Study of Effect of Water Droplets on the Surface of Polymeric Insulators

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Abstract: Polymeric insulators in service, experience adverse effects of temperature, UV radiation, rain, fog, mist and contamination. One of the major problems related to the outdoor polymeric insulators is erosion and tracking of the surface due to the effect of contamination. This paper presents the simulation results of electric field distribution along the surface of polymeric insulators under contaminated conditions and experimental studies conducted on virgin and field aged polymeric insulators.

The field enhancement due to water droplets on the surface of polymeric insulator is studied by means of computational simulations. The insulator is simulated under dry as well as wet conditions. The effect of water droplets on the surface of polymeric insulator under different contamination conditions such as coal, cement, marine and kaolin is studied through boundary element method using Coulomb 3D software. A comparative study is performed under different contamination conditions.

The long term ageing studies of polymeric insulators and the change in hydrophobicity of field aged polymeric insulators are presented along with material analysis of the insulator samples. The results show that the field enhancement due to water drops along the surface of polymeric insulator is considerable and reaches to the extent of corona formation which accelerate ageing of insulator. The effect of different contaminants on the surface of polymeric insulator is also presented. The leakage current variation in salt fog test is presented along with surface morphology changes and material structure before and after the tests.

Keywords: Polymeric Insulators, Hydrophobicity, Water Droplets, electrical discharges, Pollution layer.

I. INTRODUCTION

The use of polymeric insulators is increased significantly over the years because of their superior performance due to hydrophobic property under contaminated conditions. Contamination performance of polymeric insulators is one of the most important factors in the quality and reliable performance of the power system. Surface hydrophobicity is the desirable factor for outdoor insulation which resists the formation of continuous electrolytic layer on the surface. However, the surface hydrophobicity is temporarily or permanently lost during dry band arcing, which occurs in the presence of moisture and contamination, under the influence of electric stress. Over a period of time, dry band arcing can lead to the flashover and material degradation in the form of tracking and erosion [1].

The pollution flashover phenomena of polymeric insulators have been studied and described by various researchers. During flashover, an arc develops and bridges the weather sheds along the clean section of the insulator which is a high resistance region. The presence of water droplets and contamination layers intensify the electric field strength on the surface of a polymeric insulator. Therefore, the study of the electric field distributions of polymeric insulators under wet and contamination conditions is important for the in-depth understanding of the initiation mechanism of pollution flashovers [2].

Water droplets on insulator surface play a dominant role in the pollution flashover and ageing of polymeric insulators. Water droplets increase the electric field strength at the polymeric insulator surface because of their high permittivity and conductivity. The surface corona discharges from water droplets age the weather shed material of the insulator. The corona discharge destroys the hydrophobicity locally causing the spread of water and adjacent water droplets to coalesce [2, 3]. Hence it is necessary to quantify the energy required to cause water drop corona, material degradation and also the mechanisms involved in such a process. The continuous exposure of polymeric insulator to water drop corona allows a cumulative effect of the electrical discharges and their side reactions are to be studied.

Few researchers have reported simulation studies on polymeric insulator with water droplets of different sizes and water film of different conductivity [4]. In service conditions, the contaminants/ pollutants viz salt deposition, coal, dust, cement etc., get deposited and form a layer on the insulator surface over a period of time. This contamination layer starts conducting once it is wet by rain, dew or fog in the form of water droplets. The effect of water droplets and the conductivity of contaminant affect the flow of leakage current. Hence in order to simulate the actual service conditions, a simulation study is done on polymeric insulator with contamination layer and subsequent wetting due to water droplets. An experimental study is performed on polymeric insulator samples in order to investigate the effect of continuous discharges due to moisture by means of fog created in salt fog chamber. An experiment is also performed on the field aged samples collected from different contaminated sites to study the effect of different contaminants.

