in duct when using soil 1, (c) comparison between different buried methods when using soil 1 in the surrounding and (d) comparison between different buried methods when using soil 3 in the surrounding

It is noticed also that the cable XLPE insulation and PVC jacket temperatures are very close and exceeding the permissible limit of temperature rise which is 85 °C, expected insulation failure may be done. The reason in this case is that the thermal resistances of the PVC duct and air between the cable jacket outer surface and the PVC duct inner surface, prevent the heat produced by the cable losses to dissipate into the

		Method of cable in	nstallation	
Soil type	Temperature [°C]	In Riser	Duct in soil	Direct in soil
1–90% sand + 10% clay+0.032	Conductor temperature	119	117	33
moisture content	Air temperature	27	-	_
	Soil temperature	-	26	26
2–70% sand + 30% clay+0.05	Conductor temperature	119	117	32.5
moisture content	Air temperature	27	_	_
	Soil temperature	_	26	26
3–50% sand + 50% clay+0.071	Conductor temperature	119	116	32
moisture content	Air temperature	27	_	-
	Soil temperature	-	26	25.5
4–30% sand + 70% clay+0.13	Conductor temperature	119	115	31.5
moisture content	Air temperature	27	_	_
	Soil temperature	_	26	25.5
5–15% sand + 85% clay+0.2	Conductor temperature	119	115	31
moisture content	Air temperature	27	_	_
	Soil temperature	_	26	25.5
5–15% sand + 85% clay+0.2	Conductor temperature	119	115	31
moisture content	Air temperature	27	-	_
	Soil temperature	-	26	25.5

TABLE 6 Conductor of 0.4 kV cable, air and soil temperatures at 25 °C ambient temperature and PVC tube thickness 5 mm

surrounding air. As it is noticed when the cable is installed in PVC duct and buried in soil type (1) as given in Figure 6(b,c) there is no remarkable reduction in the cable maximum conductor temperature compared with the same cable used as riser in PVC duct, it reaches only to about 2 °C. The same observations can be seen in Figure 6(d) where the soil of type (3) was used as a substance surrounding the cable installed in a duct and buried in the soil.

Table 6 gives the maximum conductor, air and soil temperatures of 0.4 kV at 25 °C ambient temperature and PVC duct thickness 5 mm. From Table 6 it is noticed that the change in soil composition surrounding the cable installed in duct and buried in soil has a very small effect on the maximum cable conductor temperature, even with the increase of clay percent in the soil.

The reason is the high value of the thermal resistances of both the PVC duct and the air between the cable jacket outer surface and the PVC duct inner surface comparing with the soil thermal resistances regardless of its compositions given in Table 1.

From Table 6 and Figure 6(c,d), it is observed that the 0.4 kV buried directly in the soil has low maximum temperature compared with the cables used as risers in PVC ducts and also when the cables are installed in ducts and buried in soils. Reduction in the cable conductor temperature is noticed when the clay percent is increased in the soil surrounding the cable compositions. Similar calculations are done for 11 kV cable using its load cycle given in Figure 5(a). The results are drawn in Figure 7. Table 7 gives the conductor, air and soil temperatures of

11 kV at 25 °C ambient temperature and duct thickness 5 mm. From Figure 7 and Table 7 it is observed that the installation of the underground power cable directly buried in the soil has a significant decrease in the temperature of the conductors compared to its installation in a PVC duct buried in the soil, as well as in the case of placing it in a plastic duct and used as a riser. It is also noticed that the change of soil components surrounding the cable affected only if the cable was buried directly in the soil and its effect is limited in the case of installing the cable in a PVC duct and then buried in the soil. The reason as mentioned in case of 0.4 kV is that the thermal resistance and capacitance of both the PVC duct and the air between the inner surface of the duct and the cable surface have high values comparing with the thermal resistance and capacitance of the soil, which prevents heat produced by cable loss from the dissipation into the soil. Similar calculations for 33 kV cable are carried out using its load cycle given in Figure 5(a). The results are drawn in Figure 8. Table 8 gives the maximum conductor, air and soil temperatures of 33 kV at 25 °C ambient temperature and 5 mm duct thickness. Due to its high current capacity and limited space between cable surface and inner surface of the PVC duct (riser inner diameter is 100 mm), the conductor temperature of 33 kV cable is increased when it is used as riser installed in PVC duct.

