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Research Article

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Design and Analysis of High Voltage Insulator for Transmission Lines

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Abstract Reliable high voltage insulators are required for efficient power transmission. This requirement necessitates careful design of insulators that can support high electric field. High values of electric field are often responsible for audible noise, electromagnetic pollution, partial discharges and premature aging and degradation of insulator system. Unevenly distributed, electric field is strongest at the sheds nearest to the endpoints of insulators. Hence, under overvoltage condition, a phenomenon known as flashover occurs at these points. To address this problem, metal grading rings can be installed around the sheds at both endpoints, to reduce the non-uniformity of the electric field and improve the flashover voltage condition. This paper analyzed the electric field distribution along insulator surface with and without grading rings. From the results of the analysis, the electric field distribution on the surface of the insulator was observed to be more evenly distributed when grading rings were installed than when they were not. In this way, the grading rings help the insulator to withstand a higher overvoltage and thus improve the external insulation of the power system.

Keywords Grading ring, insulator, power, transmission, overvoltage

Introduction

In electric power transmission, the role of high voltage insulators is very crucial in preventing the flashover due to the sudden rise of voltage, as well as, protecting supporting towers from high voltage lines (Singh and Kushwaha, 2014). High voltage insulators are also employed to support the weight of suspended transmission conductors. The danger of poorly designed high voltage insulator with characteristics not matching the service requirements can be very grave (Vosloo et al, 2022). Insulators should be designed to reliably withstand, naturally induced lightning, system switching impulse over-voltages and adverse weather conditions. In the design of high voltage insulators, a major design consideration is the properties of the insulating materials to be used. The material must possess an excellent dielectric property with capability to withstand high electrical stress and severe environmental effects such as radiation, contamination, lightning over-voltages etc. Additional capabilities of the insulator include sufficient tensile, compressive and cantilever strength to support the loads applied and maintain its mechanical integrity over the life of the transmission system. Typical insulator materials include: porcelain, toughened glass, epoxy resin, polymer composites.

Porcelain remains a commonly used material for high voltage insulation. Electrical porcelain is made from clays and inorganic materials which, after going through the furnace, consists of various oxide and silicate crystals in a glassy matrix. When fully vitrified, that is, converted into glass in the furnace, it is completely impervious to moisture. The insulators are usually glazed to provide a smooth surface to inhibit the adherence of contaminants and to facilitate natural washing by rain. Toughened glass is utilized as high voltage insulators in order to meet the mechanical strength requirement. The toughening process involves the accelerated cooling of the insulator surface while the inner regions cool more slowly. The differential rate of solidification creates a permanent compressive pre-stressing of the outer layers to effectively prevent the formation of surface micro-cracks and inhibit crack propagation.

Epoxy resin was first employed for indoor insulation. It is, however, an organic material and can suffer from degradation owing to surface partial discharge activity. This must be carefully considered in the design of insulators intended for use in highly polluted environments. Important features of resins include the capability to be molded in many different forms to suit a variety of applications. Polymer composites refers to insulators with a fibre glass core, which provides the mechanical strength, covered by a housing to protect the core from the environment and to yield the required electrical characteristics. A wide variety of constructions and materials are used in the production of composites. The two main families of housing materials commonly used include those based on ethylene propylene diene monomer (EPDM) and those which are silicon based. EPDM has a high mechanical strength and tracking resistance. The silicones, however, have a higher resistance to ultraviolet degradation and have the unique property of maintaining a hydrophobic (water repellent) surface even when severely contaminated (Vosloo et al, 2022).

High voltage transmission lines are required for electrical energy transportation from generation to consumption. This requirement necessitates careful design of power systems that can support high electric field. It should be noted that high levels of electric field are, more often than not, responsible for audible noise, electromagnetic pollution, partial discharges and premature aging of insulation (Al-Gheilani, et al, 2017). Additionally, high electric field on transmission lines produces discharges on high voltage insulator surface which can degrade the insulation materials. The factors upon which the distribution of electric field within and on the surface of insulators depend include the voltage level, insulator design, tower configuration, corona or grading rings, phase spacing, etc. (Philips et al, 2015, Ilhan and Ozdemir, 2011, Anbarasan and Usa, 2012).

Overview of Grading Rings

The two ends of insulators, especially the high voltage end, are seriously distorted on electric field, and corona discharge is easy to occur and cause the electric erosion of insulators. Hence, the need to deploy grading ring at the high voltage end and ground end. The corona characteristic of the grading ring has important relationships with its structure size which should be designed to control the electric field strength of grading rings within a reasonable range. Grading rings encircle insulators rather than conductors. Their main purpose is to reduce the potential gradient along the insulator. They help in equalizing the potential distribution over a string of suspension insulator. Hence, they improve the string efficiency and prevent insulation breakdown. Grading rings also serve to prevent corona discharge that occurs in high-voltage power lines by nullifying the effect of shunt capacitance of string insulator.