II. ELECTRIC FIELD SIMULATION OF POLYMERIC INSULATOR

To study the effect of water droplets on complete insulator, a 33 kV polymeric insulator design is selected and modelled using COULOMB 3D software. The basic design of polymeric insulator consists of fibre reinforced plastic (FRP) core covered with silicone rubber weather sheds and equipped with metal end fittings having relative permittivity's of 6, 4.5, and 1 respectively [5]. To reduce the simulation time and tedious process of modelling water droplets all over the surface of insulator, a section of insulator is modelled with periodicity application which reflects the complete insulator as shown in fig.1. The lower metal fitting is energized with 19 kVrms AC, which is normal phase to earth voltage of 33 kV insulator and upper metal end fitting is connected to ground. The insulator is simulated to have a creepage distance of 385 mm and dry arc distance of 900 mm.

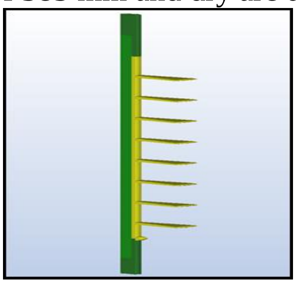
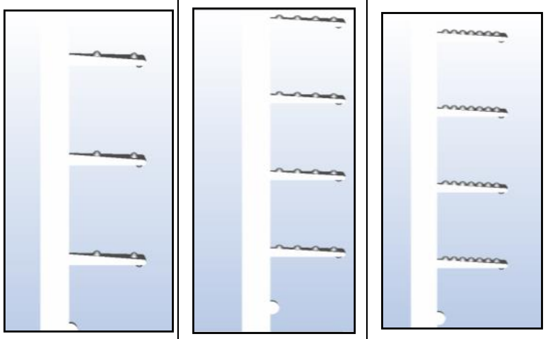


FIG.1. POLYMERIC INSULATOR MODELLING

An array of 20µl water droplets with permittivity of 80 [5] are modelled on the surface of insulator. To study the effect of increase in the number of water droplets on the surface of insulators, the number of water droplets is varied from two droplets to seven droplets on the surface of shed of the section of insulator as shown in fig.2. This implicates variation of water droplets from 72 droplets to 252 droplets on the surface of one shed of complete insulator.



(a) (b) (c)

FIG.2. VARIATION OF WATER DROPLETS ON THE SURFACE OF SHED OF INSULATOR

Similarly, water droplets are also modelled on the sheath part of the insulator to study its effect on the surface of sheath as shown in fig.3. To study the effect of water film formation on the surface of insulator in hydrophilic case, insulator with 0.1 mm thick water film is modelled on the surface of complete insulator as shown in fig.4 and insulator for completely wet condition in hydrophobic case, the water droplets are modelled all over the surface of insulator as shown in fig.5. A comparison is made between hydrophophic and hydrophilic cases.

