Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 110 (2017) 95 – 100

Energy Procedia

1st International Conference on Energy and Power, ICEP2016, 14-16 December 2016, RMIT University, Melbourne, Australia

Stress control methods on a high voltage insulator: A review

Ammar Al-Gheilani*, Wayne Rowe, Yongxiang Li, Khoi Loon Wong

School of Engineering, RMIT University, Melbourne, VIC 3000, Australia

Abstract

This review article provides a comprehensive overview of the many factors that may enhance the level of electric field along the high voltage (HV) insulators, review of existing stress control methods and new promising technologies in stress control using advanced materials. In the first section, the factors that could possibly raise electric field stress around the HV insulators are discussed. Localized field enhancement, especially in the area close to the high voltage potential and ground potential will accelerate the degradation and subsequently causing pre-mature failure of the insulating material. Other than electrical field enhancement, mechanical stresses and environmental impacts also affect the performance of the high voltage overhead insulators. Consequently, multi-facet approaches are required to improve the HV insulators performance and reliability over their service life. In the second section, the existing stress control methods that include corona ring, combined insulation assembly and end-fitting design are reviewed. In the final section, a new promising technology of stress control using field grading methods (resistive and capacitive) is presented. Field grading material (FGM) is a new technology where the inorganic fillers are added to the insulation host matrixes to enhance the mechanical and electrical performance of the insulation. FGM shows superior electrical performance compared to the conventional insulation material, which is also discussed in this paper.

Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.

Keywords: high voltage insulator; Stress control; Polymeric insulator; Field grading material;

* Corresponding author. Tel.: +61399252101.
E-mail address: s3223610@student.rmit.edu.au

Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.
doi:10.1016/j.egypro.2017.03.112

1. Introduction

A high voltage overhead insulator is providing isolation path, which insulates the live conductor from the electrical transmission and distribution tower. The HV insulators play vital parts in the transmission and distribution networks, which are used to transmit the electrical power to the consumers through the power system. The commercial needs for the high voltage lines started in 1880's, which is the most cost effective technique to transmit the electrical energy over long distance. Since then, larger and more efficient overhead insulators are required to carry and support high voltage lines. The primary function of the high voltage insulators is to separate the live conductors from each other and from the utility pole. They also provide mechanical support for the high voltage insulator [1].

The glass and porcelain insulators have been used in the power utilities for over one century. These insulators have good resistance against environmental aging and they have been used in a wide range of applications. However, due to the hydrophilic surface of the ceramic material, the pollution performance of these insulators is poor. In the 1960's, the polymer insulators, which are also referred to as composite or non-ceramic insulators, are introduced to the market. The non-ceramic insulators show many advantages over the conventional insulator, which make them more preferable than the porcelain and glass insulators. Furthermore, they have better hydrophobicity, lower leakage current, resistance to vandalism and higher mechanical strength [2].

The polymer insulators have some weakness, which must be taken into consideration during the insulator design. The life expectancy of the composite polymeric insulators is difficult to estimate and the reliability of the polymer materials is unknown. Based on field data, the polymer materials are susceptible to degradation under electric field stress, which may lead to early failure. Hence, the performance of the polymeric dielectrics must be tested and the electric field distribution along the overhead insulator must be studied. The existence of intermediate hardware also created nonlinearity of the electric field on the polymeric insulators when compared to conventional insulators. Hence, composite insulators have a certain level of stress field grading. Very high level of electrical field stress can cause electromagnetic pollution, perceptible noise, partial discharge for the system and accelerated aging of the insulator [3].

The fundamental of the electric field and the techniques of controlling the electric field strength and distribution must be considered, in order to understand the behavior of the insulation materials under the influence of AC/DC electric field. Electric field can be described as the electric force experienced by charge at any given point in the vicinity of the field. The electric force of the electric charge rises when the electric field is applied. Insulators, which are also called dielectrics, are materials where charges are not free to move through their body. However, there is no perfect dielectric because the dielectric consists some conductivity. When a high level of electric field applied over the dielectric, the insulator is heated up and conductive current will begin to flow. Hence, insulators must be tested to identify their withstand voltage level which is called "standard insulation level". If the insulation material exposes to high electric stress over its critical electric field strength, then insulation failures in the form of corona, ionization, or electric arc will occur. These partial discharge activities will lead to an early breakdown. Electric field distribution also depends on many parameters including voltage waveform, insulator design, shape and materials of the electrodes, tower configuration and atmospheric conditions and pollution [4].

