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Computation of Electric Field and Thermal Properties of 3-Phase Cable

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Abstrak

Pada makalah ini, distribusi medan listrik, tegangan dan suhu dalam kabel bawah tanah 3 fasa dalam penutup pentanahan dianalisis dan dibentangkan. Tidak seperti kabel skrin 3 fasa, distribusi regangan dalam kabel yang berikat tidaklah radial. Sebuah kabel daya tegangan tinggi 3 fasa yang dikubur dalam tanah dapat digunakan untuk menyelidiki properti listrik dan termalnya. Pada studi ini, distribusi tegangan kabel bawah tanah 132 kV dianalisis menggunakan FEM sedangkan distribusi kapasitas arus dan suhunya dikalkulasi menggunakan metoda analitik. Selanjutnya parameter kinerja diverifikasi menggunakan perangkat lunak Comsol Multiphysics. Hasil yang diperoleh dibandingkan dengan model CSM yang diperoleh melalui kajian literatur.

Katakunci: *COMSOL multiphysics, FEM, kabel daya, kapasitas arus, suhu dan medan listrik.*

Abstract

In this paper the electric field distribution, potential distribution and temperature distribution in a 3-phase underground cable in common ground enclosure is analyzed and presented. Unlike 3-Phase screened cable the stress distribution in a belted cable is not radial. A 3-phase high voltage power cable buried in soil can be used to investigate its electrical and thermal properties. In the present study the voltage distribution of an underground cable of 132 kV is analyzed using FEM and its ampacity and temperature distribution is calculated by analytical method. Further their performance parameter is verified using Comsol Multiphysics software. The results obtained using comsol software is also compared with the results of CSM model which is obtained through literature review.

Keywords: *power cable, FEM, COMSOL multiphysics, ampacity, electric field and temperature.*

1. Introduction
1.1. Electric field model

High Voltage Cables are used when underground transmission is required. These cables are laid in ducts or may be buried in the ground. Unlike in overhead lines, air does not form part of the insulation, and the conductor must be completely insulated. Power cables are much more costly than overhead lines. Also, unlike for overhead lines where tapping's can be given easily, cables must be connected through cable boxes which provide the necessary insulation for the joint. Cables have a much lower inductance than overhead lines due to the lower spacing between conductor and earth, but have a correspondingly higher capacitance, and hence a much higher charging current. High voltage cables are generally single cored, and hence have their separate insulation and mechanical protection by sheaths, as depicted in Figure 1.

In the paper insulated cables, the sheath was of extruded lead**.** The electric field in the coaxial cable varies only in radial direction and the field magnitude decreases with increasing distance from the conductor centre and can easily be calculated analytically. However, when a cable end is terminated for testing and other purposes [1].Power lines of transformation station must fit in Ambient of urban areas and for that reason usually the power cables 132kV are buried in underground tunnels. In many cases the power cables are installed in already existing underground tunnels, made for other underground installations, like gas pipes, water pipes, telecommunication cables etc [2]. The two-dimensional electrostatic models of three phases cross linked polyethylene cable containing soil has been developed using the COMSOL multiphysics finite element environment [3].

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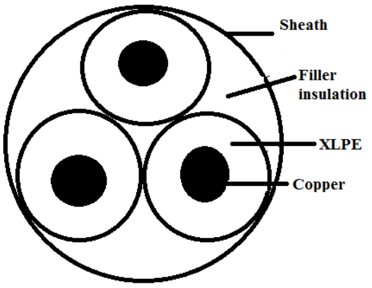


