ANALYSIS OF GRADING TECHNIQUES IN XLPE CABLE INSULATION BY FEM

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Abstract

In today's world, the use of high voltage cables is increased day by day. High voltage cables are used for the transmission and distribution of electric power. XLPE insulation is widely used now a day. Stress distribution in the insulation is the important factor for the determination of the life of the cable. Grading methods like capacitance grading and inter sheath grading are used for the linear stress distribution in the insulation and for other advantages. Finite element method is widely used method for the analysis of the electric stress and field inside the cable insulation. This paper contains the analysis of these two methods in XLPE cable using finite element method.

Keywords: *Capacitance grading, Inter sheath grading, maximum electric stress, Cross linked polyethylene (XLPE).*

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1. INTRODUCTION

In modern times high voltages are used for a wide variety of applications covering the power system, industry and research laboratory. High voltage cables are used for the transmission and distribution purpose of electric power. The transmission of electric power is carried out by the overhead lines as well as underground cables. High voltage cables are used especially for the underground transmission. These cables are laid in ducts or may be buried in the ground. In overhead lines air forms the part of insulation but in underground cables air does not form part of the insulation. So conductor must be completely insulated. Thus cables are much more costly than overhead lines. 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 or electro chemical attack, fire or any other dangerous effects external to the cable [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 vulcanized rubber, Polyvinyl chloride(PVC), Polythene, Impregnated paper etc. are used for the insulation In present scenario, cross linked polyethylene(XLPE) is used increasingly as an insulating material because of its more advantages over other materials. It offers the advantages over other materials as Low dielectric loss, low dielectric constant, high current load, easy installation and accessories, low weight and less maintenance. Cables are must be completely insulated and insulation of the cable is the back bone of the power cable. Its state is usually used to reflect the real age of the cable. The cable insulation has to be continuously exposed the variety of stresses. If this stress exceeds the limit electric field is increased, it results in partial discharge and it can result in breakdown of the insulation. So, analysis of electric stress in the insulation of the cable is very necessary. The maximum electrical stress occurs in the insulation immediately adjacent to the conductor shield and minimum stress occurs at the inner radius of the sheath. There will be a large difference between the maximum and the minimum stress in the insulation, so it means that the dielectric material will not be fully utilized. For uniform stress distribution in the insulation, grading of insulation is used. Two types of grading methods such as capacitance grading and inter sheath grading are used for that. These methods also increase the operating voltage of the cable. Analysis of these two methods is considered in this work for the XLPE cable. Numerical methods like Finite difference method, Finite element method, Charge simulation methods are used for the analysis of the high voltage equipment Finite element technique is considered here for the analysis. Finite Element Method Magnetics (FEMM) software is used for this work. This software uses the finite element method for the analysis.

2. ELECTROSTATIC STRESS IN A SINGLE CORE CABLE

It is known by the theory that in a single core cable of having 'r' radius of conductor and 'R' inner radius of insulation, the potential gradient 'g' at a distance 'x' from the center of the conductor within the dielectric material is

$$g = \frac{q}{2\pi\varepsilon x} = \mathcal{E}_x \quad (1)$$

Where, Ɛx is the electric field intensity,
q is the charge per unit length,
Ɛ is the permittivity of the dielectric material.

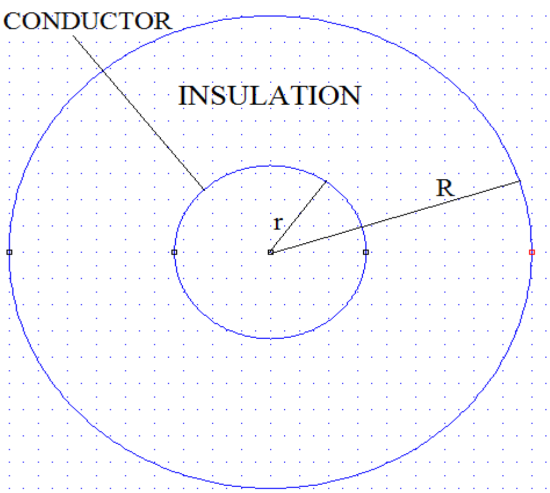

Fig -1: Single Core Cable

So, the potential of the conductor will be,

$$V = -\int_R^r \mathcal{E}_x \cdot dx \quad (2)$$

$$= \int_R^r \frac{q}{2\pi\varepsilon x} \cdot dx \quad (3)$$

Since, $g = \frac{q}{2\pi\varepsilon x} = \mathcal{E}_x$ (From eq. (1)). So,

$$\mathcal{E}_x = \frac{V}{x \log_e \frac{R}{r}} \quad (4)$$

Here, 'x' is the only variable in the equation, the maximum stress in dielectric material occurs at the minimum value of the radius (here, x=r) [1]. So,

