Performance of Insulation Materials to Enhance Grading Method Effect in High Voltage Cable

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Abstract— **In today`s life using of high voltage cables increase day by day. One of the key factor in insulating is the stress distribution that is the determining factor of the age of these cables. In this paper we work on capacitance grading method and show how the choice of material could change the stress distribution. We use three different common materials in each situation and compare them to find the best group of material to use in this sample high voltage cable. To have a good insight and trustworthy comparison between these group of materials we use finite element method that widely used nowadays for analyzing the electric stress in the cable insulation.**

Keywords- High Voltage Cable; Finite Element Method; Capacitance Grading Methods

I. INTRODUCTION

In modern times by the wide use of high voltage we don`t have other choice than to use high voltage transmission lines. It can be done by some ways like laid cables in duct or Cables may be buried in the ground or use as overhead lines. In overhead lines air forms part of the insulation but in underground cables air does not form part of the insulation. So conductor must be completely insulated. Here is where we need high voltage cables insulation and grading method. All electric cables consist of three essential points: (a) the conductor for transmitting electrical power, (b) the insulation, to insulate the conductor from direct contact with earth or other objects and (c) External protection against mechanical damage, chemical and electro chemical attack, fire or any other dangerous effects external to the cables [1]. Generally, copper and aluminum conductors are used. High voltage cables are single core as well as three cores. Generally, single core cables are used. Cables are classified depending upon the material used for the insulation. Materials like polyvinyl chloride (PVC), polythene, cross linked polyethylene (XLPE) and etc. The main type of insulation used in the cable industries are paper, rubber, plastics and compressed gas.

The cable insulation has to be continuously exposed the variety of stresses. If this stress exceeds the limit of electric field, it results in partial discharge and as a result it cause the breakdown of the insulation. So, analysis of electric stress occurs in the insulation of the cable is very necessary. The maximum electrical stress occurs in the insulation immediately near to the conductor shield and minimum stress occurs at the inner radius of the sheath so there is a high gap between minimum and maximum of stress that means the dielectric material will not be fully utilized. To moderate that we can use capacitance grading.

In this paper three different group of insulation material has been used in equal situation to find the most suitable group of material to use in this method. Calculation of electric field or stress requires the solve of hard and time consuming equation with the satisfaction of boundary conditions, because of it we focus our work and analysis on numerical method beside of the analytical one. There are some numerical method to use like: Finite Difference Method (FDM), Finite Element Method (FEM), and a Charge Simulation Method (CSM) but among those Finite Element Method is the most suitable for calculating electric field [2]. This method is widely used in almost all of the engineering field. This method divides the whole region into small finite elements and calculates for each element and so whole region is considered. Various types of computer software can be used for applying this method. In this work Ansys Maxwell v.16 Software has been used for calculating electric field and stress.

II. ELECTROSTATIC FIELD IN A HIGH VOLTAGE CABLE

A. single core cable without grading method :

It is a well-known theory that in a single cable with conductor radius 'r', the inner radius 'R', the potential gradient 'g' at a distance of 'x' from the center of the conductor is:

$$g = \frac{q}{2\pi\varepsilon x} = \varepsilon_x \qquad (1)$$

Where;

ε_x is the electric field intensity,

Q is the charge per unit length.

ε is the permittivity of the dielectric material.

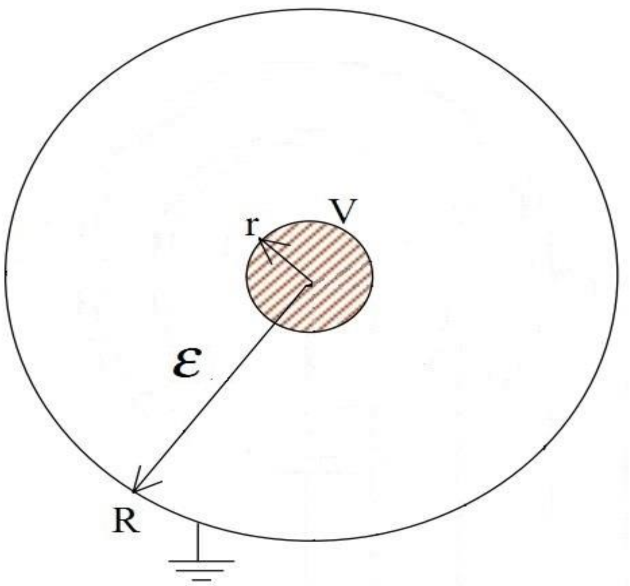


Fig-1: single core cable

So the potential of the conductor will be:

$$V = -\int_R^r \varepsilon_x \, .\mathrm{dx} \tag{2}$$

$$= \int_R^r \frac{q}{2\pi\varepsilon x} .\mathrm{dx} \tag{3}$$

With respect to (eq. (1)). So:

$$\varepsilon_x = \frac{V}{x \log e^{\frac{R}{r}}} \tag{4}$$

Here, 'x' is the only variable in the equation, the maximum stress in dielectric material occurs at the minimum value of the radius (x=r). So,

$$\varepsilon_{\max} = \frac{V}{r \log e^{\frac{R}{r}}} \tag{5}$$

B. Capacitance grading method

In this grading method different materials with different permittivity were used for layers. It means more than one dielectric material is used. To secure the same value of maximum stress in each layer, the maximum stresses in the layers are equated.

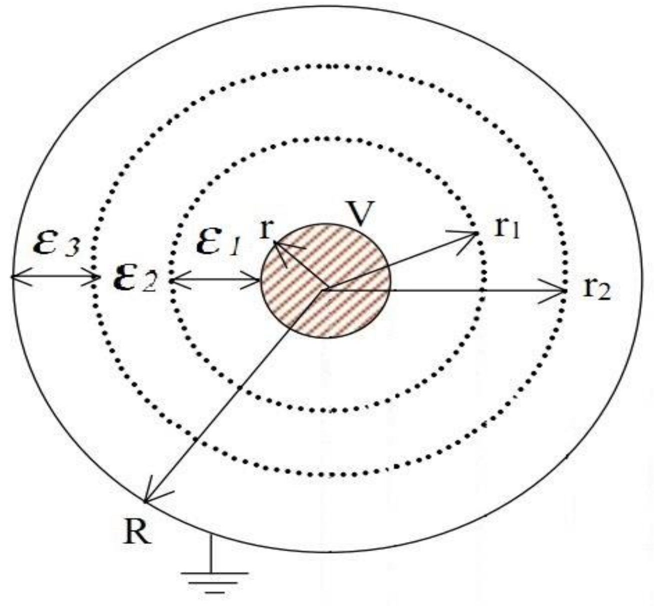


Fig-2: cable with capacitance grading

As shown in Fig-2, insulation with more than one material is used for this method. These layers have a different permittivity. In this figure three layers of permittivity of $\varepsilon_1 \ \varepsilon_2, \varepsilon_3$ are used. These layers are placed at the radius of $r_{1,} r_2$, r_3 =R. Considering the radius 'r' for conductor and voltage of V, then:

$$\frac{q}{2\pi\varepsilon_0\varepsilon_1 r} = \frac{q}{2\pi\varepsilon_0\varepsilon_2 r_1} = \frac{q}{2\pi\varepsilon_0\varepsilon_3 r_2} \tag{6}$$

So,

$$\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2 \tag{7}$$

And then,

$$V_1 = \varepsilon_{\max} r \log e^{\frac{r_1}{r}} \tag{8}$$

In similar way V_2 and V_3 can be determined. At the end the total voltage across the dielectric can be obtained:

$$V = \varepsilon_{\max} (r \ln \frac{r_1}{r} + r_1 \ln \frac{r_2}{r_1} + r_2 \ln \frac{r_3}{r_2}) \tag{9}$$

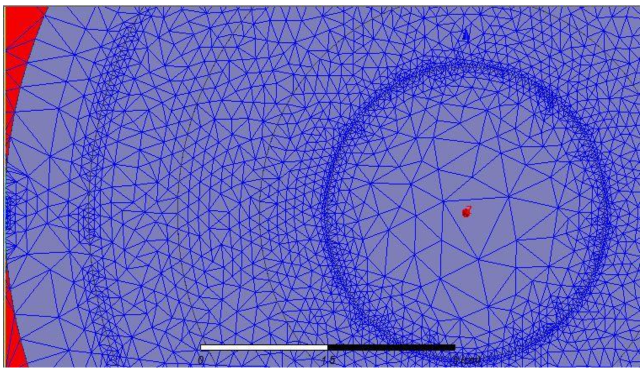
In this method by grading the insulation, without increasing the overall diameter of the cable, the operating voltage increased but the limitation of this method is that, the wide range of permittivity is not possible [1].