Figure 1. Constructive elements of the three-core power cable

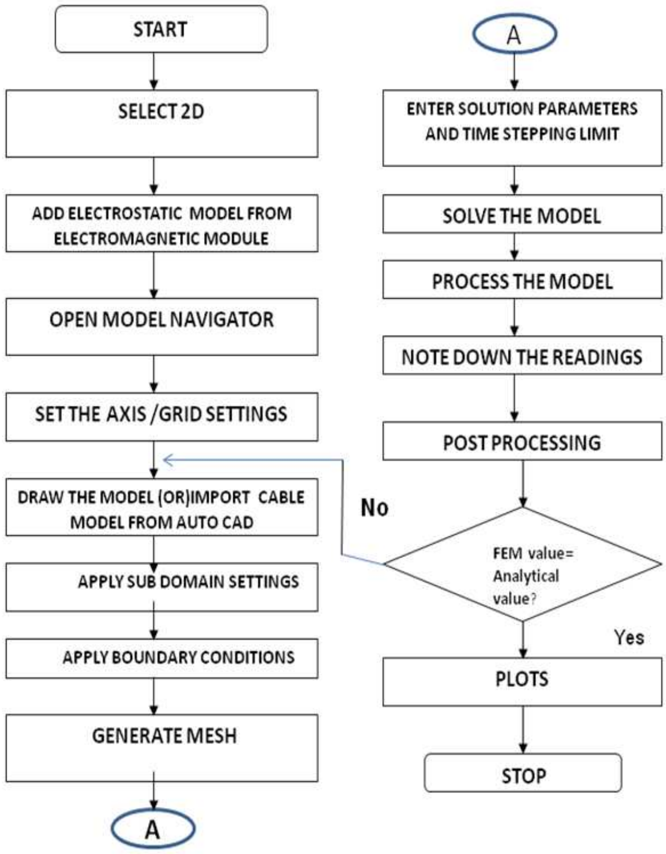


Figure 2. Flow chart cable modelling in COMSOL

The finite element method is a numerical procedure that can be applied to obtain solutions to a variety of problems in engineering and science. Steady, transient, linear and non linear problems in electromagnetic, structural analysis and fluid dynamics may be analyzed and solved with it. Its main advantage is its capability to treat any type of geometry and material in homogeneity without a need to alter the formulation of the computer code that implement it providing geometrical fidelity and unrestricted material treatment [4-6]. Also FEM allows to take into account the actual field, voltage distribution over conductor surfaces.

1.2. Thermal Model

The most important indicator of the health of electrical systems is the condition of their insulation. In the case of underground cables an important issue is the operating temperature and indeed the thermal history of the cable. There are several factors which will determine the thermal behaviour of a given cable installation. The work presented in this XLPE involves the use of COMSOL multiphysics [3] finite element software to develop an integrated electrical, thermal and mechanical model of buried single or multiphase cables that simulates the behaviour occasioned by a varying time .The thermal and electrical systems are coupled via the temperature dependence of the resistivities of the conductor and sheath materials. The output takes the form of the temperature and heat flux response of the cable for given installation and ambient conditions.Fourier Law describes the heat transferred by conduction. In very simple terms, the heat flux is proportional to the ratio of temperature over space. In an underground cable installation heat conduction occurs everywhere except in the air space in the conduit. Convection of heat occurs in moving fluids (air, water, etc.) and obeys Newton's Law. The flow of heat is proportional to the temperature difference [7]. Easy construction, good heat transfer through the dielectric, low losses and inexpensive terminations are some of the advantages of the gas insulated cables. They are now used for the transmission of high electrical power and in SF6 Insulated substations [5-8].

1.3. Comsol Multiphysics

Comsol multiphysics has a multiple tools for all engineering applications, here two modes of applications are used they are namely Electrostatics and Heat transfer modules. In electrostatics module we model the cable for obtaining the electric field, potential distribution and heat transfer module we model the cable for obtaining the temperature distribution and heat transfer through cable. The modelling of cable in electrostatic and thermal model is obtained by using a flow chart shown below and mesh generation using finite element method in COMSOL is shown in Figure 2.

2. Research Method

In the present study, the electric field, Potential distribution and temperature distribution is performed and the actual electric field and temperature is calculated. The obtained results were analysed and compared with taking 1pu voltage magnitude using charge simulation method (CSM). In the charge simulation method, the actual charges on the conductor surfaces are replaced by fictitious line, ring, or point charges. These fictitious charges are placed outside the region where a field solution is desired.

The magnitude of these charges should be such that the net potential is equal to the known potential at a selected number of boundary points on the conductor surfaces, therefore the charges are computed from the equation:

$$[P]\,[Q] = [¢] \tag{1}$$

where [P]=the potential coefficient matrix
[Q]= the column vector of values of the unknown charges,
[¢]=Potential at boundary points.