The following sections of this manuscript identify the factors that may increase the electric field strength along the high voltage (HV) insulators. The existing stress control methods and new technologies in stress control using advanced materials are discussed in more details.

2. Failure Factors of Insulation

The HV insulators are located at the top of the utility poles. After years of service in the field, the performance of the dielectric will degrade over time. For porcelain and glass insulators, defects such as cracks, surface tracking and structural damage will start to occur within the insulation materials. For the composite insulator, exposure to UV radiation may accelerate the aging of the polymer housing, which may lead to brittle and crack in the insulation structure.

As a result, the partial discharge will occur and leakage current will flow between the line conductor and the power pole through and over the surface of the insulator. Partial discharge (PD) of the high voltage overhead insulator can be defined as local electric stress on the surface of the insulator or inside the insulation materials. Chemical reactions, light, emission of sound and heat are the features of the partial discharge activities. Partial discharge constitutes one of the main causes of the early dielectric breakdown [5].

2.1. Effect of pollution

Pollution is one of the major issues that affect the performance of the HV insulators throughout their service life. Gradual increase of the pollution layer has a significant impact on the electrical performance of the HV insulators. The pollution layer along the insulator surface distorts the electric field distribution. Moreover, leakage current may flow along the creepage distance. Figure 1a reveals the electric field distribution along the leakage path on dry-clean and wet-polluted insulator surface [6].

There are three major types of non-uniform pollution along the overhead insulator, which are transversal, longitudinal periodic and longitudinal non-periodic. Boudissa et al. have investigated the impact of non-uniform pollution on HV insulators flashover under AC voltage [7]. Different theoretical models have been developed to study the behavior of pollution layer along HV insulators. For instance, Marich et al. have conducted the experimental study to show the differences between disc models and open models through the total resistance recorded [8].

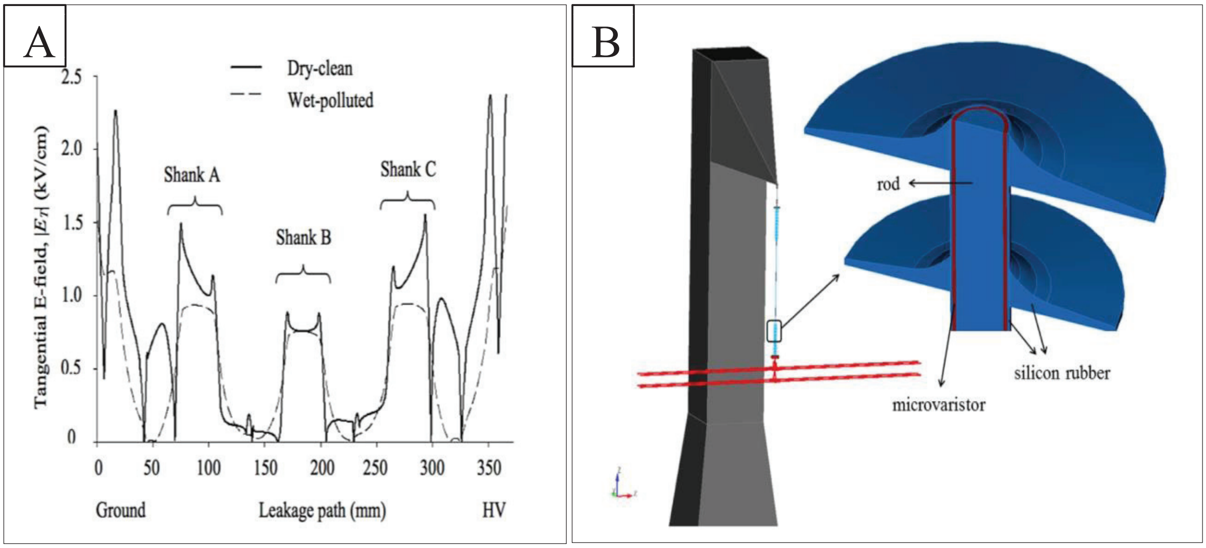

Fig. 1. (a) Electric field distribution along the leakage distance [6]. (b) A section of insulator with FGM material layer [9].

