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Author............... Cuneyt OYSU

Address............ Kocaeli Üniversitesi
Mekatronik Mühendisliği Bölümü
Veziroğlu Kampüsü
41040 İzmit/Kocaeli

Phone

(262) 5282467

(532) 6173037

Fax

(262) 5271635

Other authors:

Faruk ARAS

Güneş YILMAZ

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AMPACITY ANALYSIS OF XLPE INSULATED HV UNDERGROUND CABLES USING FINITE ELEMENT METHOD

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AMPACITY ANALYSIS OF XLPE INSULATED HV UNDERGROUND CABLES USING FINITE ELEMENT METHOD

[1]Cüneyt Oysu, [2]Faruk Aras, [3]Güneş Yılmaz

coysu@kou.edu.tr, arasfa@kou.edu.tr, gunes.yilmaz@tr.pirelli.com
[1]Kocaeli University, Engineering Faculty, Mechatronics Engineering
[2]Kocaeli University, Technical Education Faculty, Electricity Department
[3]Türk Pirelli Kablo ve Sistemleri AŞ, R&D Department

I. ABSTRACT

Endurance of an insulation material to high temperatures determines the maximum current-carrying capacity (ampacity) of an underground power cable. Cable ampacity is calculated conventionally using the installation conditions and maximum steady state operation temperature according to IEC-287 standard. In this work, ampacity analyses of 154 kV and 380 kV high voltage XLPE underground power cables are made by using ANSYS 5.6 finite element analysis software. Ampacity analysis of cables in various insulation thicknesses together with thermal analyses is made analytically and numerically. 380 kV cables, which are planned to be used in Turkey, are also examined in single-cable layout. Additionally the effects of manufacturing tolerance of centrally skewed conductor material are investigated.

II. INTRODUCTION

Underground power cables are more expensive to install and maintain than overhead lines. The greater cost of underground installation reflects the high cost of materials, equipment, labor and time necessary to manufacture and install the cable. The large capital cost investment makes it necessary to use their full capacity. On the other hand, its conductor temperature limits ampacity of a power cable. Also the operating temperature adversely affects the useful working life of a cable. Excessive conductor temperature may irreversibly damage the cable insulation and jacket.

The first model proposed for calculating ampacity of underground cable by Neher-McGrath in 1957 (1). The Neher-McGrath Model has been widely accepted for over 50 years. Today, the greater majority of utilities and cable manufactures have been using the IEC-287 standard (2) based on the Neher-McGrath Model. This method employs a lot of simplifications and has its limitations. Thus it cannot be used for the analysis of complex configurations.

The finite element method (FEM) is more powerful and precise in terms of geometrical modeling complexity. The finite element method solves problems that are described by partial differential equations, using numerical techniques. A domain to be analyzed is represented as an assembly of *finite elements*. Approximating functions in finite elements are defined in terms of nodal values of a physical field. A continuous physical problem is transformed into a discretized finite element problem with unknown nodal values. For linear problems developed system of linear algebraic equations are solved numerically. Values inside finite elements can be obtained using nodal solutions.

Although the idea of dividing a continuum into small finite pieces had been first suggested by Courant in 1943, the development of the finite element method coincided with major advances in computers technology and programming languages.

III. AMPACITY CALCULATION

The ampacity calculation of a power cable can be found by applying the analogy between electrical and thermal circuit can be written in the following form:

$$\theta_c - \theta_a = w_c(T_1 + T_3 + T_4) + w_d(\frac{T_1}{2} + T_3 + T_4) + w_s(T_3 + T_4) \quad (1)$$

$$\Delta\theta = w_c \underbrace{(T_1 + (1+\lambda_1)(T_3 + T_4))}_{T_A} + w_d \underbrace{(\frac{T_1}{2} + T_3 + T_4)}_{T_B} \quad (2)$$

$$I = \sqrt{\frac{\Delta\theta - w_d T_B}{T_A R_{ac}}} \quad (3)$$

Where,

θ_c Maximum operating temperature ^oK

θ_a ambient temperature ^oK

w_c heat loss of conductor ($I^2.R_{ac}$) W/m

w_d	dielectric losses W/m
w_s	sheath loss (w_c. λ_1) W/m
λ_1	sheath loss factor W/m
T_1 T_3 T_4	Thermal resistances of insulation, sheath and soil (^{o}Km/W) according to IEC standards
R_{ac}	ac resistance of conductor at temperature θ_c
I	the ampacity of cable

IV. FINITE ELEMENT METHOD

A basic equation of heat transfer for an isotropic body with temperature dependent heat transfer has the following form;

$$-\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}\right)+Q=\rho c\frac{\partial T}{\partial t} \tag{4}$$

where q_x and q_y are components of heat flow through the unit area; Q is the inner heat generation rate; q is density; c is thermal heat capacity; T is temperature and t is time.

