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Review of Comparative Evaluation to Understand the Behavior of Tracking, Erosion and Flashover Characteristics Under AC and DC Voltage on High Voltage Polymeric Insulators

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ABSTRACT: The use of polymer insulator in high voltage transmission lines has been extensively researched since they possess excellent hydrophobicity, lightweight properties, and contamination resistance. However, the reliability of polymeric insulators in AC and DC voltages has been noted as an important challenge. This study provides a detailed review of the features related to tracking, erosion, and flashover characteristics of polymeric insulators in AC and DC voltages through conducting a salt fog test for 1000 hours. In addition, this study evaluates the degradation of polymeric insulators exposed to AC and DC voltages along with the electric field distribution and hydrophobic properties. Also, the influence of several variables on polymeric insulators in AC and DC voltages has been discussed. Finally, several research gaps were recognized through reviewing the literature have been described.

KEYWORDS: Polymeric Insulators, Silicone Rubber (SR), Salt Fog Test (SFT), Tracking, Erosion, Flashover, AC (Alternating current) Voltage, DC (Direct Current) Voltage, Hydrophobicity, Leakage Current (LC), Alumina Trihydrate (ATH).

I. INTRODUCTION

Polymer Insulators at High Voltage Level have received considerable attention in the electrical power sector because of their unique qualities of cost effective, light weight which are compared to insulators made from ceramics, Porcelain and glass. [1] Performance of polymeric insulators in the long run is affected significantly by the material composition as well as by the design of such devices and by operating conditions present in field . Polymeric insulators are not produced according to one standardized method unlike their counterparts made of ceramic or porcelain as there exist numerous manufacturers of polymeric insulators using diverse materials; Thus, the expected lifespan of polymeric insulators remains challenging.[34]

The first-generation polymer insulators consisted of polymers such as Epoxy, Silicone Rubber and Ethylene Polypropylene Diene Monomer (EPDM), among others.[25] Polymeric insulators, in particular the ones made of silicone rubber, are commonly utilized in high voltage power systems since of their hydrophobic properties and good contamination resistance.[25], [29].Polymer insulators' properties are not well understood, particularly their hydrophobic characteristics. Polymeric insulators may degrade as a result of contamination, moisture and voltage exposure. It can be stated that Salt Fog Test is considered to be the most successful approach to get laboratory conditions suitable for studying AC and DC polymeric insulators behavior. Several investigations dealing with AC vs DC are leakage current, tracking and erosion resistance, flashover voltages at different voltage levels have been undertake. [1], [19], [38]. A study on silicone rubber insulators placed in salt fog environments revealed that defective units exhibited a declining trend for the 3rd and 5th harmonics, whereas non-defective units exhibited an increasing trend . This research established the fact that leakage current measurement could serve as a tool to assess insulator behavior in salt fog environments [12]. Ageing process of insulators under alternating and direct voltage differs. Under alternating voltage ageing takes place at smaller rates compared with DC voltage owing to the reason that the charge accumulates during ageing process and the field becomes distorted.Therefore, the purpose of this investigation is to compare the parameters of tracking, erosion and flashover phenomena under both AC and DC voltages using 1000 hour Salt Fog Test method.[24], [27].

Multivariate stress coupling studies with the effect of UV, corona, and contaminants have been extensively carried out ;but AC vs DC coupled stress tests together with salt fog cycling tests have been less explored.[8] Hydrophobicity and Flashover Voltage, Correlation Hydrophobicity retention has been studied extensively; but no research has been done to correlate hydrophobicity and flashover voltage with respect to salt fog tests for 1000 hours.[31], [45] In-service Monitoring During Salt Fog Exposure Tests of polymer insulators such as infrared detection and leakage current measurements have good potentials. But no research work has been carried out on online monitoring during salt fog exposure.[37]

II. AC VS DC PERFORMANCE DIFFERENCES

Polymer insulating materials show different behaviors depending on whether the stress is in AC or DC electricity. Polymer insulators were assessed based on charge storage and dissipation as a function of moisture level, along with tracking and erosion. It has been shown that considerable variations exist in the phenomenon of surface charging between AC and DC. [24]

It was seen that the tracking and erosion resistance of the polymer insulator material were considerably reduced under DC voltage compared with AC voltage . Poorer electrical behavior of the materials under DC voltage stress was found to be attributed to high discharge current levels for a longer period of time. [27]