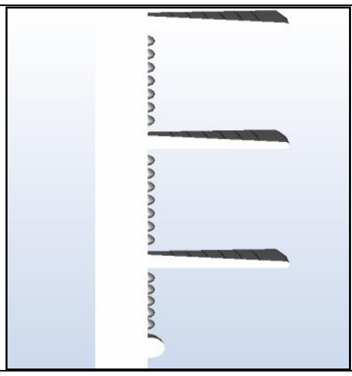


FIG.3. WATER DROPLETS ON THE SURFACE OF SHEATH OF INSULATOR

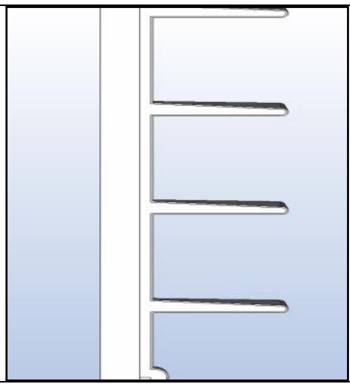


FIG.4. WATER FILM ON THE SURFACE OF INSULATOR

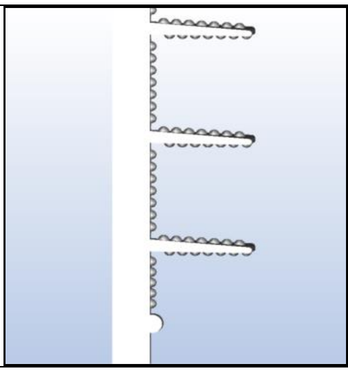


FIG.5. WATER DROPLETS ON THE SURFACE OF COMPLETE INSULATOR

The results in fig.6 show that, with the increase in number of water droplets on the surface of insulator there is increase in the magnitude of electric field and the increase in the number of water droplets also causes non-uniformity in electric field distribution. The increase in the electric field more than the threshold value of 5 kV/cm ambient electric field [6] suggests the initiation of water drop corona in the insulator section with seven drops. It is evident from results shown in fig.7 and fig.8 that electric field due to water film formation is highest when compared to water droplets on the surface of insulator and exceeds the air breaking strength of 30 kV/cm. The results also show that by increase in water droplets on the surface of polymeric insulator also causes increase in non-uniformity of potential distribution and it is completely non-uniform for a water film case as shown in fig.9.