The same observations can be seen when installing the cable in the PVC duct and buried in the soil. Comparing this to the cable temperature that is directly buried in the soil, a significant decrease in the temperature of the cable conductors can be noticed when the cable is directly buried in the soil. It is

TABLE 7 Conductor	; air and soil temperatures	of 11 kV at 25 °C	ambient temperature and	duct thickness 5 mm
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		Method of cable in	stallation	
Soil type	Temperature [°C]	In Riser	Duct in soil	Direct in soil
(1) 90% sand + 10% clay+0.032	Conductor temperature	111	106	39
moisture content	Air temperature	27	27	-
	Soil temperature	-	26	33
(2) 70% sand + 30% clay+0.05	Conductor temperature	111	106	38.5
moisture content	Air temperature	27	27	-
	Soil temperature	-	26	32.5
(3) 50% sand + 50% clay+0.071	Conductor temperature	111	106	38
moisture content	Air temperature	27	27	-
	Soil temperature	-	26	32
(4) 30% sand + 70% clay+0.13	Conductor temperature	111	105	37
moisture content	Air temperature	27	27	-
	Soil temperature	-	26	31
(5) 15% sand + 85% clay+0.2 moisture content	Conductor temperature	111	104	36
	Air temperature	27	27	-
	Soil temperature	-	26	30.5

TABLE 8 Conductor, air and soil temperatures of 33 kV at 25 °C ambient temperature and duct thickness 5 mm

		Method of cable instal	lation	
Soil type	Temperature [°C]	in Riser	Duct in soil	Direct in soil
(1) 90% sand + 10% clay+0.032	Conductor temperature	133	129	43
moisture content	Air temperature	27	27	_
	Soil temperature	-	26	34
(2) 70% sand + 30% clay+0.05	Conductor temperature	133	129	42
moisture content	Air temperature	27	27	_
	Soil temperature	-	26	33
(3) 50% sand + 50% clay+0.071	Conductor temperature	133	129	41
moisture content	Air temperature	27	27	_
	Soil temperature	-	26	33
(4) 30% sand + 70% clay+0.13	Conductor temperature	133	129	40.5
moisture content	Air temperature	27	27	_
	Soil temperature	-	26	32.5
(5) 15% sand + 85% clay+0.2	Conductor temperature	133	127	39.5
moisture content	Air temperature	27	27	-
	Soil temperature	-	26	32

observed from Figures 6-8 and also Tables 1, 6-8 that no dry band is formed around the cable duct buried in soil, may be because the thermal resistance of the air between the outer surface of the cable and the inner surface of the duct is high and does not allow to the retained heat that is produced by the cable conductor to dissipate into the soil. These findings are consistent with the results reported in reference [35].

To investigate the effect of increasing the PVC duct diameter on the cable conductor and insulation temperatures, the duct diameter is changed from 40 to 60 mm in case of 0.4 kV (three cores), the reduction in temperature was 9 and 6 °C for conductor and insulation temperatures respectively. The same observations are noticed when the duct diameter is increased from 160 to 180 mm in case of 11 kV (trefoil) and from 80 to 100 mm in case of 33 kV (flat). Finally it can be concluded that the duct diameter has remarkable influence on the cable conductor and insulation temperatures. These findings are in agreement with the calculations given in refs. [27,35].



FIGURE 7 11 kV cable temperature loaded by it cyclic loading, (a) cable in vertical riser, (b) cable in duct when using soil 1, (c) comparison between different buried methods when using soil 1 in the surrounding and (d) comparison between different buried methods when using soil 3 in the surrounding, and duct thickness 5 mm



FIGURE 8 33 kV cable temperature loaded by it cyclic loading, (a) cable in vertical riser, (b) cable in duct when using soil 1, (c) comparison between different buried methods when using soil 1 in the surrounding and (d) comparison between different buried methods when using soil 3 in the surrounding

4 | CONCLUSIONS

This article presented thermal analysis of cables installed in PVC duct which is used as risers or buried in soils. The analysis is done in both continuous and cyclic current loading conditions. This analysis is carried out by using models based on IEC 60287-1-3 and IEC 60853-2 standards of continuous current loading and cyclic current rating of power cables respectively. It is concluded that high increase in the cable conductor temperature is observed when the cable is installed in duct as riser or even when it is buried in soil with duct, especially three core cable and trefoil cable installations. As example an increase in cable conductor temperature by about 15 °C is noticed when the cable is installed in duct and buried in soil type (1) and also when it is installed as riser in duct for 33 kV loaded by 375 A. In some cases of cable loading it is noticed that the maximum conductor temperature reached to about 119 °C after 60 h loading exceeding the allowable limit by about 29 °C. A rise in the conductor temperature between 10 and 15 °C was observed with the increase in the PVC duct thickness. Significant decrease in the temperature of the cable conductors can be noticed when the cable is directly buried in the soil. Soil decomposition has unnoticeable effect on the cable conductor temperature installed in duct and buried in soil due to the high value of the PVC duct thermal resistance compared with that of the soil. The PVC duct diameter has an influence on cable conductor and insulation temperatures, as example reduction in temperature between 9 and 6 °C was observed in conductor and insulation temperatures respectively with the increase of duct diameter from 40 to 60 mm for 0.4 kV cable.

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How to cite this article: Gouda, O. E., Osman, G. F. A.. Enhancement of the thermal analysis of power cables installed in polyvinyl chloride (PVC) ducts under continuous and cyclic current loading conditions. *IET Gener Transm Distrib.* 2020;1–15. https://doi.org/10.1049/gtd2.12092