$$\mathcal{E}_{max} = \frac{V}{r \log_e \frac{R}{r}} \quad (5)$$

3. GRADING METHODS FOR HIGH VOLTAGE CABLES

In dielectric material, the reduced difference between the maximum stress and minimum stress is obtained by using the grading of cables. So, a cable of same size could be operated at higher voltages or for the same operating voltage a cable of relatively smaller size could be used. Two methods of grading are used: 1. Capacitance grading and 2. Inter sheath grading [5].

3.1 Capacitance Grading Method

In this method of grading, various layers are taken for the insulation material. These layers have different permittivity. 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 [5].

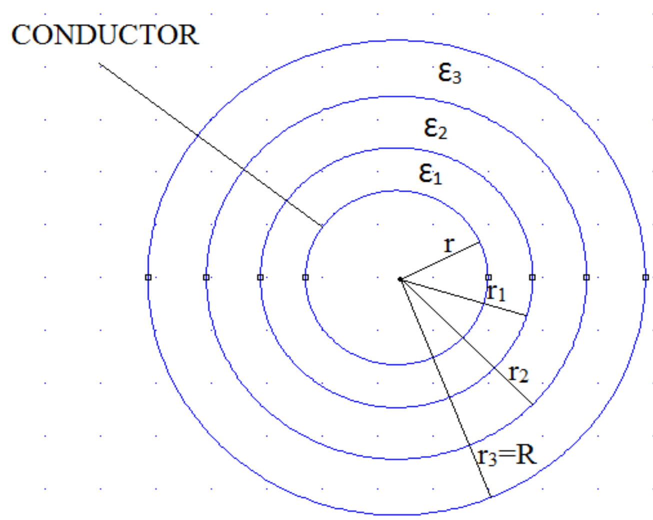

Fig -2: Cable with Capacitance Grading

As shown in Fig.-2, layer of more than one material is used for the capacitance grading method. These layers are of different permittivity. In this figure three layers of permittivity of $\mathcal{E}_1$, $\mathcal{E}_2$, and $\mathcal{E}_3$ are used. These layers are placed at the radius of r_1, r_2 and r_3=R. Let the voltage of the conductor having radius' r 'is given a voltage of V. Then consideration are taken as

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

So,

$$\varepsilon_1 r = \varepsilon_2 r_1 = \varepsilon_3 r_2 \quad (7)$$

And so

$$V_1 = \mathcal{E}_{max}\, r \log_e \frac{r_1}{r} \quad (8)$$

Similarly, V_2 and V_3 can be determined.

Therefore the total voltage across the dielectric can be obtained as follows.

$$V = \mathcal{E}_{max}\left(r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{r_3}{r_2}\right) \quad (9)$$

By grading the insulation, without increasing the overall diameter of the cable, the operating voltage can be increased. The wide range of permittivity is not possible. This is a limitation of this method [1].

3.2 Inter sheath Grading Method

In this method, same insulating material is used in the insulation of the cable. This material is divided into two or more layers by means of cylindrical screens or inters sheaths as shown in Fig.-3. Then these inter sheaths are connected to tapings from the supply transformer and the potentials are maintained at various layers such that each layer of insulation takes its proper share of the total voltage. Since there is a potential difference between the inner and outer radius of each layer, we can treat each section separately as a single core cable [1].

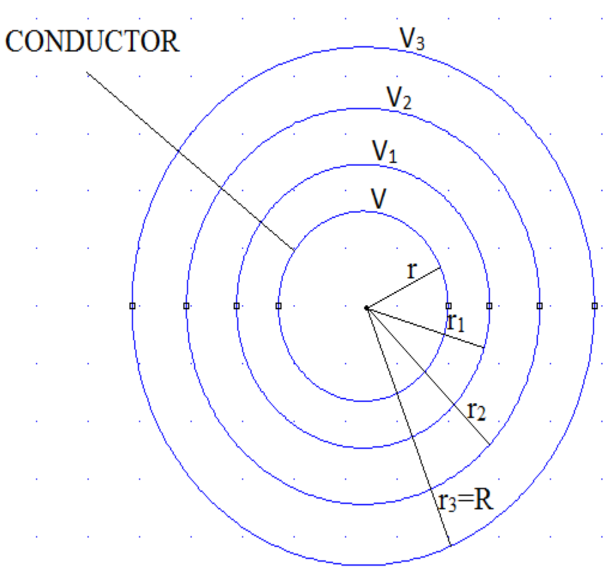

Fig -3: Cable with Inter sheath Grading

If V_1, V_2 and V_3 are the potential difference across the sections of the insulation as sown in figure then,

$$\mathcal{E}_{max} = \frac{V_1}{r \log_e \frac{r1}{r}} = \frac{V_2}{r \log_e \frac{r2}{r1}} = \cdots \quad (10)$$