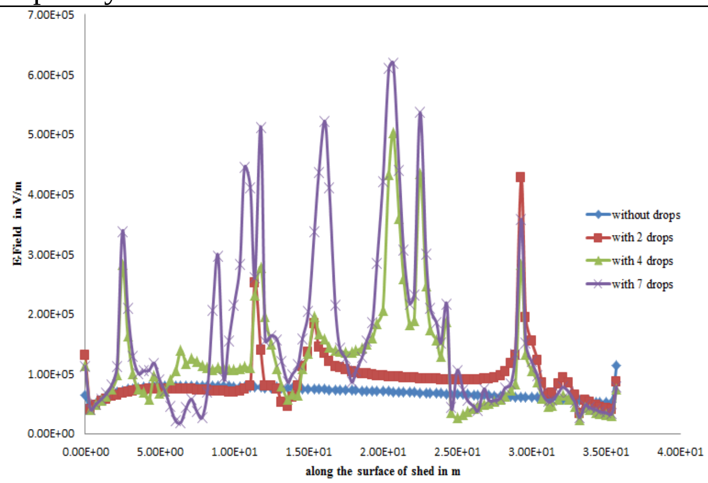


FIG.6. ELECTRIC FIELD VARIATION ALONG THE SURFACE OF FIRST SHED WITH INCREASE OF WATER DROPS

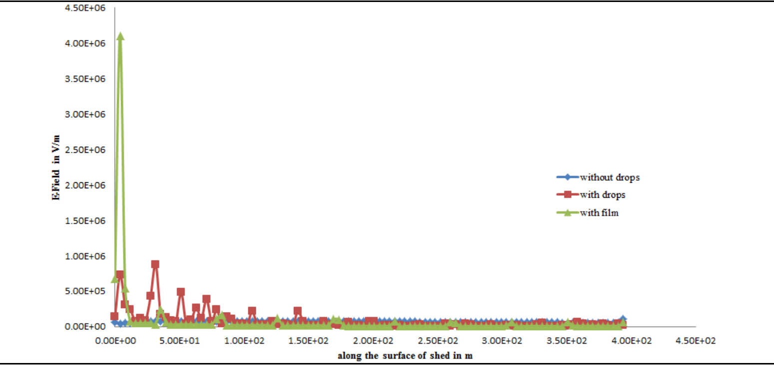


FIG.7. ELECTRIC FIELD VARIATION ALONG THE SURFACE OF FIRST SHED FOR INSULATOR WITH WATER DROPS AND WATER FILM

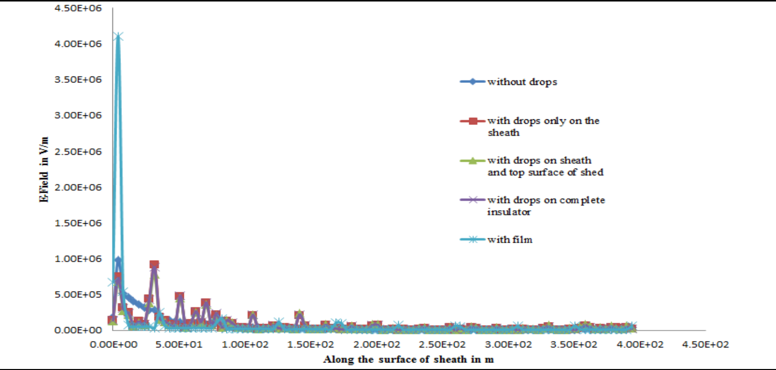
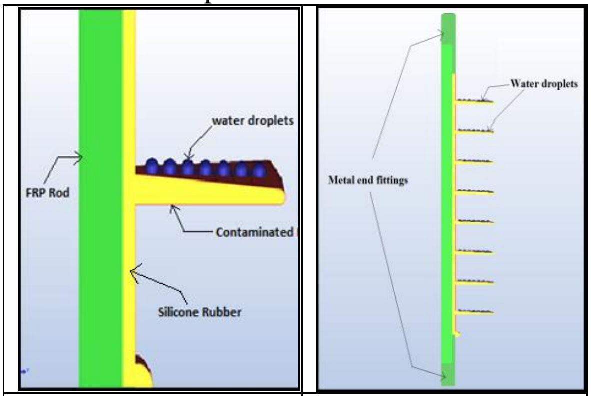


FIG.8. ELECTRIC FIELD VARIATION ALONG THE SHEATH OF INSULATOR

The polymeric insulators in service conditions are exposed to various kinds of pollution, such as industrial, marine pollution, etc. Hence, these pollutants get accumulated over a period of time and form a layer on the surface of insulators during the service. During wet conditions due to fog, dew and rain, water droplets form on the surface of the contaminated polymeric insulator because of its hydrophobicity transfer property. Hence, to study this phenomenon, a polymeric insulator is modelled with a layer of contamination and water droplets above the contamination layer as shown in fig.9.



(a) (b)

FIG.9. MODEL OF POLYMERIC INSULATOR WITH CONTAMINATED LAYER AND WATER DROPLETS ON THE SURFACE OF SHED.

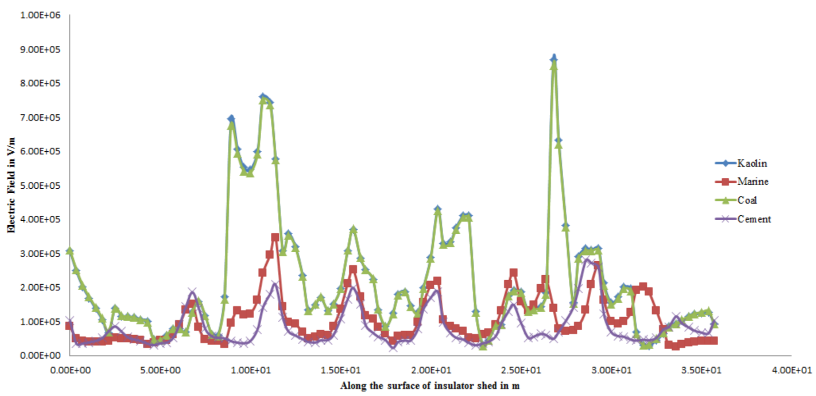


FIG.10. COMPARISON OF ELECTRIC FIELD VARIATION DUE TO WATER DROPLETS ON THE SURFACE SHED OF CONTAMINATED POLYMERIC INSULATORS OF DIFFERENT CONTAMINATIONS

A relative performance is studied for polymeric insulator with different contaminations of kaolin, coal, marine and cement. The thickness of the contamination layer modelled is 0.1 mm and relative permittivity of kaolin, coal, marine, cement, selected are 3.5, 4.5, 5.9, 1.5 [7]. It can be seen from the fig.10 that the electric field variation due to kaolin and coal contamination layers and water droplets has comparatively more impact on the surface of polymeric insulators.

III. EXPERIMENTAL STUDIES ON POLYMERIC INSULATORS

3.1 Salt-Fog test:

To study the effect of continuous discharges on the surface of polymeric insulators, salt fog test is performed. The basic principle of the salt fog test is the generation of discharges continuously by exposing the energized insulator to salt water spray. Polymeric insulators when subjected to combined stress of voltage and salt-fog may experience tracking, erosion, cracks on housing and shed puncture. The combined stress of voltage and salt-fog accelerate the ageing of the polymeric insulators.