After using above equation to calculate the values of charges, the potential and field at any point outside the electrodes may be calculated easily. Thus calculated values are compared with finite element method values, so as to check their conformity.

2. 1. Electrostatic Model

COMSOL's electrostatic application mode solves Poisson's equation

$$-\nabla.(\epsilon_o.\epsilon_r\nabla V) = \rho \tag{2}$$

and obtains the electric field E from the gradient of the potential

$$E = -\nabla V \tag{3}$$

The PDE (1) is solved subject to the following boundary conditions:

$$\text{Sheath:} \quad V = 0 \tag{4}$$

$$\text{Conductors } V(t) = V_0\cos(wt + \frac{2n\pi}{3}) \tag{5}$$

where n=0,1,2 on the 2 dimensional domain represented by the cable cross section (Figure 1). $V_0$is set at 132 kV, ε_r is taken as 2.3 for the insulation and filler.

The metallic sheath in cables consists of lead sheath with or without an additional insulation shield formed by application of non-magnetic metallic tape, a metalized paper tape or a semiconducting tape. In this paper while modeling, the sheath is treated as a perfect conductor for the purpose of field computations. The insulating material surrounding the cable conductor is uniform with the relative permittivity of 2.3.The field distribution in a.c belted cable insulation is complex.

The three conductors are given 3-phase supply, as Figure 3. This results in to time dependent variations in electric stresses. This is to say that the electric stress (field distribution) in the cable is not stationary but varies with respect to time.

V_A , V_B , V_C are the core(conductor) potential

$$V_A = \mathrm{V}\cos(wt) \quad (6)$$

$$V_B = \mathrm{V}\cos\left(\mathrm{wt}+\frac{2\pi}{3}\right) \quad (7)$$

$$V_C = \mathrm{V}\cos\left(\mathrm{wt}+\frac{4\pi}{3}\right) \quad (8)$$

Then applied potentials are:

$$V_A = 132\text{kV} \qquad V_B = -66\text{kV} \qquad V_C = -66\text{kV} \quad (9)$$

2.2. Cable Parameter Details

The cable specifications are selected for the modelling of underground cable from IEC 60287[1] and cable corporation of India. The parameters of cable shown below.

2.2.1. Conductor Details

Type of conductor copper, diameter of conductor 33.70mm, relative permittivity $(\epsilon_r) - 1.0$, thermal conductivity (K)-398 W/m.K, applied voltage (v)-132Kv,current-979.427 amps.

2.2.2. Insulator Details

Type of insulation is Cross Linked Polyethylene (XLPE), diameter of conductor insulation-63.70mm, thickness of insulation-15mm, relative permittivity$(\epsilon_r) - 2.3$,thermal conductivity(K)-6.034 W/m.K.

2.2.3. Sheath Details

Material used in sheath is Lead, inner sheath diameter-74.00mm,outer sheath diameter-76.5mm,sheath thickness-2.5mm,relative permittivity $(\epsilon_r) - 1.0$,thermal conductivity(K)-35.3 W/m.K

2.2.4 Soil Details

Soil type is dry, depth of cable in soil-1m, relative permittivity $(\epsilon_r) - 1.0$, thermal conductivity (K)-1 W/m.K

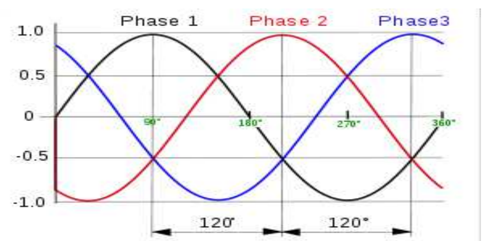


Figure 3. Three phase sinusoidal wave form

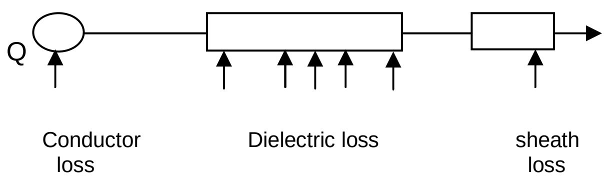


Figure 4. Heat transfer in a cable due to losses

2.3. Thermal Model

In an underground cable system the main heat transfer mechanism as Figure 4 is by conduction [10].

$$\rho Cp\,\frac{\partial T}{\partial t} + \nabla.(K\nabla T) = Q \quad (10)$$

Power loss in the cable can occur due to a variety of reasons (Figure 3). They may be caused by the conductor current passing through the resistance of the conductor - conductor loss (also sometimes called the copper loss on account of the fact that conductors were mainly made out of copper), dielectric losses caused by the voltage across the insulation, sheath losses caused by the induced currents in the sheath.. The dielectric loss is voltage dependant, while the rest is current dependant [11-12].