Fourier's law describes the heat flow equations as;

$$q_x=-k\frac{\partial T}{\partial x},\quad q_y=-k\frac{\partial T}{\partial y} \tag{5}$$

Here k denotes the thermal coefficient of the material. Substitution of above relations gives;

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+Q=\rho c\frac{\partial T}{\partial t} \tag{6}$$

Then the variation of the temperature and temperature gradients inside an element can be expressed in terms of nodal temperatures using shape functions N_i as

$$\{T\}=[N]\{T^e\} \tag{7}$$

Differentiation of the temperature field gives

$$\left[\frac{\partial T}{\partial x}\right]=\left[\frac{\partial N}{\partial x}\right]\{T^e\} \tag{8}$$

where T^e are the nodal temperatures for the e^{th} element. N represents the quadratic shape functions for 8-node quadrilateral elements (serendipity elements)

While shape functions are expressed through the local coordinates ξ, η, the matrix contains derivatives in respect to the global coordinates x, y. Derivatives can be easily converted from one coordinate system to the other by means of the chain rule of partial differentiation:

$$\begin{bmatrix}\dfrac{\partial N_i}{\partial \xi}\\ \dfrac{\partial N_i}{\partial \eta}\end{bmatrix}=\begin{bmatrix}\partial x/\partial\xi & \partial x/\partial\eta\\ \partial y/\partial\xi & \partial y/\partial\eta\end{bmatrix} \tag{9}$$

Using Galerkin method, we can rewrite equation (6) in the following form:

$$\Pi=\iint\left(\begin{matrix}\frac{1}{2}\{T_n\}^T k\left(\frac{\partial^2[N]^T}{\partial x^2}\frac{\partial^2[N]}{\partial x^2}+\frac{\partial^2[N]^T}{\partial y^2}\frac{\partial^2[N]}{\partial y^2}\right)\{T_n\}-\\ \{T_n\}^T[N]^T q\end{matrix}\right)dx\,dy \tag{7}$$

equations are rearranged to give stiffness matrix of [K] and force vector of {f} as;

$$[K\}=\iint\left(\frac{\partial^2[N]^T}{\partial x^2}\frac{\partial^2[N]}{\partial x^2}+\frac{\partial^2[N]^T}{\partial y^2}\frac{\partial^2[N]}{\partial y^2}\right)k\,dx\,dy \tag{8}$$

$$\{f\}=\iint[N]^T q\,dx\,dy \tag{9}$$

FEM equations are found by minimization of functional Π in terms of nodal temperatures.

$$\left\{\frac{\partial\Pi}{\partial T_n}\right\}=0\ \text{ve}\ [K]\{T_n\}=\{f\} \tag{10}$$

Stiffness matrix [K] and force vector {f} Integrals are calculated on each element numerically (Using Gaussian Quadrature) and then total stiffness matrix is set up by summation of each equation system. Then the total equation system is solved for each nodes.

V. Numerical Calculations and Discussions

I. 154 kV Underground Cable Analysis

The ampacity of the underground cable whose sectional view illustrated in Figure 1 is analyzed using the finite element method. Under the operation conditions the amount of heat generated from the cable should be calculated to determine ampacity. Since the limiting operation temperature of XLPE cables is 90 ^{o}C, the heat generated from charged cable should be transferred to environment to reside under this temperature. That's why the correct calculation of heat transfer from the cable affects the ampacity analysis directly. According to IEC-287 standard the soil temperature for Turkey is 20 ^{o}C for north regions. 1.2 m is the depth normally the underground cables are buried under. Using these conditions and assuming the soil is homogenous, heat transferred and ampacity are calculated both by Neher-McGrath and Finite element method.

The steady state calculation of the heat transfer gives general operating ampere capacity. For shorter times this current can be exceeded under cable manufacturer's limiting values. In this analysis transient effects are not considered thus time is not a parameter.

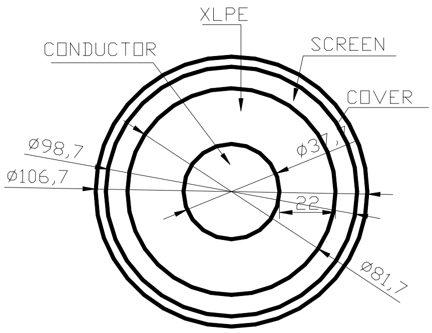

Figure 1 Sectional view of the cable.