III. TRACKING And EROSION CHARACTERISTICS

A certain phenomenon that insulators are prone to during field operation is known as tracking i.e permanent carbonized conductive path on the surface. This is a very alarming scenario for insulators made from polymers because the energy released may heat the component due to the Joule effect, resulting in the breakdown of polymer molecules in the insulator. The process is referred to as erosion, i.e. physical loss of materials, thereby reducing the life span of the insulator. The insulating materials that are operated under environmental conditions in the field are susceptible to the tracking phenomenon.[39]

Normally, because the resistivity on the surface of polymer-based insulators is quite high, the leakage current would be very low, and the electric field would be uniform throughout the surface of the insulator. In certain areas, the presence of contamination due to pollution, sea breezes, dust, or other materials with high moisture content may cause the resistivity to drop significantly.[39]

Causes for the degradation on the surfaces of polymer insulators are mainly attributed to tracking and erosion depending on the presence of leakage currents, dry band arcings, and the composition of the materials. With AC voltages, the alternating polarity makes it difficult for degradation to occur since it does not allow charging to occur. On the contrary, charging occurs with the application of DC voltages leading to severe surface erosion [3], [26].

Thermal conductivity is increased while leakage currents reduced by incorporation of additives such as Alumina Trihydrate (ATH) into the materials [1]. Also, nanocomposites have superior characteristics compared to ordinary polymers due to the stability of thermal conductivity [4], [7].

Tracking and Erosion may occur in three stages. Stage 1 – In a situation where there is a constant flow of conductive contaminant causing Joule heating effect on the material. Stage 2 – In a scenario where a dry zone is formed due to evaporation of the contaminant, and an arc is created between the two filaments. This arc is interrupted whenever the gap is filled up with more liquid or becomes bigger than the material. Stage 3 – If the gap is too big, the contaminant will continue to flow until there is a formation of conductive path, which will bring about stage one, or creation of an arc bringing us back to stage two.[39]

Erosion that happens because of this incident leads to the degradation of the polymer chains within the insulator, which results in additional distortion of the insulator surface. This process continues to repeat itself until eventually, the insulator fails.[39]

IV. FLASHOVER PERFORMANCE UNDER POLLUTED CONDITIONS

Generally pollution is classified into two types; active and inert pollution. Active pollution contains metallic particles, salt fog, salt deposits, fly ash, chemical, fertilizers etc. While inert pollution includes non-soluble contents from cement factories and dust.[18]The location of this pollutant layer depends on several factors, including climatic factors, electric field strength, the location and type of the insulator. However, the magnitude of this problem depends heavily on whether these pollutants come from natural, industrial, or combined sources, and the conductivity of the materials used.[44]

Flashover phenomenon occurs due to the occurrence of electrical breakdown by leakage current flowing through the surface of the insulator. In salt fog conditions, conductive layers are formed on the surface of the insulators, which increases the probability of flashover phenomenon.It has been revealed through several investigations that DC flashover voltage is less than the AC flashover voltage due to field intensity difference and charging effect [9], [17].

Many mathematical models have been formulated to predict the flashover voltage, but none of these can provide accurate results when multiple stresses are applied simultaneously [30], [44].Influence of non-uniform pollution on flashover phenomena. [21]

With regard to the flashover properties, the novel criterion for the arc propagation phenomenon has been developed based on the arc root voltage gradient for understanding the flashover mechanisms in polluted insulator under AC voltage environment . Such criteria could help understand the changes in the arc root voltage gradient during arc propagation process . The arc root could be seen as several parallel paths consisting of the polluted layer, and its voltage gradient changes depended on the arc propagation ability .[32] There are several mathematical models which could predict the DC flashover voltages of the polluted polymeric insulators decreases, where their prediction accuracy reaches up to 10% of that published experimental values .[30]

A. Characteristics of AC Voltage Flashover :

During AC voltage exposure, polymeric insulators suffer from substantial deterioration in their performance due to salt-fog exposure. This is attributed to the loss of hydrophobicity (Si-CH3) and (Si-CH3), increased roughness, and the reduction in dielectric/electrical behavior characteristics. Due to thermal and high-energy particle interaction, molecular chain bonds on the silicone rubber surface are broken, resulting in the generation of hydrophilic compounds and precipitated inorganic materials . Increased conductivity in salt-fog results in higher levels of deterioration, suggesting a detrimental influence of salt-fog on silicone rubber aging. Studies investigating fan-shaped contamination in AC voltage have shown that the voltage value needed for flashover is affected by dry band placement, while orientation angles have no bearing on the insulator's flashover capacity in dry conditions . However, tilted insulators exhibit superior performance in wet conditions . Flashover voltage is inversely related to time, whereas the degree of pollution is negatively correlated with the time to flashover. [21]