A 100 h limited ageing test was performed on 11 kV polymeric insulators. A continuous salt-fog is maintained throughout the 100 h of the ageing test [8]. The test is performed in an ageing chamber of size 2 m x 2 m x 2.5 m. The insulator sample is suspended along with dummy insulator inside the ageing chamber as shown in the fig.11. A test voltage of 10 kV line to ground is applied to the sample. The higher test voltage is applied inorder to accelerate the ageing of the insulator. The test source used is 33 kV, 66 kVA, transformer. The flow rate of water is maintained at 250 ml/min ± 10 ml/min and the air pressure was kept in the range of 4 to 5 kg/cm2 as scale down parameters for the selected chamber size [9, 10]. Tap water is used for the fog whose conductivity is in the range of 3.5 to 3.7 mS/cm. The surface leakage current was measured using DAS (Data Acquisition System). The samples arrangement is shown in fig.12. To evaluate the performance of the insulator after the salt-fog ageing test, hydrophobicity and material analysis are conducted.

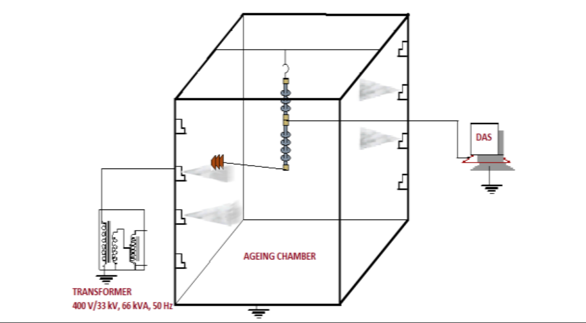


FIG.11. EXPERIMENTAL TEST SETUP

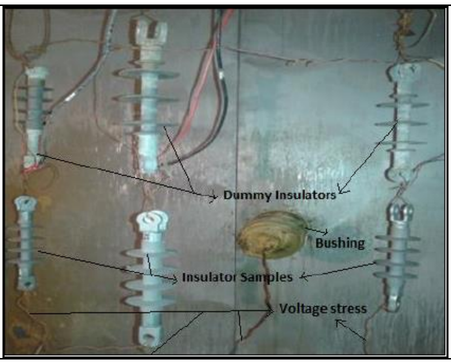


FIG.12. SAMPLES ARRANGEMENT INSIDE AGEING CHAMBER

3.2. Hydrophobicity analysis

The hydrophobicity of the material is the main indicator of the performance of the polymeric insulator. The hydrophobicity test is performed in reference to STRI guide [11]. The hydrophobicity class of virgin sample is HC-1 whereas the hydrophobicity class of 100 h aged sample is HC-3 as shown in fig.13 and fig.14. After the 100 h limited salt fog test there were no tracking and erosion observed on the sheds.

FIG.13. VIRGIN SAMPLE

FIG.14. AGED SAMPLE

3.3. Leakage current variation

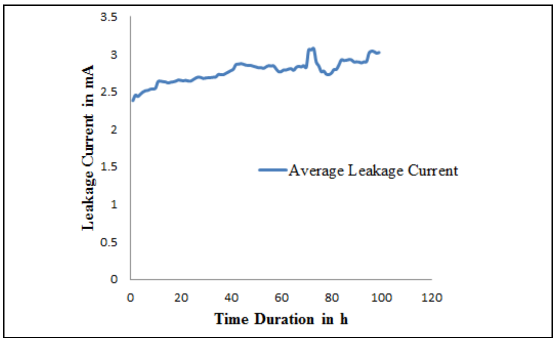


FIG.15. VARIATION OF LEAKAGE CURRENT WITH TIME DURATION

The leakage current recorded using DAS (Data Acquisition System) over the period of 100 h is shown in fig.15. The maximum leakage current recorded is 3.2 mA over the period of 100 h.

