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A critical study on detection of pollution level of overhead insulators by measuring pH and conductivity of the contaminants

Umer Ijaz, Muhammad Fraz Anwar *, Muhammad Nadeem, Muhammad Farhan, Kashif Nisar Paracha, Muhammad Saad Sharif

Department of Electrical Engineering and Technology, Government College University Faisalabad Pakistan

* Corresponding author: Muhammad Fraz Anwar, Email: mfrazanwar@gcuf.edu.pk

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ABSTRACT

The flow of electric power requires overhead insulators to maintain a safe distance between charged conductors and supporting structures. These insulators are installed in outdoor locations and are hence subjected to a variety of adverse environmental conditions, such as airborne dust and other contaminants. In moist conditions, these pollution factors can cause flashover, resulting in the loss of energy in the form of heat and light. Therefore, it is crucial to determine various types of contaminants based on geographical conditions and analyze their effects on the insulation capabilities of these insulators. This research work analyzes the accumulation of certain contaminants on the insulators installed at various geographical locations. Experimental approaches for detecting the level of contamination of insulators have also been examined, along with their limitations. Moreover, the findings of pollution tests performed in industrial, coastal, desert, inland, agricultural, and biological areas are presented as well. The flash-over voltage (FOV) of disc insulators made of porcelain for various pH and conductivity values has been observed to correlate FOV with pH and conductivity values of the pollutants. The pH and conductivity of contaminants are crucial factors impacting the insulator's flashover voltage, which is influenced by surrounding atmospheric conditions. Understanding the composition and monitoring these parameters can aid in developing preventive maintenance programs based on specified pH values, ensuring the reliability and performance of overhead insulators.

1. Introduction

To meet the ever-increasing demand of electricity due to rapid industrialization and improvement in quality of living standards, the long-distance high-voltage (HV) transmission of large amounts of power has been adapted widely as most of the bulk generation facilities are normally far away from consumers. However, effective, and dependable power transmission demands a constantly reliable insulating system, particularly overhead line insulators, which are the foundation of power transmission. Overhead power transmission lines travel across a variety of environments. As a result, overhead insulators are exposed to a variety of contaminants, including industrial smoke, salt deposits, dust, and so on. These factors contribute to insulation deterioration, flashovers, and, eventually, insulation failure in worst case [1].

Therefore, to determine the degree of contamination of disc insulators, information about the geographical locations of insulators and the accompanying pollutants is critical [2]. Pollutants are less of a worry under dry conditions due to their small conductivity and hence minimal likelihood of flashover. In damp conditions, such as fog, rain, snow, or mist the contaminant on the insulation surface dissolves, forming a conductive layer that causes partial discharge activity and leakage current, finally causing the insulator to flash over [3].

A long-duration flashover produces uneven expansions of the porcelain material, breaking the insulator body with large cracks and consequently interrupting the supply. As a result, it's crucial to monitor insulator pollution levels in order to avoid a flashover and ensure power transmission reliability [2].

Pollution-induced flash-over is the most critical concern with high voltage insulators in Pakistan's northern territories. Industrial emissions, dust, dirt, traffic pollution, desert salts and saline deposits are all prominent sources of environmental pollution. Several approaches for monitoring the level of contamination of insulators have been presented in recent years. [4] These methods are based on a variety of characteristics, including electromagnetic radiations, acoustic emissions, leakage current, pH levels, conductivity, and the equivalent salt deposit density (ESDD) of the electrolytic layer generated on the insulator's surface [5]. This research describes the best approach for determining the level of contamination in real time on the insulator surface. This work also discusses the limitations of the methodologies mentioned above.

2. Adverse Conditions of Insulators

An insulator is a material that serves both electrical and mechanical purpose [6]. It keeps the conductor or busbar at a set safe distance from the ground mechanically and provides the necessary insulation between conductor and the pole. Insulators are said to be in poor condition when one or both of these roles are compromised or no longer being met. Insulators are subjected to the following unfavorable conditions:

2.1 External Stress

When insulator is subjected to mechanical force through its conductor, if there is a weak section of the insulation owing to a manufacturing defect, it can break from that weak spot. Ice deposits or high winds can also cause breaking [5].