The differential equation which is used to Calculate the temperature in state thermal field is defined as equation (10) [13].

$$-\nabla(\mathrm{K}\nabla\mathrm{T}) = \mathrm{Q} + \mathrm{h}(\mathrm{T}_{\mathrm{est}} - \mathrm{T}) \tag{11}$$

The boundary condition for the most outside interface is set to a certain temperature which is equivalent to the ambient temperature.

$$-\nabla(\mathrm{KT}) = \mathrm{h}(\mathrm{T}_{\mathrm{est}} - \mathrm{T}) \tag{12}$$

In the separation between the different materials of the cable, calorific flow continuity is fulfilled at the separation surface, which is described by equation (12)

$$K_1 \frac{\partial T}{\partial l} = K_2 \frac{\partial T}{\partial l} \tag{13}$$

Likewise, the temperature in both materials at the border points must be the same [14]. For temperature distribution in a cable the ampacity of cable is required. The ampacity of cable which depends upon the temperature and losses.

The modified form of ampacity is shown below equation

$$\mathrm{I} = \left[\frac{\Delta\theta - Wd(S+G)}{R(S+G)}\right]^{0.5} \tag{14}$$

$$\mathrm{S} = \frac{K}{6\Pi}\left[0.85 + \frac{0.2t}{T}\right]\ln\left[\left(4.15 + \frac{1.1t}{T}\right)\left(\frac{T+t}{r}\right) + 1\right] \tag{15}$$

$$\mathrm{G} = \frac{kH}{3\Pi}\ln\left(\frac{2h}{r}\right) \tag{16}$$

$$\mathrm{H} = 2\Pi r_2(\theta_c - \theta_a)^{1.25} \tag{17}$$

Dielectric loss (Wd)

$$\mathrm{Wd} = \frac{2\Pi f \times SIL \times \left(\frac{V}{\sqrt{3}}\right)^2 \times Tan(\delta) \times 10^{-9}}{18\ln\left(\frac{D_{insulator}}{D_{cond-shield}}\right)} \tag{18}$$

$$\mathrm{R1} = R_{dc}(20^0 c) \times \left(\frac{234.5 + \theta_c}{234.5 + \theta_a}\right) \tag{19}$$

$$\mathrm{R} = \mathrm{R1}(1 + Y_{cs} + Y_{cp}) \tag{20}$$

According to IEC 60287, SIL=2.3 , and Tan δ =0.001

The analytical calculation of temperatures is given by

$$Q = KA\frac{dt}{dr} \qquad (21)$$

where

R	Radius of cable(m)	K_1, K_2	Thermal conductivities of medium 1,2
r	Radius of conductor(m)	G	Cable resistance of ground from cable surroundings ($\Omega.m$)
ρ	Density(kg/m^3)	S	Total thermal resistance of cable ($\Omega.m$)
Cp	Specific heat capacity (J/$K.m^3$)	T	Thickness of conductor insulation (mm)
Q	Heat source (W/m)	t	Thickness of belt insulation(mm)
T_{est}	Ambient temperature (K)	H	Depth of buried soil
T	Conductor temperature (K)	Ycs	Skin effect factor
h	Convective heat transfer coefficient(W/m^2K)	Ycp	Proximity effect factor

3. Results and Analysis

3.1. Electric Field and Potential Distribution

The electric field inside the conductor is zero but it should be maximum at conductor surface and decreases from conductor surface till R/r=2.718 at this point electric field is minimum and then again it increases up to the outer surface of the sheath as shown in Figure 5.