2.2 Effect of atmospheric conditions

Rainfall has a significant impact on the electrical performance of HV insulators. Study of electric field along a porcelain post insulator shows a small increase in discharge activities and field enhancement along the creepage path due to the precipitation rate of the rain lower than 1.6mm/min and conductivity less than 250 μS/cm [10]. Rainfall may lead to the loss in hydrophobicity, which consequently increases the flow of leakage current over the insulator surface. Study on the impacts of rain condition on the composite insulator in three different positions (horizontal, vertical and inclined) was done in [11].

Effect of wind velocity and wind direction on voltage distribution along string insulators has been investigated using a newly proposed voltage distribution model. Simulation results showed that the voltages through insulator body and sheds can be affected by the wind speed and wind direction [12]. Gao et al. have studied flashover voltage over composite insulators under AC voltage in wind tunnel. The results revealed that flashover voltage increased with wind velocity. Interestingly, however, the wind helps to dry out wet contamination over the insulator, which may reduce the risk of flashover [13].

3. Existing stress control methods

The electric field stress along HV insulators must be controlled and kept below the maximum level for three main reasons:
• To prevent the internal partial discharge inside the insulator and the weather sheds.
• To reduce the partial discharges on the surface of the insulator.
• To prevent the corona discharges which may occur on the insulator and the associated metallic parts.

Existing stress control methods that are applied to HV insulator include corona ring, combined assembly and optimised end-fitting design.

3.1. Corona ring

Corona may occur on insulator surface due to the accumulation of water drop or at triple junctions where electric field enhancement exists. This may lead to accelerated degradation, permanent loss of hydrophobicity and finally early breakdown. In order to reduce electric field stress at end fitting, a metal ring called corona ring (CR) is used. The smooth surface of corona ring distributes the electric field to reduce field stress near end fitting. There are many CR parameters that should be considered during the design. These parameters include: the radius of the ring tube, the radius of the corona ring and the vertical position of the ring [14].

M'hamdi et al. have used particles swarm optimization (PSO) with a dynamic population size to identify the optimal design parameters of CR on HV insulators. Normally, corona rings are installed at both ends of the insulator (HV and ground end) in voltage level above 345 KV. However, only one CR is required at HV ends in voltage level between 230 and 345 KV. CR for voltage below 230 KV is seldom used. Moreover, the grading ring may be added to the corona ring for further reduction in electric field stress and to prevent radio and television interference and audible noise. Until now, there is no exclusive standard for the design and location of grading and corona rings [15].

3.2. Combined Insulator assembly

Due to the structure design of non-ceramic insulators, high electric field enhancements always exist at both ends of the insulator. This may lead to partial discharge at the triple junctions. Hence, Qing et al. have proposed a new optimization structure, which combined the use of non-ceramic insulator and glass insulator. The proposed combined assembly configuration has been tested under several voltage levels and the electric field strengths have been reduced in all cases [16]. As shown in the literature, there is no specific standard associated with the installation of corona ring and improper installation can lead to further enhancement in the electric field distribution. Therefore, the combination of three different control methods (composite insulator, porcelain units and grading rings) has been proposed, in order to achieve better electric field uniformity. This proposed method revealed that the electric field strength could be decreased by nearly 40% [17].

3.3. Optimised end-fitting design

Additional mechanical parts such as corona ring or ceramic units may result in increase in the overall weight of the insulation. Careful end-fitting design can avoid additional weight and provide self-grading mechanism. Small radius elements, sharp edges and needle points must be avoided in insulator design. Hrastnik et al. proposed a new design of upper-fitting for post insulator. The normal metal upper-fitting was replaced by insulation upper-fitting, which improve the electric field distribution around the end-fitting [18].