To ensure the durability of high voltage insulators used in power transmission lines, grading rings are installed at the end of the insulator next to the high voltage conductor. This is to reduce the electric field gradient at the ends. Consequently, achieving a more evenly distributed potential gradient along the insulator. The design of the grading rings is such that they encircle the high voltage insulators. This is because since under normal circumstances, the potential gradient or electric fields across the insulator is non-uniform and the strongest potential gradient is often observed at the endpoints of the insulators towards the high voltage transmission line. Due to this continuous grading at high voltage, the insulators near the high voltage conductor easily weakened and breakdown. Therefore, the advantages of installing grading rings to encircle the endpoints of the insulators include:

i) Reduction of potential gradient along the insulator;
ii) Prevention of electrical insulator breakdown;
iii) Creation of a uniform distribution of voltage; and
iv) Reduction of stress, deterioration and aging effects on the insulator.

Electric field is unevenly distributed on the surface of high voltage insulators. It is strongest at the sheds nearest to the endpoints. Hence, under an overvoltage condition, a phenomenon known as flashover occurs at these points. To address this problem, metal grading rings can be installed around the sheds at both endpoints, to reduce the non-uniformity of the electric field and improve the flashover voltage condition. The goal of this paper is to study the electric field distribution along the surface of high voltage insulators with and without grading rings.

Literature Review

In recent years, several research efforts have been focused on the electric field optimal distribution along high voltage insulators in order to reduce degradation, breakdown and flashovers. Different methods and designs considerations have been proposed.

Heshmatian, et al (2016) reported the study of corona ring design for a 400kV composite insulator with respect to electric field and voltage regulation along the insulator. The analysis results obtained through simulations of the effects of the corona ring's design parameters on electric field and overvoltage level. It was observed that composite insulators are more widely utilized in power systems than non-ceramic insulators and that their effective use entails adjusting the voltage and electric field distribution along the insulator surface (Al-Gheilani, et al, 2017).

Singh, et al (2014) observed the crucial role played by high voltage insulators in the transmission of power, particularly, in protecting the supporting towers from the high voltage lines and prevention of flashover. The effects of pollution on the insulator on the critical flashover voltage was analyzed. From the analysis of the energy and transmission line, a new equation describing the flashover voltage and its effect on the insulator was developed.

M'hamdi, et al (2016) proposed an improvement to electric field and potential distributions using corona ring at the high voltage end in order to minimize corona discharges on transmission line composite insulator. The study of the performance of high voltage insulator strings on designs and locations of corona ring, the effects of the corona ring radius, the ring tube radius and the ring vertical position was conducted. 3D finite element analysis method was used to compute the electric field. Optimization of corona ring design was realized by the objective function linking the electric field strength to the corona ring structure parameters.

Misha (2021) presented the condition monitoring techniques and test methods for evaluating four design parameters of insulator. These include: hydrophobicity, the resistance against corona discharge, flammability and weathering. It was noted that the organic polymeric insulator housing degrades gradually with time and achieving durability of service is a major problem.

Morocutti, et al (2012) investigated the economic performance of high voltage porcelain post insulators. It was observed that the objective of insulator design is to develop a technically and economically optimized HV component, with a high grade of reliability over decades. It was noted the with possible optimization of certain design parameters such as arcing distance, length of the insulator, mechanical strength and stiffness, core diameter, form factor and shed profile, material and cost can be saved.

Murawwi, et al (2013) studied the optimization of corona ring design for a 400kV non-ceramic insulator. Two parameters were changed during the study which are: the ring diameter (R) and the diameter of the ring tube (r). The optimization problem was solved and the reduction of electric field value was achieved.

Xie and Peng (2012) reported a finite element method for modeling of three phase power system and simulated the potential and electric field distributions of porcelain insulators on a 750-kV compact double-circuit transmission line. In consideration of the mutual effects among the three phases, the structural parameters of the grading ring were optimized to reduce the voltages and electric field intensities on the insulators. The results showed that the significant mutual effects among the three phases need to be taken into account in the design and testing of the insulators and fittings.

Usa, et al (2012) presented the performance analysis of non-ceramic insulators for better energy efficiency on transmission lines. It was observed that achieving a compact and reliable design of electrical insulation, better and smart insulating materials are urgently needed on high voltage transmission, particularly, non-ceramic insulators rather than classical ceramic insulators. Non-ceramic insulators were observed to withstand adverse environmental conditions, exhibits superior resistance to shock loads due to conductor or hardware failure.