3.4. Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray analysis (EDX) analysis

To study the effect of ageing on the material, material analysis was conducted on sample size of 2x2x0.5 cm2 before and after the salt-fog test. The samples selected for the analysis are shown in the fig.16 and fig.17.

FIG.16. VIRGIN SAMPLE

FIG.17. AGED SAMPLE

3.4.1.Scanning Electron Microscopy:

An analysis of polymeric insulator surfaces using SEM shows the molecular structural changes on the surface of the silicone rubber [12]. Fig.18 and fig.19 show the micrographs for virgin and aged samples at 1000x. The overall observation is that aged sample showed visible degradation along the sheath part of the insulator. The virgin sample has a smooth, more homogenous surface while the surface roughness increases with ageing for polymeric insulators.

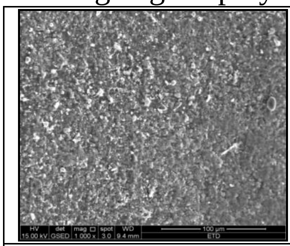


FIG.18. VIRGIN SAMPLE

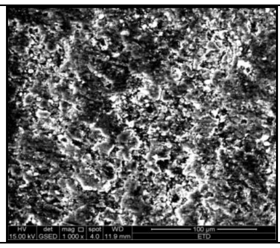


FIG.19. AGED SAMPLE

3.4.2.Energy Dispersive X-Ray analysis:

EDX is an X-ray technique used to identify the elemental composition of materials. EDX systems are attachments to SEM instruments [12]. The data generated by EDX analysis consists of spectra showing peaks corresponding to the elements making up the composition of the sample. The EDX survey spectrum of the virgin and aged samples reveals the presence of Oxygen, Carbon, Silicone and Aluminium as major elements present.

The results of quantitative analysis of EDX are represented in table.1. It shows atomic percentage of elements on the surface of the virgin and aged samples. There is increase in the aluminium percentage in aged sample in comparison to virgin sample. This is due to exposure of ATH as a result of erosion or depletion of large amount of low molecular weight polymer chains on the top of the insulator surface, which indicates the degradation of the material. However, changes in aluminium content alone cannot be taken as quantitative measure of degradation due to non-uniform particle size and heterogeneous nature of ATH, it provides supplementary evidence that the material is degraded [12]. The increase in the deposition of sodium and chlorine contents may also accelerate the degradation of the material.

TABLE.1.
QUANTITATIVE ANALYSIS OF EDX

Atomic percentage	C	O	Al	Si	Na	Ca	Mg	Cl
Virgin Sample	26.3	37.78	7.17	26.78	0.58	1.37	-	-
Aged Sample	26.97	29.37	10.05	26.72	1.67	2.28	2.22	0.72

IV. TESTS ON THE FIELD AGED SAMPLES

Hydrophobicity and material analysis were performed on 25 kV polymeric insulator samples which were in service for 5 to 6 years are collected from different contaminated sites such as coal, cement and marine.

4.1 Hydrophobicity test:

Comparing the figures (fig.20) with STRI guide [11] figures for hydrophobicity, concludes that the hydrophobicity of the samples after removal from service is ranging between HC1 to HC4 shown in table.2. This indicates that all the polymeric insulators still retain their hydrophobicity even after six years of service.

(a). S2 (b).S3 (c). S6

FIG.20. HYDROPHOBICITY PICTURE OF IN SERVICE SAMPLES

TABLE.2.
HYDROPHOBICITY CLASS OF IN SERVICE SAMPLES

Sample	Hydrophobicity Class
S2-Coal	HC3
S3-Cement	HC4
S6-Marine	HC3

4.2 Scanning Electron Microscopy (SEM) and Energy Dispersive X-Ray analysis (EDX) analysis:

FIG.21. FIELD AGED SAMPLES FOR MATERIAL ANALYSIS

For the material analysis of the field aged insulators to investigate the changes in the material properties in comparison with virgin sample, the specimen size of 2x2x0.5 cm2 approximately is chosen [12]. The samples selected for the analysis are shown in the fig.21.