4. Stress control methods using advanced material

Recently, many researchers have studied the use of field grading material (FGM) to reduce the electric field enhancement on HV insulators. There are two main types of FGM: resistive and capacitive grading materials. They are classified based on their nature of displacement nature inside the insulation material. Unlike other geometrical control methods, the grading action of the FGM appears within the insulation bulk [6]. The use of FGM in stress grading has been proposed a while back in 1960's. However, the concept of FGM has only been adopted in limited HV applications e.g. HV motor and cable terminations. There is continuous endeavor within the power utilities to apply these concepts to other HV equipment such as bushing and outdoors insulator [19]. Stress control using advanced material could lead to better design of the equipment.

4.1. Resistive grading

Resistive grading materials have the nonlinear conducting behavior where the conductivity varies with the electric field. In order to achieve the nonlinear behavior, the base polymer such as epoxy resins or silicone rubber (SiR) is filled with the inorganic filler. The nonlinear grading material becomes conductive when the electric field strength exceeds a withstand level and this effect helps to homogenize the electric field distribution within the insulation bulk and eliminate the field enhancement effect [20]. Ye et al. have studied the effectiveness of thin resistive layer coated on the core rod of the insulator structure in mitigating the electric field strength along the insulator as shown in figure 1b [9]. Pradhan et al. have done comprehensive functional behaviors study of resistive grading materials and the parameters that describe the stress grading properties of FGM have been discussed. These parameters include threshold field (E_b), low field conductivity (σ_0) and non-linearity coefficient (α). Applying resistive grading materials directly on the surface of insulator reveals sufficient controlling effect but may promote erosion and tracking resistance [19]. Moreover, nonlinear conductivity material may also be affected by electrical aging [21] [22].

4.2. Capacitive grading

Capacitive grading materials can be obtained by introducing various fillers to the host matrix. The fillers increase the relative permittivity of the dielectric material. This stress field control method, which is also called the "refraction control", redistributes the electric field over bushing or overhead insulators [23,24]. The electric field is regulated when passing over different dielectric materials having varies dielectric constant values. Frost et al. have investigated the dielectric property of $BaTiO_3$ and Al_2O_3 filled epoxy matrix [25]. Unlike resistive grading, permittivity of capacitive grading material is not affected by electrical aging. However, the electric field distribution inside the bulk material does not show much improvement with capacitive grading material [21].

5. Conclusion

Clearly, the environmental impacts such as pollution, rain and wind have a significant effect on the electric field distribution along the surface of insulator. Currently, the existing field stress control methods have achieved mix results in mitigating the field enhancement inside and over the insulator. The advantages and disadvantage of varies existing field enhancement control methods have been discussed in this paper. Field grading (resistive and capacitive grading) materials are of great interest to researchers in mitigating the electric field stress. However, these advanced materials have limited commercial use due to lack of understanding in their long form performances. Hence, there is a lot of room for improvement, in order to make them more adoptable for other HV equipment in the power industry. One of the possible improvements might be the combination of the resistive and capacitive materials.

Reference

[1] J. Looms, *Insulators for High Voltages*.: IEEE Power Engineering Review , 1991.

[2] J. Holtzhausen and W. Vosloo, "High Voltage Insulation Materials," *High Voltage Engineering - Practice and Theory*, 2011.

[3] M. Tunay, "The comparison of ceramic and non-ceramic insulators ," *e-Journal of New World Sciences Academy* , vol. 2.

[4] W. Rowe and K. Wong A. Bojovschi, "Electromagnetic field intensity generated by partial discharge in high voltage insulating materials," *Progress In Electromagnetics Research- PIER*, vol. 104, 2010.

[5] K. Khor, "Partial discharge propagation and sensing in overhead power distribution lines," RMIT University, Melbourne, 2010.

[6] R. A. Rahman, "Investigation of ZNO Microvaristor for Stress Control on Polymeric Outdoor Insulators ," Cardiff University , Wales, UK , 2012.