III. INSULATION MATERIALS

We use three different set of material: The first set is the compound of Paper, XLPE, XLPE (BPH4201s), second one is Delrin (acetyl resin), PVC, XLPE (BPH4201s) and the third set is Delrin (acetyl resin), EPR, XLPE (BPH4201s).
Paper insulated lead sheathed cables are still used because of their reliability, high dielectric strength, low dielectric loss, and long life [3]. Cross Linked Polyethylene (XLPE) insulation has excellent chemical resistance and is also resistant to cold temperatures. XLPE has vastly take the place of tradition paper insulation in order to prevent the penetration of moisture and also extending the duration of life [4]. XLPE insulation possess a variety of dielectric constant, the XLPE (BPH4201s) Possess a dielectric constant of 2.3 that is suitable for cable insulation [5]. Ethylene Propylene Rubber (EPR) formulations vary from manufacturer to manufacturer. According to the literature, EPR has been in commercial use in high voltage cables rated 150 KV since the late 1970s [6, 7] . one of the common insulating material for low and medium voltage cables are polyvinyl chloride (PVC). PVC is not suitable for high voltage applications because of its high dielectric constant and high loss [8].

IV. SIMULATION RESULTS

This paper presents the results of using the finite element method in the capacitance grading method of high voltage cables by using three different set of insulation materials. Based on the above respects, finite element simulation has been done for each of the high voltage cable with capacitance grading method and different material and electric field in each of the situation has been shown to have a good insight for comparison. As we know capacitance grading method could lessen the stress nearer to the conductor then in the first simulation high voltage cable has been simulated without any grading method and in the other simulation capacitance grading method has been used, and in each of them new set of material used to compare them in the equal situation and reach to the conclusion that which of these set could give the best results. These materials first choose by considering the electro static field equation in the high voltage cable (eq. (7)). Fig. 3 shows the mesh diagram of cable.



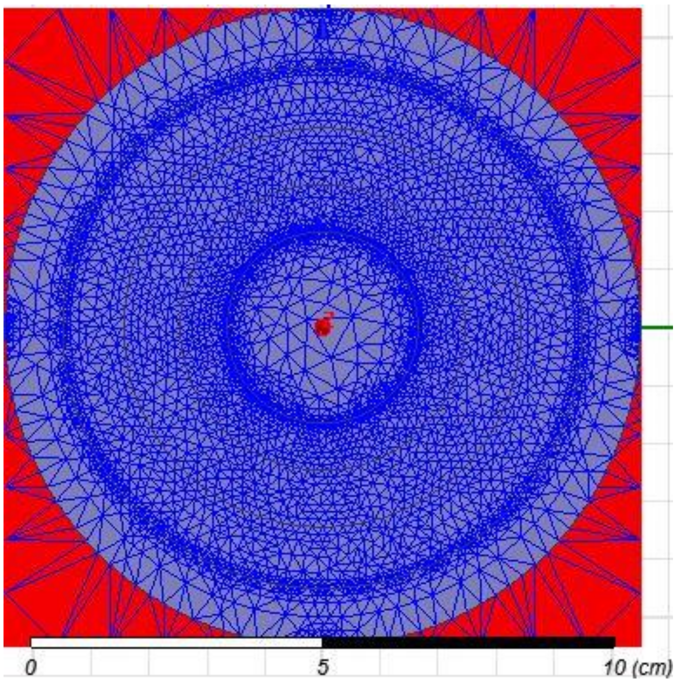


Fig. 3: Mesh diagram of simulated cable

A. *XLPE Cable without Grading Method*

Cable configuration:
Conductor radius (r) = 1.65 cm
Insulation thickness = 2.85 cm
Permittivity of material = 2.5
Conductor voltage (V) = 66 kv