4.2.1 Scanning Electron Microscopy:

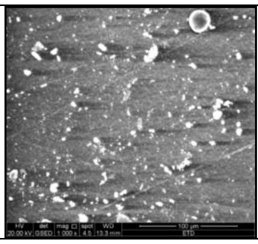


FIG.22. VIRGIN SAMPLE

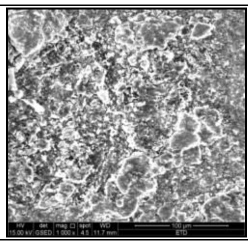


FIG.23. COAL CONTAMINATED SAMPLE

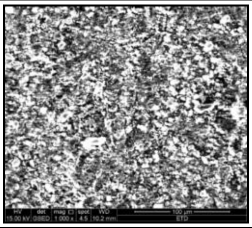


FIG.24. CEMENT CONTAMINATED SAMPLE

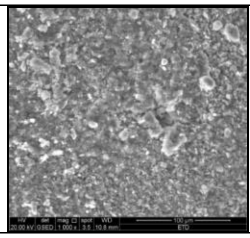


FIG.25. MARINE CONTAMINATED SAMPLE

Fig.22, fig.23, fig.24 and fig.25 show the micrographs for virgin and field aged samples at 1000x [12]. The overall observation is that coal contaminated and cement contaminated samples showed slightly more degradation than the marine contaminated sample.

4.2.2 Energy Dispersive X-Ray analysis:

The EDX survey spectrum of the virgin and field aged samples reveal the presence of Oxygen, Carbon, Silicone and Aluminium as major elements present. The results of quantitative analysis of EDX are represented in table.3. It shows atomic percentage of elements on the surface of the virgin and field aged samples. There is increase in the percentage of aluminium and decrease in the percentage of silicon in field aged samples in comparison to the virgin sample. This is due to depletion of low molecular weight silicone chains and exposure ATH results in release of aluminium. The presence of traces of sodium, magnesium, sulphur and potassium are the indication of deposits due to different contaminants on the surface of insulator. These deposits may also accelerate the ageing of the material.

TABLE.3.
QUANTITATIVE ANALYSIS OF EDX

Atomic percentage	C	O	Al	Si	Na	Ca	Mg	S	K
Virgin Sample	28.04	25.24	15.63	29.03	0	0.41	1.65	-	-
Coal Contaminated Sample	36.83	20.48	25.26	15.5	1.04	-	0.9	-	-
Cement Contaminated Sample	34.63	22.21	16.09	16	1.47	6.46	1.49	0.94	0.71
Marine Contaminated Sample	26.27	23.58	22.48	27.67	-	-	-	-	-

V. CONCLUSIONS

From the results of the simulation studies conducted on polymeric insulators with water droplets and contamination layer and experimental studies the following conclusions can be drawn:

a) The electric field on the surface of complete insulator with water droplets and contamination layer can be evaluated on a section of an insulator.

b) Electric field and potential distribution in water droplets for discharges on the surface of insulator is a function of droplets number and their position. Hence higher discharges are expected for the surfaces covered with more number of water droplets due to higher field concentration.

c) The difference observed in the electric field enhancement for hydrophobic and hydrophilic cases through simulation of polymeric insulator suggests that the discharge activity could also differ for hydrophobic and hydrophilic cases.

d) The electric field enhancement on the surface of sheath in both hydrophobic and hydrophilic cases observed through simulation suggests higher discharge activity and could result in electrohydrodynamic force that helps moisture ingression into the body of insulator. A visible erosion is witnessed after salt fog test on the sheath part of the insulator which indicates the high field concentration on the sheath of the insulator.

e) The electric field enhancement observed through simulation of insulator with the contamination layer of different contaminants in the field under wet conditions is a function of type of contaminant. The surface roughness, increase in the amount of aluminium and the class of hydrophobicity exhibited by field aged samples collected from different contaminant sites justifies the dependency on the type of contaminant for field enhancement.

f) The loss of hydrophobicity is observed more in coal and cement contaminated insulator samples than in marine contaminated insulator sample. This indicates that coal and cement contaminants may age insulator faster.

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