Since the heat transfer coefficients of XLPE and the semi conductor material are very close to each other, they are assumed to be same and considered as a single layer. The effects of coating layers and very thin metallic screens are omitted as their thermal resistivities are very small and have a very little effect on the results. Generalized layer dimensions of a 154 kV underground cable and the dielectric losses generated on XLPE are as follows;

$D_{Conductor}$	= 38 mm
$D_{XLPE+Semi\ Conductor}$	= 82 mm
D_{Screen}	= 99 mm
D_{Cover}	= 107 mm
h_{depth}	= 1200 mm
$q_{dielectric}$	= 3.57 W / m

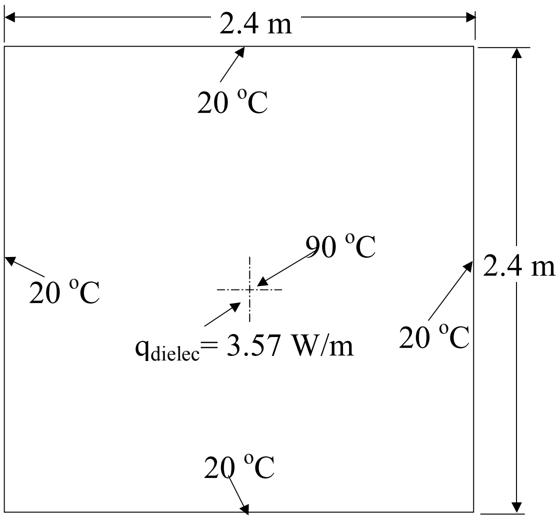

Figure 2 The layout position of the 154 kV cable is given above.

The insulation thickness of a cable affects the permissible maximum current and heat transferred from the cable. Higher insulation thickness block also the heat generated in the conductor. Various insulation thicknesses for a 154 kV underground cable are analyzed in this example.

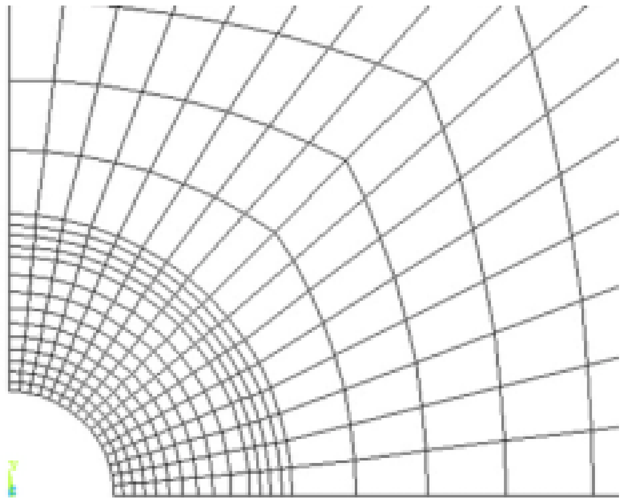

Figure 3 FEM mesh around the cable.

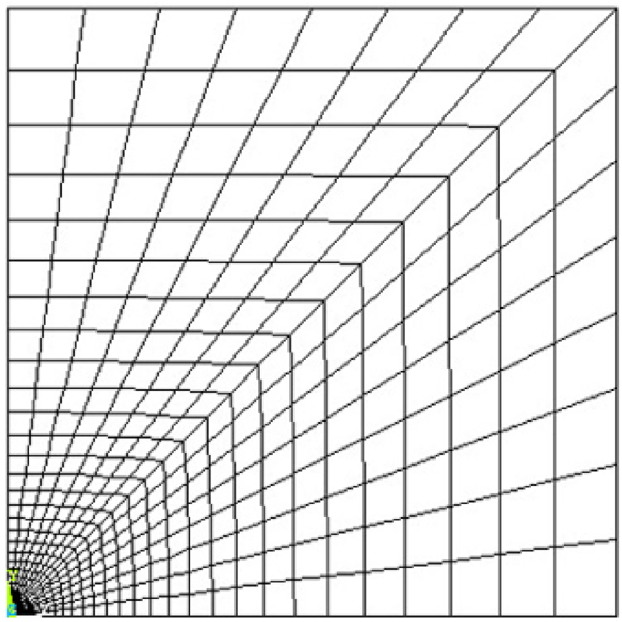

Figure 4 The mesh modeling both the cable and the surrounding soil with 608 elements.

Since the model is symmetrical about both x and y-axis, only a quarter of the domain is modeled. As a general rule of finite element method element shapes are kept close to a aspect ratio of unity. Heat generation by dielectric losses is applied on the XLPE domain.