[7] R Boudissa , A Bayadi , and R Baersch , "Effect of pollution distribution class on insulators flashover under AC voltage," *Electric Power*

Systems Research, July 2013.

[8] M Marich, R Amiri, and H Hadi, "New approach for the modeling of the polluted insulators," in *Electrical Insulation and Dielectric Phenomena, CEIDP*, 2006.

[9] Hanyu Ye, Markus Clemens, and Jens Seifert , "Electroquasistatic Field Simulation for the Layout Improvement of Outdoor Insulators Using Microvaristor Material," *MAGNETICS* , vol. 49, 2013.

[10] Reuben Hackam , "Outdoor HV Composite Polymeric Insulators," *Dielectrics and Electrical Insulation* , vol. 6, 1999.

[11] Witold Bretuj, Janusz Fleszynski, and Krzysztof Wiecz, "Test Method of Composite Insulators Aged in High Voltage Rain Chamber," in *High Voltage Engineering and Application-ICHVE*, 2010.

[12] Ercan İzgi, Aslan İnan, and Selim Ay, "The Analysis and Simulation of Voltage Distribution over String Insulators Using Matlab/Simulink," *Electric Power Components and Systems*, 2008.

[13] Jun Gao and Jianghai Geng, "Research on Flashover Voltage of Composite Insulator with Wind Tunnel Test," *Asia-Pacific Power and Energy Engineering Conference, APPEEC*, 2010.

[14] T Doshi and R. S. Gorur , "Electric Field Computation of Composite Line Insulators up to 1200 kV AC," *Dielectrics and Electrical Insulation* , June 2011.

[15] B M'hamdi, M Teguar , and A Mekhaldi , "Optimal Design of Corona Ring on HV Composite Insulator Using PSO Approach with Dynamic Population Size," *Dielectrics and Electrical Insulation* , vol. 23.

[16] Yang Qing , Sima Wenxia , Deng Jiazhuo , Yuan Tao , and Chen Lin , "New Optimization Method on Electric Field Distribution of Composite Insulator," in *Electrical Insulation and Dielectric Phenomena* , 2010.

[17] Zongren Peng , Peng Liu , and Peng Yu , "Structural Optimization of a New-style Insulator Used in High-Voltage Transmission Lines," in *Properties and Applications of Dielectric Materials*, Bali, Indonesia, 2006.

[18] Joze Hrastnik and Joze Pihler, "Designing a New Post Insulator Using 3-D Electric-Field Analysis," *POWER DELIVERY* , vol. 24, 2009.

[19] Manoj Pradhan, Helena Greijer, Göran Eriksson , and Mikael Unge , "Functional Behaviors of Electric Field Grading Composite Materials," *Dielectrics and Electrical Insulation* , vol. 23, 2016.

[20] Feifeng Wang, Peihong Zhang, Mingze Gao, and Xin Zhao, "Research on the Non-linear Conductivity Characteristics of Nano-SiC Silicone Rubber Composites ," in *Electrical Insulation and Dielectric Phenomena* , 2013.

[21] J.P Rivenc, A Loubiere, and T Lebey , "Conformal mapping comparison of resistive and capacitive grading materials," *Electrostatics* , 1998.

[22] H Ahmad et al., "Electrical characterisation of ZnO microvaristor materials and compounds," in *Electrical Insulation and Dielectric Phenomena*, 2015.

[23] Syed Abdullah Qasim and Nandini Gupta , "Functionally Graded Material Composites for Effective Stress Control in Insulators," in *the Properties and Applications of Dielectric Materials (ICPADM)* , 2015.

[24] Lise Donzel , Felix Greuter , and Thomas Christen , "Nonlinear Resistive Electric Field Grading Part 2: Materials and Applications," *Dielectrics and Electrical Insulation Society (DEIS)* , 2011.

[25] N Frost and P McGrath, "Dielectric properties of barium titanate and alumina filled epoxy," in *Electrical Insulation and Dielectric Phenomena (CEIDP)*, 1995.