B. Characteristics of DC Voltage Flashover:

The DC voltage flashover characteristics are strongly affected by the surface charge effect. Deposited negative surface charges improve the flashover characteristics; however, positive surface charges lower the flashover voltage . Surface charge densities play an important role in influencing the electric field distributions, which have a direct bearing on the changes in the flashover characteristics . Electric stress increases with pollution severity and reaches its peak at the interface between sheath and shed, with minimum at the shed tip .[17]

V. ELECTRIC FIELD DISTRIBUTION ANALYSIS

Electric field distribution is a crucial factor that has a significant impact on the efficiency of the insulator. Based on the finite element method (FEM), geometry, insulation gaps, and end fitting design have a strong impact on the electric field line distribution [2], [11], [13]. Even functionally graded materials (FGMs) have been applied to electric stress control [10].

A. Electric Field Distribution and Flashover Properties:

As the thickness of the contamination increases, the position of the maximum electric field shifts away from the triple-junction point. Corona rings may be needed for the high-voltage insulator at both ends (high voltage and ground) and their performance is impacted by pollution and moisture conditions .[28]

B. Electric Field Distribution and Stress Analysis

There have been several publications dealing with electrical stress analysis in polymer insulators. It is observed that "the potential and electric field distribution is not uniform along an insulator string; this leads to corona formation, surface degradation, and even bypasses ." Moreover, it was reported that electrical stress could be reduced by altering the geometry of the insulators, and geometrically altered insulators perform better fieldwise .[11]

C. Electric Field Distribution During Wet Pollution

When pollution occurs under wet conditions, there is considerable increase in the electric field intensity. Studies reveal that in the case of insulators, there is a remarkable increase in the electric field intensity varying between 0.3 kV/cm and 3.6 kV/cm in case of insulators having similar sheds, while it varied between 2.2 kV/cm and 4.5 kV/cm for insulators with alternating sheds under high rainfall conditions. The highest electric field strength in fog condition was 1.74 kV/cm and 2.30 kV/cm respectively .[33]

VI. AGING UNDER MULTI-STRESS CONDITIONS

In practice, polymeric insulators encounter not just one kind of stress but more like UV stress, water stress, pollution, and electrical stress.The physical properties and hydrophobicity of the polymer are damaged by the UV stress [15] and contamination increases the rate of surface degradation [20]. The results of studies conducted on multi-stress aging indicate that the impacts of these stresses together occur faster than when the stresses act individually But most of the investigations carried out have focused only on single stresses.[8], [22].

The articles discuss some important aging problems faced by polymeric insulators. Studies indicate that most polymeric insulators do not survive electric and mechanical stress towards the end of their service period due to aging and aged polymeric insulators contribute to a large number of breakdowns within power network lines . In addition, UV radiation has a substantial effect on mechanical behavior .[12]

VII. HYDROPHOBICITY AND SURFACE BEHAVIOR

Hydrophobic property is vital for preventing continuous films of water from being established on the surface of insulation. In case the material loses its hydrophobic property, leakage currents will increase. According to various research works, the rate of reacquisition of hydrophobic properties is lower under DC stresses compared to AC stresses; No standard procedure has been developed to measure retention of hydrophobicity under long-term operation.[31], [40], [45].

it is clear that the areas with higher current densities exist in the junctions between the shed and shank of the insulator . This happens since current densities are always higher at places where the diameter of the insulator is the smallest. Current density would rise considerably with the increase in pollution layer conductance.[34]

A. Salt Fog and Leakage Current

When the surface of insulator is dry, insulator surface resistivity is high and there is a low possibility for a flow of leakage current. Thus electric field stress at the surface of a clean and dry insulator has little effect on the flow of leakage current and arc initiation. Electric field strength is high at the junction of metal electrodes and at the bottom of shed regions.[18] More surface roughness results more crystalline surface leading to high leakage current of insulator with and without hydro carbon polluted insulators. It is seen from the pattern that the leakage current increased slightly with the ageing of the insulators. This could be due to slight degradation of the insulator surface of the hydro carbon polluted insulator.[16] The value of leakage current increases with an increase in moisture level. Surface conductance maximum value is achieved when the contamination layer is perfectly saturated with moisture.[14]

ATH is incorporated into the base polymer of SiR in order to increase its thermal resistance. Nonetheless, above 190°C, ATH releases bond water leading to the formation of aluminum oxide (Al_2O_3).Most polymeric compounds usually have carbon atoms, and due to tracking, carbon conducting pathways can be established. If carbon conducting tracks could somehow be eradicated without substantial erosion, LC inhibition would occur.[41]