The potential distribution is a main role in cable. According to possion's equation, the potential is non zero inside the conductor and it is constant at boundary of conductor and goes on decreses as shown in below Figure 6.

The field in left hand side conductor (i.e. phase A) is maximum compare with other two conductors. The maximum part is indicates by red colour. Figure 9 indicates the electric field and potential lines are perpendicular to each other. The soil electric field is very less compare with individual conductors and initially phase B electric field is less compare with phase C but after reaching 180 degree phase shift it should be higher than the phase C.

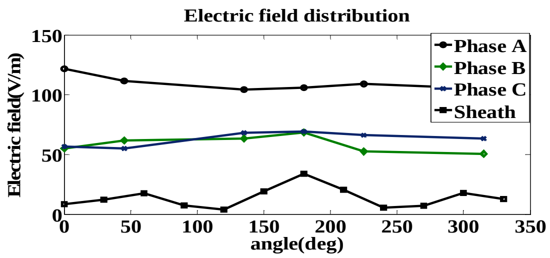


Figure 5. Electric field stress on conductor and shield with 1pu magnitude

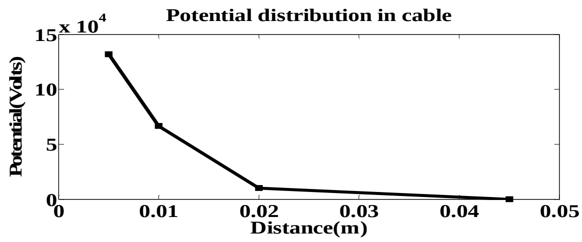


Figure 6. Electric potential distribution in cable

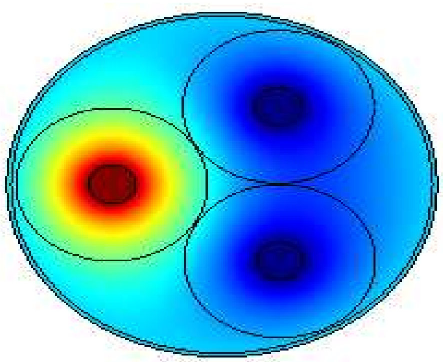


Figure 7. Field and potential distribution in a cable

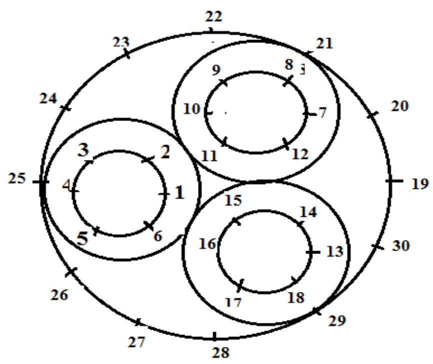


Figure 8. Point location on cable conductor and sheath

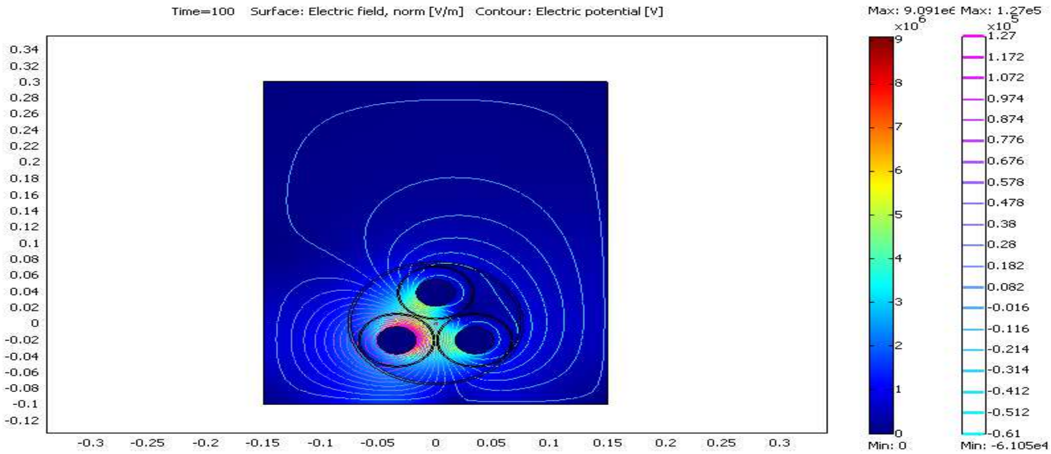


Figure 9. Field and potential distribution in cable

The typical field distribution in cable conductor surface, insulator surface and sheath surface with changing azimuth angle for 1pu magnitude voltage is compared with charge simulation method (CSM) is shown below Table 3.