Nageswara, et al (2016) presented a performance analysis of electric field for 400 kV silicone composite insulator. It was observed that in electrical power system, high voltage insulators are necessary for consistent performance since they are exposed to both mechanical and electrical stresses. Thus, the performance analysis of polymer insulators is desirable before adopting polymer insulation for new transmission lines.

Theoretical Concepts

A major performance measure for insulators is the leakage current. It is to be noted that at certain threshold value of leakage current, the probability of flashover is very high (Vosloo et al, 2022). This value has been experimentally defined as the amplitude of the leakage current peak of the half cycle immediately preceding flashover (I_{max}):

$$I_{max} = \left(\frac{S_{CD}}{15.32}\right)^2 \text{ in ampere} \tag{1}$$

With S_{CD} being the specific creepage distance, given by:

$$S_{CD} = \frac{L_{CD}}{U_m} \quad (2)$$

Where:
L_{CD} = total insulator creepage distance, in mm
U_m = maximum rms system voltage phase to phase, in kV.
The main factor determining the magnitude of the insulator leakage current and insulator flashover is the surface layer resistance. The surface layer resistance (R) for an ideal case of a uniform electrolytic pollution layer on an insulator is given by:

$$R = \frac{\rho l}{A} \quad (3)$$

Dividing the surface electrolytic pollution layer into small incremental sections dl along the insulator creepage path LCD and using the basic formula, the resistance dR_{pol} of the incremental section is given by:

$$dR_{pol} = \frac{\rho_{pol}.dl}{A_{pol}} \quad (4)$$

Substituting A_{pol} and integrating both sides result in:

$$R_{pol} = \frac{\rho_{pol}}{h_{pol}} \int_0^L \frac{dl}{\pi.D(l)} \quad (5)$$

Also,

$$\sigma = \frac{1}{\rho_{pol}} \quad (6)$$

$$\sigma_s = \sigma.h_{pol} \quad (7)$$

Where:
σ = volume conductivity of the insulator electrolytic pollution layer, in µS/mm
σ_s = surface conductivity of the insulator electrolytic pollution layer, in µS.
Substituting of Equations (6) and (7) into Equation (5) leads to

$$R_{pol} = \frac{F}{\sigma_s} \quad (8)$$

Where: F is defined as the form factor of the insulator and given by:

$$F = \int_0^L \frac{dl}{\pi.D(l)} \quad (9)$$

Assuming that the effects of dry bands and spark/arc resistance are negligible. When the insulator surface resistance (R_{pol}) reaches a critical low value, the critical flashover voltage of the insulator in kV is given by:

$$V_c = k_1.10^{-3}.\left(\frac{R_c.10^6}{L_{CD}}\right)^{k_2}.L_{CD} \quad (10)$$

Where:
V_c = critical insulator flashover voltage, in kV peak
R_c = critical insulator resistance in MΩ, the critical value Rpol
k_1 = 7.6
k_2 = 0.35.
It is therefore clear that the power frequency pollution flashover performance of an insulator is dependent on the surface resistance (R_{pol}) of the electrolytic pollution layer.
The electric potential V is defined, under static conditions by:

$$E = -\nabla V \quad (11)$$

Using this together with the constitutive relation

$$D = \varepsilon_r \varepsilon_0 E \quad (12)$$

Setting the free space charge to zero, the Gauss' law can be rewritten as a variant of Poisson's equation

$$-\nabla.(\varepsilon_r \varepsilon_0 \nabla V) = 0 \quad (13)$$

where ε_0 is the permittivity of vacuum and ε_r the relative permittivity of the material.

Methodology

The methodologies employed in the study of the electric field distribution in the high voltage insulators include: finite element modeling and simulation of the insulator with and without grading ring; definition of insulator material properties; boundary condition definition and study of electric field distribution. Figure 1 shows the high voltage insulator with grading rings at the endpoints.

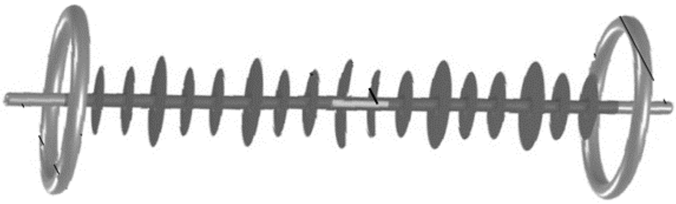

Figure 1: High voltage insulator with grading rings

The model geometry definitions and material properties are shown in Tables 1 and 2.