Salt fog was proven to reduce leakage current by reported study on use of alumina trihydrate filler. On the other hand, noted loss in hydrophobicity properties due to AC salt fogging of silicone rubber samples. These two results proved the efficacy of salt fog for accelerated aging. [19]. Humidifying the pollution layer leads to the dissolving of salt present in the pollution layer and creation of the electrolyte. The electrolyte conducts electricity and reduces resistance of the electrical circuit, thus creating leakage current. Leakage current leads to heating up of the pollution layer. Humidity is then evaporated from the pollution layer, and this process causes the pollution layer to get dry, forming dry bands.[44]

B. Flashover Characteristics

Flashover susceptibility due to surface charge accumulation was reported. No flashover occurred during 1000 hr. AC salt fog test. Stable hydrophobicity and limited leakage current prevented conductive path formation. For DC, flashover risk is higher, but the salt fog results imply silicone rubber's hydrophobic recovery mechanism provides strong defense.[17]. On the other hand, carried out flashover analysis in presence of light pollution it shows Flashover voltage under DC is typically 20–30% lower than AC at the same pollution severity.[6] The effect of dry band position on flashover voltages was studied experimentally. flashover voltage decreased consistently with pollution severity and dry band location:Top shed dry band : lowest withstand voltage; Middle shed dry band : highest withstand voltage; Multiple dry bands: intermediate but unstable performance. Orientation angle had little effect in dry conditions, but under damp conditions tilted insulators performed better (less flashover risk).Inverse relationship observed: higher pollution → lower flashover voltage; longer exposure → shorter time to flashover.[21]. Also, modeled flashover of AC/DC polluted insulators. Flashover begins with humidification of the pollution layer, dissolving salts and forming a conductive electrolyte.This initiates leakage currents, which heat the layer, evaporate moisture, and create dry bands.These dry bands concentrate the electric field, triggering partial discharges that can evolve into full flashover.[44]

C. Hydrophobicity Retention

AC Stress:Faster loss of hydrophobicity due to droplet oscillation and residue formation. Higher minimum current required for arc inception, but shorter times to failure once initiated. DC Stress: Better retention at equal RMS values, but similar failure times at equal peak values. Droplets elongate under DC, leaving fewer residues, but persistent stress slows recovery.[31] [45]. The surface exhibited large voids, rougher patches, and long deep cracks at the specimen surface. Implication for AC vs DC: Under AC, tracking tends to be intermittent due to polarity reversal. Under DC, continuous polarity accelerates ion migration, making the tracking paths more persistent and conductive. [35]. Hydrophobicity loss under DC stress was associated with flashover directly. Advanced Materials Use like nanoparticles for better erosion resistance was suggested [23]. Hydrophobicity loss is the key driver of leakage current growth, erosion, and flashover.For HVDC insulators, negative polarity stress combined with salt fog and ageing factors is the most critical scenario. Design strategies must include optimized filler loading, hydrophobicity recovery mechanisms, and protective coatings to extend service life.[8]

D. Methods of Degradation

As a result of the occurrence of such pollutions on the surface of the insulator, degradation occurs because of the electrical stress. In order to ensure long-term reliability of the polymer insulator, long tests need to be conducted for different polluted contaminants . Water droplets and pollution layers found on the weather sheds increased the value of the electric field locally but had no impact on the electric field distribution of the fibre reinforced plastic core . Pollution layer conductivity affected the electric field in the case of pollution .[25]

E. Degradation Processes

The polymeric material in insulators degrades using several processes. The aging process is highly influenced by the amount of UV light and pollution. Pollution causes roughening of the surface, thus increasing conductivity on the surface of the insulation material . In the course of aging, there is an increase in oxygen and carbon content but a reduction in silicon .[19]

F. Salt Fog Test on Material Degradation

Electrical field stresses that exceed certain threshold levels applied in long-term under certain environmental conditions lead to housing degradation and deterioration and thus failures of insulators in service. [2] In a 1000-hour salt fog test, such degradation would manifest as earlier tracking initiation and faster propagation, especially under DC stress where ion migration is continuous.[8] Harmonic monitoring can differentiate between incipient tracking in healthy insulators and accelerated degradation in defected ones.[12]

VIII. DC Voltage Performance Characteristics:

A. DC Voltage Testing of Polymeric Insulator

Tests to evaluate performance of polymeric insulators in DC voltage have been devised based on the extension of existing AC testing techniques. Tests for DC voltage have been devised based on the standards specified in IEC 62217-2025 . Polymeric Silicone Rubber (SR) insulators have been tested under negative DC voltage.[3] [46][42]