Table 3. Field distribution in cable conductor and sheath surface taking voltage magnitude is 1pu

location	Using FEM COMSOL	Using CSM
1	1.2176880	1.2466
2	1.2131540	1.2440
3	1.1409547	1.1903
4	1.1582504	1.1422
5	1.0902908	1.1905
6	1.1509666	1.2443
7	0.5497630	0.5840
8	0.6173676	0.6792
9	0.6326279	0.6300
10	0.6840632	0.6654
11	0.5258878	0.5489
12	0.5055222	0.5489
13	0.5651912	0.5891
14	0.5502619	0.5541
15	0.6786685	0.6288

location	Using FEM COMSOL	Using CSM
16	0.6922596	0.6703
17	0.6626740	0.6349
18	0.6315700	0.6248
19	0.0829302	0.0896
20	0.1214670	0.1251
21	0.1760388	0.1281
22	0.0747833	0.0759
23	0.0392149	0.0449
24	0.1932216	0.2017
25	0.3373285	0.3574
26	0.2030545	0.2016
27	0.0552741	0.0445
28	0.0710601	0.0768
29	0.1782092	0.1796
30	0.1277914	0.1259

3.2. Temperature Distribution in Cable

3.2.1. Steady State Analysis

In steady state temperature analysis temperature cannot depends on the time.The amount of heat flux is maximum at conductor surface and it will be minimum at sheath. Steady state Temperature distribution in cable surface plot is shown in Figure 10.

3.2.2. Transient Analysis

The problem of temperature distribution at cable of XLPE selected by boundary type of Dirichlet condition.

Transient conduction occurs when the temperature within an object changes as a function of time. Analysis of transient systems is more complex and often calls for the application of approximation theories or numerical analysis by computer, the heat flux is more in surface of the conductor and the remaining surfaces are very less as shown in Figure 14.