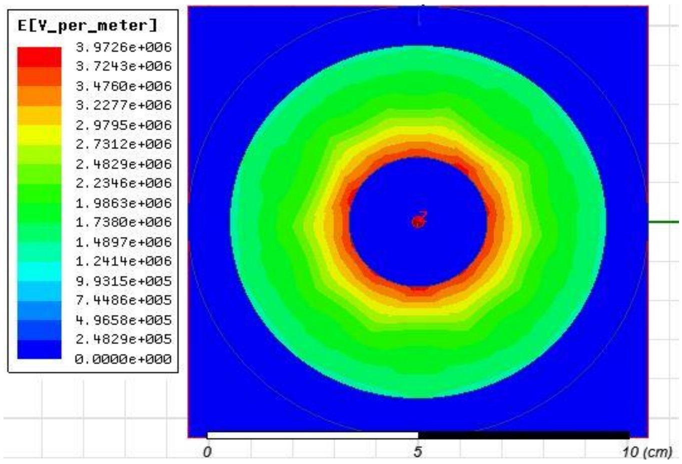


Fig-5: Cable without Capacitance Grading by XLPE Insulation

B. *Cable with Capacitance grading method by set of material 1*

Cable configuration:
Conductor radius (r) = 1.65 cm
Insulation thickness = 2.85 cm
Conductor voltage (V) = 66 kv
$\varepsilon_1 = 3$(Paper)

$\varepsilon_2 = 2.5(\text{XLPE})$

$\varepsilon_3 = 2.3(XLPE\ /\ \text{BPH 4201s})$

r_1=2.463 cm, r_2=3.439 cm, r_3=4.5 cm

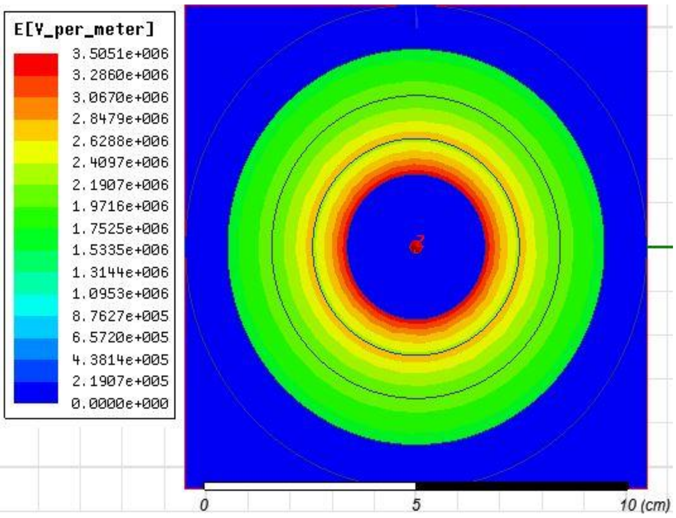


Fig-5: Cable with Capacitance Grading by set of material 1

C. Cable with Capacitance grading method by set of material 2

Cable configuration:
Conductor radius (r) = 1.65 cm
Insulation thickness = 2.85 cm
Conductor voltage (V) = 66 kv

$\varepsilon_1 = 3.7(Delrin, acetyl\ \ resin)$

$\varepsilon_2 = 2.9(PVC)$

$\varepsilon_3 = 2.3(XLPE\ /\ \text{BPH 4201s})$

r_1=2.463 cm, r_2=3.439 cm, r_3=4.5 cm

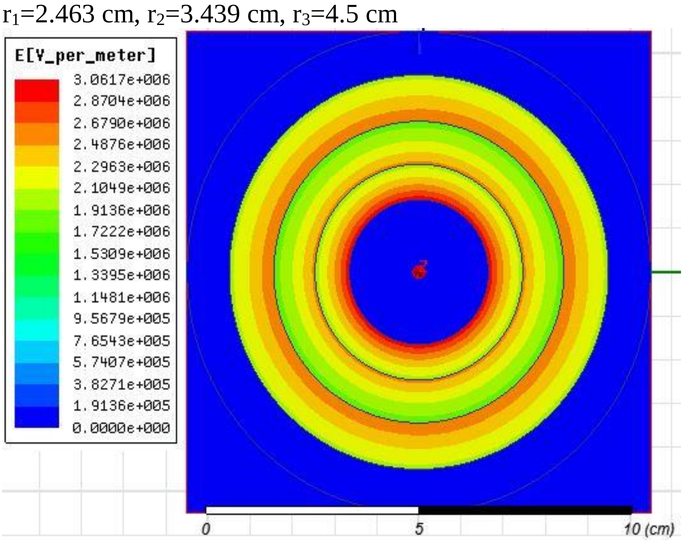


Fig-6: Cable with Capacitance Grading by set of material 2

D. Cable with Capacitance grading method by set of material 3

Cable configuration:
Conductor radius (r) = 1.65 cm
Insulation thickness = 2.85 cm
Conductor voltage (V) = 66 kv