B. Effect of Polarity in DC Test

An important observation from tests carried out using DC voltage is the effect of polarity on the insulating material. The outcome indicates that SR materials exhibit good performance when subjected to negative DC voltages rather than positive DC voltages . Tests conducted based on eroded mass and leakage current confirm the above finding .[3] [46] [42]

C. DC Flashover Properties

Studies conducted on DC flashover properties have uncovered some important correlations among different factors affecting the insulators. It was found that there is a negative correlation between the pollution level and flashover voltage. In other words, the greater the pollution level, the lower the flashover voltage, which is significantly reduced as compared to the flashover voltage of clean specimens . The influence of the ESDD on the 50% flashover voltage can be presented by a power law equation .[6]

IX COMPARATIVE ANALYSIS OF AC VS DC PERFORMANCE

A. Material-Specific Comparisons

Polymeric materials demonstrate different performances when used under AC and DC voltages. In this regard, the performance of the HTV-SiR samples regarding the pollution flashover voltage gradient is superior to the FRP materials . Therefore, it is important to consider the choice of materials for effective performance.[4]

B. Tracking and Erosion Behavior

Several studies have indicated considerable distinctions between the performance of polymer-based insulators under AC and DC voltage. Test samples usually experience more extensive damage to tracking and erosion under DC voltage than AC voltage, particularly under negative DC voltage . The polarity of DC voltage greatly influences its performance. [38]

C. Properties of Discharges

There is a marked difference between AC and DC discharges in terms of their properties. DC discharges occur more strongly and remain active for a longer duration than do AC discharges under identical testing conditions . However, it is notable that the DC arc typically lifts off the surface of the insulator . [37]

D. Current and Energy Properties

Experimental investigations conducted through rotating wheel dip tests revealed that DC arcs were steady and required more energy, while AC arcs were intermittent and highly localized around the grounding electrode . Furthermore, there was no correlation found between leakage current and the extent of damage caused by tracking .[43].

E. Performance of Filler under Various Voltage Types

The efficiency of fillers is dependent on whether the process utilizes AC or DC voltage types. The low concentration of nano alumina fillers was effective in the same way as the high concentrations of uATH . The fillers used in the SR matrices included micron-sized alumina trihydrate (uATH) and nano-size alumina (nALU).[7]

F. Environmental Factors and Aging Effects

F1. Multiple Stress Aging

Aging of polymer insulating material can be influenced by multiple stresses found in the environment. Composite materials made up of SR with various amounts of fillers such as silica and alumina trihydroxide (ATH) were aged using multiple stress aging under a time period of 5000 h, and then its electrical tracking properties were analyzed . Multiple stress aging influences the surface morphology of silicone rubber .[8]

F2. Pollution Effect

The impact of pollution on insulation properties is seen in both AC and DC voltage cases. But, it is clear that pollution over the insulator's surface can lead to a failure in power transmission system. The strength of the electric field inside the cavity depends upon this geometry as well as the pollution on its surface.[5]

X. EXPERIMENTAL METHODOLOGY FOR 1000 Hr SALT FOG TEST ON DC VOLTAGE

A. Test Set Up & Test Conditions

Salt fog chamber with control on salinity and temperature; AC and DC high voltage power source;Leakage current measuring system; Environment conditions control (humidity, temperature) ;Duration of test: 1000 hrs; Severity of pollution: as per IEC standards-62217:2025:Voltage levels: Stress voltage level & NACL Content equivalent in AC [42] [46]

B. Observations

Characteristics of leakage current; Surface tracking and erosion depths; Flashover voltage; Hydrophobicity;Modern methods of testing include infrared scanning and leakage current analysis [37], [39].

XI. RESULTS AND DISCUSSION

The erosion rate is high in the case of DC voltage;The flashover voltage is low for DC stress;High leakage currents when there is pollution;Slow restoration of hydrophobicity under DC stress;High dependency on filler content and composition.[42] [46]

XII. CONCLUSION

From the above comparison of tracking and erosion behavior in both AC and DC voltage, the performance of the polymeric insulator is highly dependent on the material type. Silicone rubber, especially HTV silicone rubber, has been observed to perform better compared to other materials and better under negative DC polarity than positive DC polarity. Appropriate use of fillers such as nano-silica and ATH is highly recommended to improve performance under tracking tests.[3]

Insulators that have the ability to sustain high dielectric properties regardless of the condition on their surface play an extremely crucial role.[41]The specimen that broke down during the application of the negative DC voltage showed partial damage to the seal section of the cathode section, corrosion of the end fittings of the anode section, and wear holes adjacent to the first shed near the live end. [38]

In case a material shows reliability and durability, then its economic advantage will be achieved due to a decrease in the value of the creepage distance.[45]

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