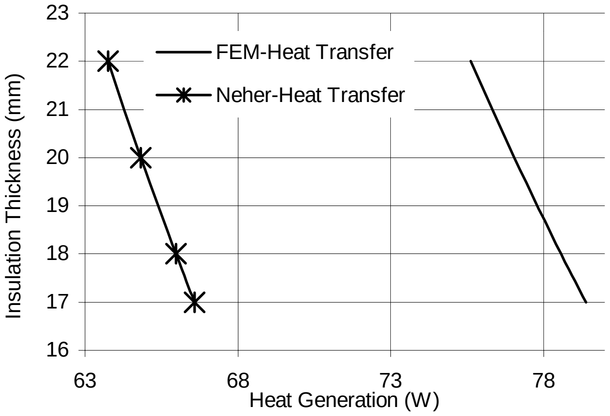

Figure 5 The amount of heat transferred for different insulation thickness by both FEM and Neher-McGrath model.

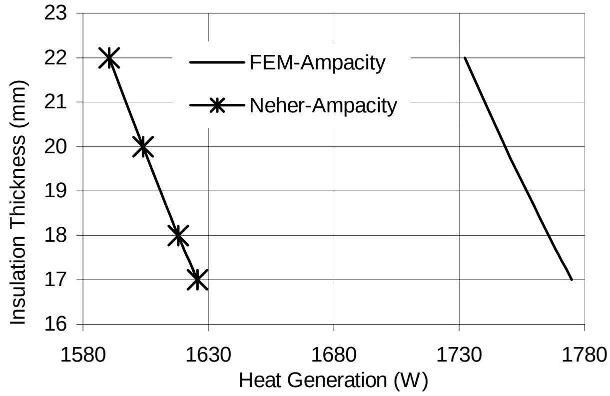

Figure 6 The Ampacities for different insulation thickness by both FEM and Neher-McGrath model.

Figure 5 and Figure 6 show that the heat transfer from the cable show a difference of around 16 % and consequently on the ampacity. The reason for this comes from that the finite element method models the problem much correctly. The model of soil effects by Neher-McGrath formula should be revised.[3] The results illustrated also that the reduction in the insulation thickness by 22 % (from 22 to 17 mm) has an effect of 5 % increase in the heat transferred and 2.5 % increase in the ampacity. Since the heat transfer mechanism is conduction and this is directly proportional to the contacting surface area, reduction in the diameter reduce both thermal barrier and contacting surface.

II. 380 kV Underground Cable Analysis

In this case study heat transfer calculations of the 380 kV underground cables and accordingly the ampacity analysis are done. Moreover the extreme effects of manufacturing tolerances of cables are estimated in the case of skewed cable conductor. The cable properties and the dielectric losses are given below.

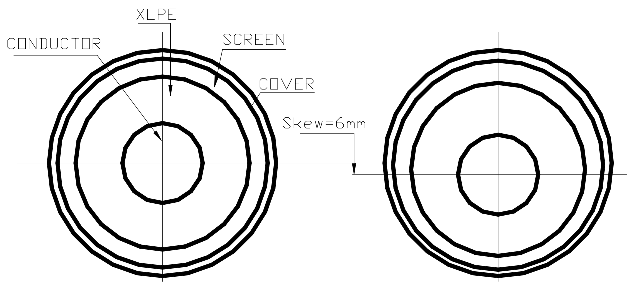

Figure 7 Conductor is centrally skewed by 6 mm

A commercial 380 kV high voltage underground cable with following dimensions are modeled. The conductor temperature is again kept in the maximum of 90 ^{o}C and the cable burial depth is 1500 mm. Thermal conductivities of soil and XLPE are given below as well. The screen thermal conductivity is an equivalent one since screen is an composite layer.

$D_{Conductor}$	= 40 mm
$D_{XLPE+Semi\ Conductor}$	= 104 mm
D_{Screen}	= 109 mm
D_{Cover}	= 121 mm
h_{depth}	= 1500 mm
$q_{dielectric}$	= 18 W / m
d_{Error}	= 5 mm (maximum)
k_{soil}	= 1.2 W/m
k_{XLPE}	= 0.2857 W/m
k_{screen}	= 0.6 W/m

The layers of the cable are simplified to three in this example, the semiconductor and XLPE properties are similar thus they assumed to be same. Some very thin film layers are also omitted as they have very little effect on the results. The effects of manufacturing tolerances are calculated by analyzing the core skewed by 5 mm from the center case. This case is selected for the reason that such effects can not be considered in Neher-McGrath models.