$\varepsilon_1 = 3.7(Delrin, acetyl\ \ resin)$

$\varepsilon_2 = 2.6(\text{EPR})$

$\varepsilon_3 = 2.3(XLPE, \text{BPH 4201s})$

r_1=2.463 cm, r_2=3.439 cm, r_3=4.5 cm

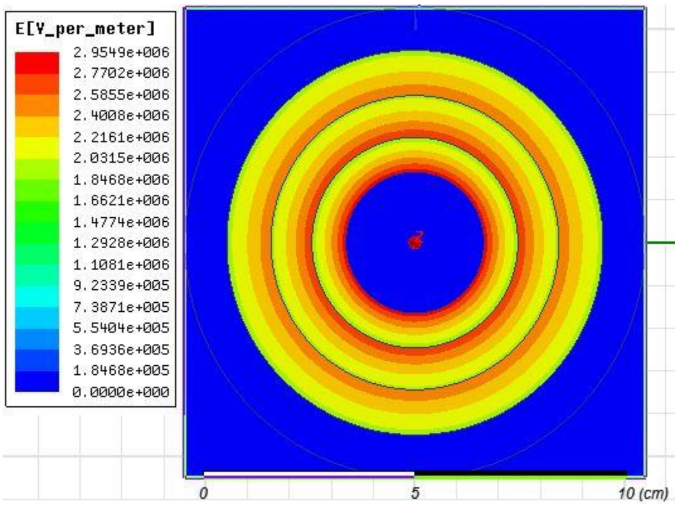


Fig-7: Cable with Capacitance Grading by set of material 3

V. CONCLUSIONS

In this paper, finite element analysis has been done to determine the most suitable material for capacitance grading method for simulated high voltage cable. In order of comparing, each set of the materials has been used in the same conditions. As we know Maximum stress nearer to the conductor is the best factor to determine which set of material has the best efficiency in lowering the stress near to the conductor. Results can be seen in the following table.

TABLE I. PROUTPUT TORQUE OF THE HEYSTERESIS MACHINE BY EACH OF THE MATERIALS

Name	$\varepsilon_{\max}\ () \frac{v}{m}$
Cable without Capacitance Grading by XLPE Insulation	$3.9726 \times 106 \frac{v}{m}$
Cable with Capacitance Grading by set of material 1	$3.5051 \times 106 \frac{v}{m}$
Cable with Capacitance Grading by set of material 2	$3.0617 \times 106 \frac{v}{m}$
Cable with Capacitance Grading by set of material 3	$2.9549 \times 106 \frac{v}{m}$

With respect to the outcome of simulation it`s evident that the use of material from set 3 by using capacitance grading method, the maximum stress nearer to the conductor minimized and the optimum use of insulation material reached. So, the cable of the same size can operate with higher voltage that result in less cost of preparation. It should be noted that determining the best material for this purpose depend on other factors too, such as mechanical and thermal characteristics that could be the subject of further works.

References

[1] Wadhwa, C.L., *Electrical Power Systems*, ed. t. Edition2012: New Age International Publishers.

[2] Thue, W.A., *Electrical Power Cable Engineering*. 2nd Edition ed. INC NEW YORK, ed. M. Dekker2003.

[3] Yaacob, M., L. Sin, and A. Aman. *A new polyvinyl chloride cable insulation using micro and nano filler materials*. in *Power Engineering and Optimization Conference (PEOCO), 2010 4th International*. 2010. IEEE.

[4] Jones, A., B.E. Smith, and D.J. Ward, *Considerations for higher voltage distribution.* Power Delivery, IEEE Transactions on, 1992. **7**(2): p. 782-788.

[5] Nikolajevic, S., N. Pekaric-Nadj, and R. Dimitrijevic, *The influence of some construction parameters on electric stress grading in XLPE cable terminations.* 1997.

[6] Parvopassu, P., et al., *150 KV EPM cable connections between transformers and SF6 insulated switchgear for 5 substations in Rome.* Power Apparatus and Systems, IEEE Transactions on, 1977. **96**(1): p. 178-183.

[7] Chan, J., M.D. Hartley, and L. Hiivala, *Performance characteristics of XLPE versus EPR as insulation for high voltage cables.* Electrical Insulation Magazine, IEEE, 1993. **9**(3): p. 8-12.

[8] Bassiouni, M., et al., *Temperature and electric field effects on the dielectric dispersion of modified polyvinyl chloride.* Materials Letters, 2003. **57**(9): p. 1595-1603.