The cable insulation now consists of a number of capacitors in series formed by the different inter sheaths. So, all potential differences V1, V2 and V3 are in phase.

So, V = V1 + V2 + V3 ….

By simplifying, we can get the equation of the total voltage as,

$$V = \mathcal{E}_{max}\left(r\, ln\frac{r_1}{r} + r_1\, ln\frac{r_2}{r_1} + r_2\, ln\frac{r_3}{r_2}\right) \quad (11)$$

In this method a consideration is taken like $\frac{r_1}{r} = \frac{r_2}{r_1} = \frac{r_3}{r_2} = \alpha$, where α is a positive integer. The limitation of this method is there is a possibility of damage of inter sheath during laying operation and secondly since charging current flows through the inter sheath which in case of a long cable may result in overheating.

Table -1: Comparison between Capacitance Grading and Inter sheath Grading

No.	Capacitance Grading	Inter sheath Grading
1	More than one dielectric material is used.	Same dielectric material is used.
2	Materials having different permittivity are considered for this method.	Potentials at certain radius are held to certain values by using auxiliary transformer.
3	$\mathcal{E}_1 > \mathcal{E}_2 > \mathcal{E}_3$. The dielectric material with highest permittivity should be placed nearest to the conductor and other layers will be in the descending order of their permittivity.	The insulation thickness between successive inter sheaths is constant.
4	Capacitance grading is difficult of non-availability of materials with widely varying permittivity. And with the time, permittivity of the material may change as a result this may completely change the potential gradient distribution and may even lead to complete rupture of the dielectric material.	There is possibility of damage of inter sheath during laying operation and since charging current flows through the inter sheath which in case of a long cable may result in overheating.
5	In capacitance grading, materials with different permittivity are used. So, it is not so easy to get the different materials with different permittivity. So, material cost will be higher than without grading method.	In inter sheath grading method, thin metal sheaths are used and also an auxiliary transformer is used. So, the cost of metal sheaths and the cost of auxiliary transformer are added. So, overall cost will be high.

4. FINITE ELEMENT METHOD FOR ANALYSIS

Electric fields or stress calculation requires the solution of Laplace's and Poisson's equations with the boundary conditions satisfied [2]. The solution of these equations can be done by either analytical or numerical methods. In many cases, the situation is so complex that the analytical solutions are difficult or impossible. The analytical method takes much time for solving the equations. So, numerical methods are commonly used for engineering applications. Some widely used numerical methods are: Finite Difference Method (FDM), Finite Element Method (FEM), and Charge Simulation Method (CSM) [4]. Among these methods Finite Element Method is most suitable for its some advantages [2]. So, this method is used here for the calculation of the electric stress. For almost all fields of engineering, this method is useful. This method divides the whole region into small finite elements and calculates for each element and so whole region is considered. Finite element method is easier to apply and requires less time for computation. It is capable of working with regular or irregular geometries. This method is best suited for the electro static problems. Various types of computer software are also available those are using finite element method for solving various types of problems. So, for the electric stress analysis Finite element method is considered here for the analysis. Finite Element Methods Magnetics (FEMM) software is used here for the calculation [3].