Table 1: Model Geometry

SN	Material Name	Relative Permittivity
1	Overvoltage amplitude	500kV
2	Thickness of grading ring	30mm
3	Diameter of grading ring	350mm
4	Distance of grading ring from the endpoint	150mm

Table 2: Material Property

SN	Material Name	Relative Permittivity
1	Core Rod	5
2	Weather Shed	3
3	Air	1

Analysis of electric field distribution along the surface of high voltage insulators was conducted under high voltage condition (500kV). Many other studies in literature employed modeling parameters such as the electric field, current density, and pollution layer conductance (Nazir et al, 2020). However, the effect of grading rings is taken into consideration with specific thickness and diameter values of 30mm and 350mm respectively. The distance of grading rings from insulator endpoints was set at 150mm. The system was modeled and the electric field distribution on insulator surface was analyzed.

Results and Discussion

Figure 2 depict the modeling results of high voltage insulators for the electric field distribution on the surfaces with and without grading rings. The flashover voltage of the insulator is mainly determined by properties of the vertical component of the tangential electric field. Figure 2 compares the vertical component of the tangential electric field along the first six sheds from the line end. It is shown that the inhomogeneity and the maximum values of the field are greatly reduced with the installation of the grading rings.

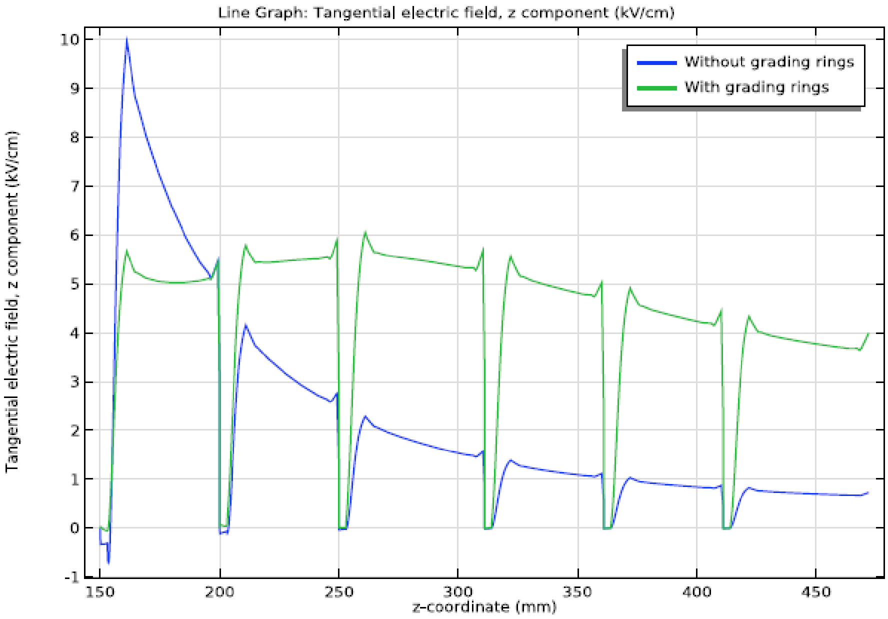

Figure 2: Electric field distribution along the surface of the insulator sheds from the line end without and with grading rings

The maximum value of the tangential electric field was observed to be around 10kV/cm and 6kV/cm for insulator without grading rings and with grading rings respectively. Additionally, the electric field distribution on the surface of the insulator was observed to be more evenly distributed when grading rings were installed than when they were not. In this way, the grading rings help the insulator to withstand a higher overvoltage and thus improve the external insulation of the power system.

Conclusion

In conclusion, high voltage transmission lines are required for electrical energy transportation from generation to consumption. This requirement necessitates careful design of insulators that can support high electric field. It should be noted that high levels of electric field are, more often than not, responsible for audible noise, electromagnetic pollution, partial discharges and premature aging and degradation of insulator system. Electric field is unevenly distributed on the surface of high voltage insulators. It is strongest at the sheds nearest to the endpoints. Hence, under overvoltage condition, a phenomenon known as flashover occurs at these points. To address this problem, metal grading rings can be installed around the sheds at both endpoints, to reduce the non-uniformity of the electric field and improve the flashover voltage condition. This paper analyzed the electric field distribution on surface of insulators with and without grading rings. From the results of the analysis, the electric field distribution on the surface of the insulator was observed to be more evenly distributed when grading rings were installed than when they were not. In this way, the grading rings help the insulator to withstand a higher overvoltage and thus improve the external insulation of the power system.

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