After various mesh densities are examined, the following mesh is selected to give converged results.

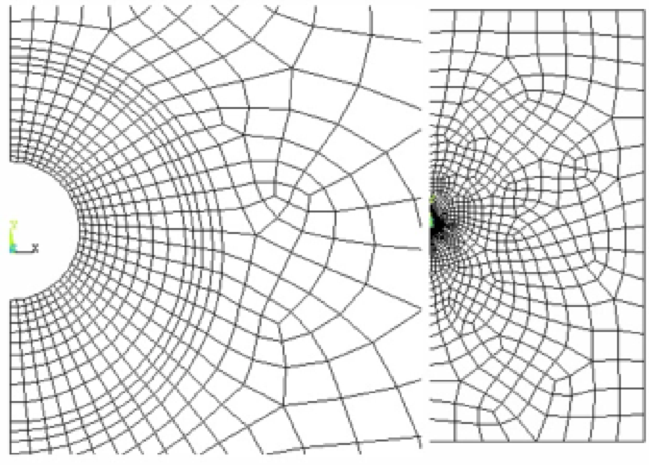

Figure 8 Mesh around the off-center conductor and whole domain with 1218 elements.

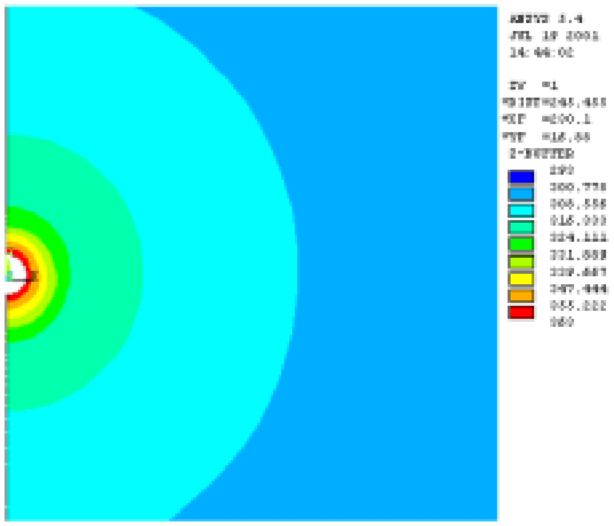

Figure 9 Temperature contours around the skewed core.

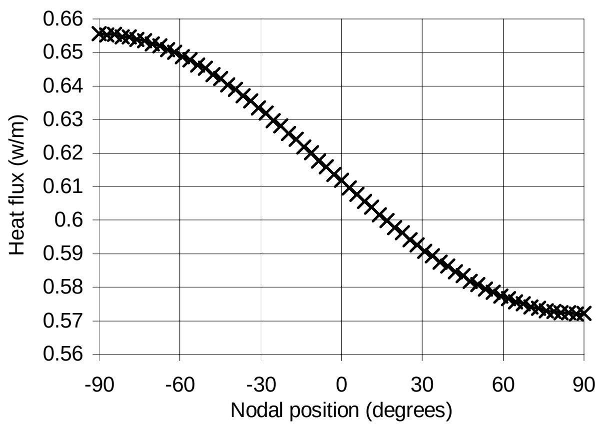

Figure 10 Thermal heat flux variation by nodes polar position.

Figure 9 shows the temperature distribution around the cable core. As the conductor is off-center by 6 mm thermal heat fluxes varies by 16 % around it depending on the thickness. The total amount of heat transferred for 380 kV cable and ampacities are given below;

	Q (W)	Ampacity(Ohm)
FEM	57.5	1510.5
Neher-McGrath	49.3	1398.5
FEM-Skewed	58.8	1527.5

The difference between the analytical model and finite element method is 8.2 %. Neher-McGrath model's solution is again gave results less the value of finite element method however this means less ampacity and lower operating conditions. Even if Neher-McGrath's model is on the safe side, a precise solution by either finite element method or finite difference method can be obtained.

VI. Conclusions

The analytical modeling of heat transfer mechanism by Neher-McGrath has been worked well in simple cable installations. However simplifying assumptions and empirical correlation to obtain the analytical method can be significant in complex installation like crossing cable ducts, cables on trays, cables near buildings, cable splices, etc. thus the solution becomes impossible. Today's computer technology gives finite element method a capability to solve any of these cases with very complex geometrical configuration. It can solve complex installations in any environment and subjected to any type of load condition together with transient analysis efficiently.

The numerical solutions for the underground cables showed that the finite element method gives a solution in any of the domain and free from any geometrical complexities.

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