5. SIMULATION WORK

5.1 XLPE Cable without Grading Method

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

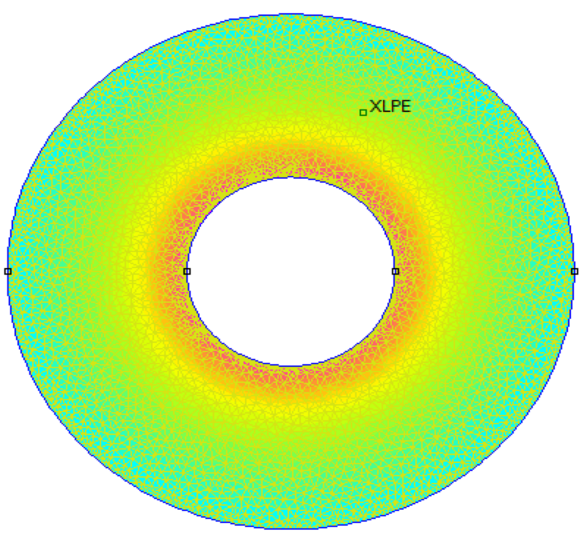

Fig -4: XLPE Cable

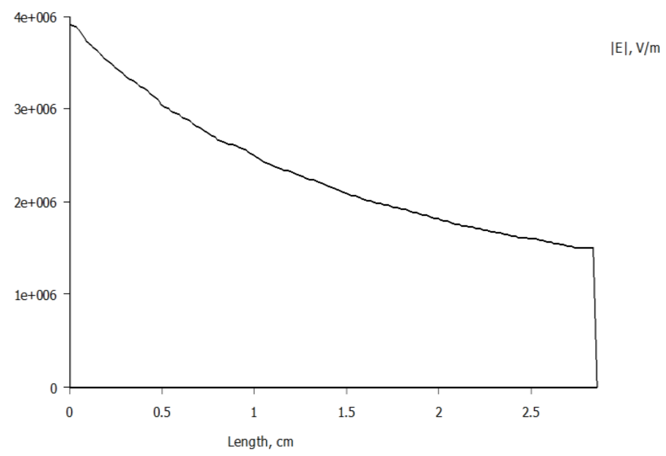

Fig -5: Stress Distribution in XLPE Cable Insulation

5.2 XLPE Cable with Capacitance Grading Method

Cable Configuration:
Conductor radius (r) = 1.65 cm
Insulation thickness = 2.85 cm
r_1 = 2.463 cm
r_2 = 3.439 cm
r_3 = R = 4.50 cm
ε_1 = 3 (Paper)
ε_2 = 2.5 (XLPE)
ε_3 = 2.3 (Polyethylene)
Conductor Voltage (V) = 66 kV
$\varepsilon_1 r_1 = \varepsilon_2 r_2 = \varepsilon_3 r_3$

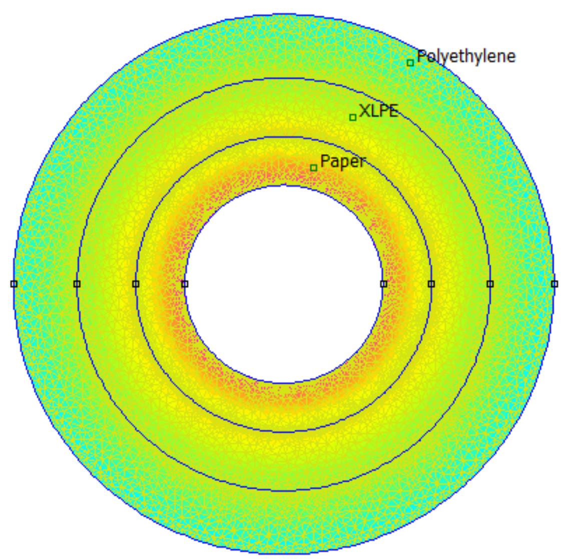

Fig -6: XLPE Cable with Capacitance Grading

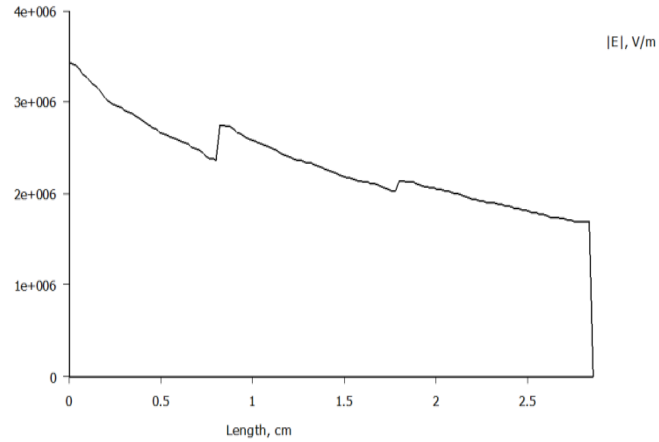

Fig -7: Stress Distribution in XLPE Cable Insulation with Capacitance Grading

5.3 XLPE Cable with Inter sheath Grading Method

Cable Configuration:
r = 1.65 cm
r_1 = 2.6 cm
r_2 = 3.55 cm
r_3 = R = 4.50 cm
V_1 = 66000 V
V_2 = 44000 V
V_3 = 22000 V
Ɛ = 2.5 (XLPE)