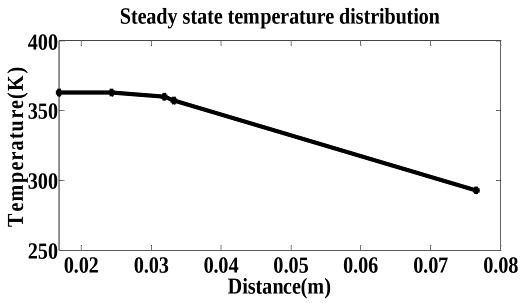


Figure 10.Temperature distribution in cable

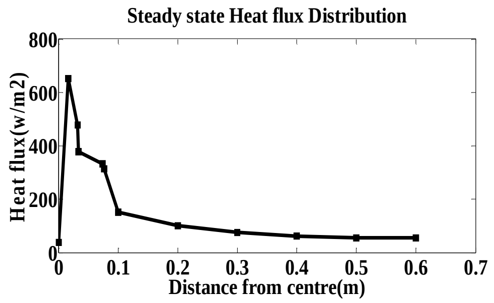


Figure. 11. Heat flux distribution in cable

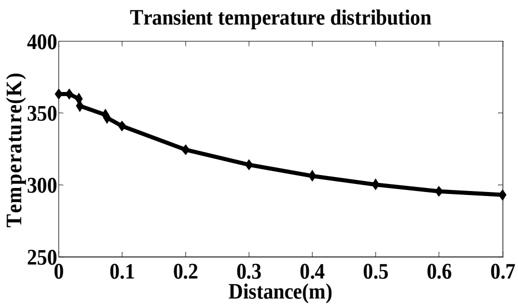


Figure 12. Transient temp. distribution in cable

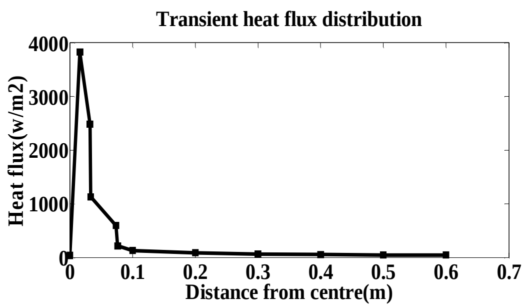


Figure 13. Heat flux distribution in cable

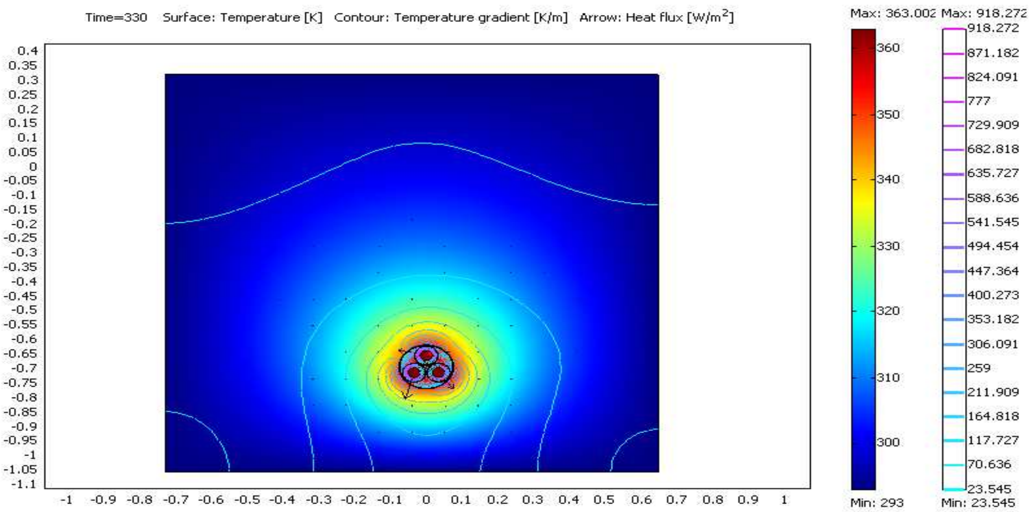


Figure 14. Transient temperature distribution

Table 4. Comparison of analytical and comsol results

Parameter	Temperature(K) (Theoretical)	Temperature(K) (Using COMSOL)
Centre	362.587	363.001413
Conductor surface	362.981	363.000000
XLPE surface	354	354.892567
Sheath surface	345	346.657381
Soil	293	293.000000

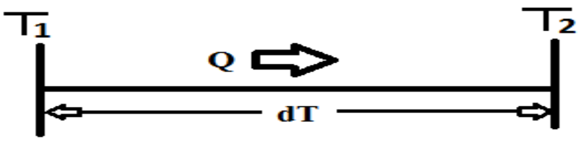
Table 4 concludes that the theoretical calculation of steady state temperature analysis is almost similar to the COMSOL Multiphysics results. The used equation is derived in Appendix 1.

4. Conclusion

From the above plots and analysis can be pulled that the electric field inside the cable conductor is zero and it will be minimum at R/r=2.718. Distribution temperature form of radial that happened in cable insulation of XLPE 132 kV which varies with time indicate that cable insulation of XLPE will not exceed boundary of work temperature 90 ℃(363K) at boundary condition of soil 293K (20 ℃). Distribution of th e temperature is not flattening in the cable. Highest temperature in the conductor layer and distribution to all layers until at ground i.e. at boundary 293K.

Appendix 1

Derivation for theoretical temperature calculation:



$$\int_{r1}^{r2} \frac{Q}{r}\,dr = -\int_{T1}^{T2} 2\pi KL\,dT$$

$$Q = \frac{2\pi KL(T_1 - T_2)}{\ln\frac{r2}{r1}}$$

$$Q = \frac{T_1 - T_2}{R} \qquad R = \frac{\ln\frac{r_2}{r_1}}{2\pi KL}$$

$$Q = KA\frac{dT}{dX}$$

$$Q = KA\frac{dT}{dr}$$

$$Q = 2\pi RLK\frac{dT}{dr}$$

where R Thermal resistance
L length of the cable
K Thermal conductivity

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