$$\frac{r_1}{r} = \frac{r_2}{r_1} = \frac{r_3}{r_2} = \alpha = 1.5757$$

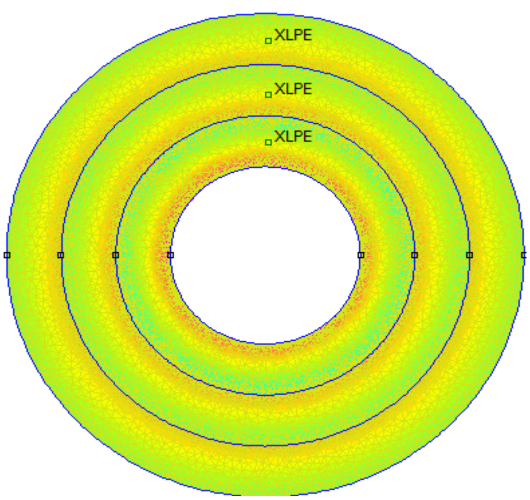

Fig -8: XLPE Cable with Inter sheath Grading

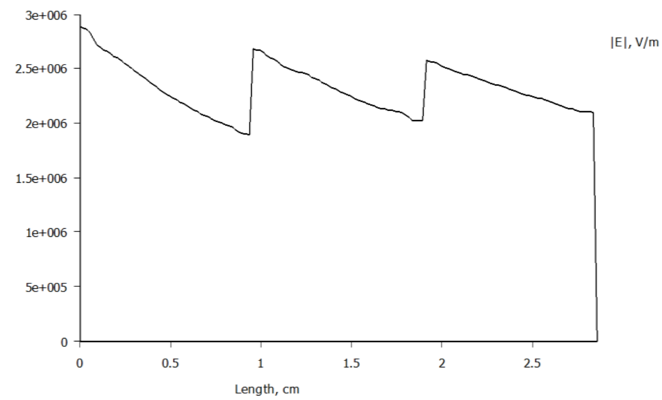

Fig -9: Stress Distribution in XLPE Cable Insulation with Inter sheath Grading

6. RESULTS AND DISCUSSION

6.1 XLPE Cable without Grading Method

Maximum stress nearer to the conductor is
$Ɛ_{max}$ = 3.91 x 106 V/m.

6.2 XLPE Cable with Capacitance Grading Method

Maximum stress nearer to the conductor is

$$Ɛ_{max} = 3.42 \text{ x } 106 \text{ V/m.}$$

Maximum Safe Working Voltage is

$$V = Ɛ_{max} [r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{R}{r_2}]$$

V = 82560 V.

6.3 XLPE Cable with Inter sheath Grading Method

Maximum stress nearer to the conductor is

$Ɛ_{max}$ = 2.88 x 106 V/m.

Maximum Safe Working Voltage is

$$V = Ɛ_{max} [r \ln\frac{r_1}{r} + r_1 \ln\frac{r_2}{r_1} + r_2 \ln\frac{R}{r_2}]$$

V = 103104 V.

In case of XLPE cable without using any grading method, the maximum stress nearer to the conductor is very higher compared to other methods. So, the possibility of breakdown of insulation is higher. The difference between the maximum and minimum stress is very large. It can be easily seen by the Fig.-5. This difference can be minimized in the capacitance grading method and Inter sheath grading method as shown in

Fig.-7 and Fig.-9 respectively. In capacitance grading, the maximum stress nearer to the conductor is lower than the previous case and the maximum safe working voltage is around 82 kV for a 66 kV cable. In inter sheath grading, the maximum stress nearer to the conductor is very lower than other two cases and maximum safe working voltage is around 100 kV for a 66 kV cable is obtained by the analysis. So, by using the grading methods the cable of same size can be operated at higher voltages. By the analysis of the results it can be seen that the inter sheath grading method is better than the capacitance grading method.

7. CONCLUSIONS

The grading methods like capacitance grading and intersheath grading in a high voltage cable can be analyzed by finite element method. In XLPE cable without using any grading method, the maximum stress nearer to the conductor is very higher. So, possibility of breakdown of insulation is higher. By using the grading methods, the maximum stress nearer to the conductor can be minimized and the optimum use of insulation material can be obtained. The cable of same size can be operated at higher voltages. The practical implementations of these grading methods are is hard because of some limitations of these methods but this work will help the engineers to work forward in this direction.

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BIOGRAPHIES

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