2.2 Internal Stress

The disc insulator is made up of three different materials: the basic porcelain shell, the metal fitting course of action, and the cement used to bond the metal section to the porcelain [7]. These materials grow or shrink at different rates as a result of changing climate conditions, producing internal tension [8]. The main cause of cover splitting is this uneven swelling or compression of porcelain body, cement, and the metal fitting [5].

2.3 Short Circuits

Because of huge birds and other such items, short circuit of the conductor to earth occurs often in pin insulators. The use of a bird’s guard at the insulator on the crossbar prevents such an occurrence. Furthermore, this problem can be controlled by increasing distance between conductor and earthed portions or employing disc insulators rather than pin type insulators [5].

2.4 Overvoltage

Switching processes, lightning strokes, and other sources of overvoltage generate anomalous voltage gradients along the insulator's surface [7]. This could result in a flashover or insulator perforation. Surge arresters, on the other hand, are utilized in the system to minimize the over-voltages created by both of these circumstances [9].

2.5 Pollution Induced Flashover

Flashover caused by pollution is one of the reasons of HV insulator failure. Contaminants on the surface of the insulator melt, making a layer which conducts and causes leakage and partial discharge, eventually leading to flashover [10]. A long-duration flashover produces uneven spreading of the porcelain material, breaking the insulator and causing large cracks. This insulator smashing leads in a loss of power supply as well as an increase in maintenance and engineering expenditures [11].

3. Pollutants Corresponding to Different Geographical Locations

3.1 Industrial Area

Smoke, chimneys ash, and dirt from the industries extensively pollute insulators in industrial zones. Pollutant chemical characteristics differ depending on the type of industry. Bassanite ($2CaSO_4.H_2O$) will be the dominant soluble constituent in the field near the steel industry, with SiO_2, Fe_2O_3, CaO, and MgO as non-soluble contaminants [5].

3.2 Coastal Area

Overhead insulators in seaside areas are subjected to strong sea breezes. This wind carries a lot of salt in the form of sodium chloride (NaCl). It also contains magnesium chloride ($MgCl_2$), which quickly absorbs and retains moisture from the surrounding environment. As a result, sodium chloride and magnesium chloride severely contaminates the insulators [5].

3.3 Desert Area

There is minimal rain in arid places; insulators are extensively accumulated by grit, dirt, and other impurities, as the self-cleaning action is absent [12]. In arid environments, the principal soluble components are sodium chlorides (NaCl), calcium sulphates ($CaSO_4$), and potassium chlorides (KCl). Because of the saline breezes that blow from the sea, deserts near the seacoast have a lot of NaCl [13].

3.4 Inland Area

Inland insulators have surfaces coated by sand and dust carried by the wind. Calcium sulphates ($CaSO_4$), sodium nitrates ($NaNO_3$), and calcium nitrate ($Ca(NO_3)_2$) are the major elements of sand and soil. Other salts including magnesium chloride ($MgCl_2$), sodium chloride (NaCl), magnesium sulphate ($MgSO_4$), and potassium chloride (KCl) have also been spotted to some extent [5].

3.5 Agricultural Area

In agricultural areas, calcium sulphate ($CaSO_4$) is a common soluble component. In addition, electrically conductive ions such as phosphates and nitrates have also been found in agricultural fertilizers. Winds or birds might deposit these contaminants on the insulation's surface, reducing its performance [14].

3.6 Biological Area

Fungi and algae cover the bottom surface of insulators deployed in biological zones. Wet environments promote the growth of algae and fungi. Algae and fungi, for example, include soluble salts such as NaCl, which significantly impair the insulation's strength [5].

4. Experimental Procedure

To conduct the research, four typical places in and around Faisalabad were chosen, representing a road highway, agricultural area, an area near a brick kiln, and a residential area (Pakistan). The four places are around twenty miles apart. Faisalabad is in the northern Pakistani state of Punjab. It is located at 31.42°N latitudes and 73.08°E longitudes, at a height of 186 m above mean sea level, in the subtropical climate zone.

Summers are hot and dry, with mean temperatures ranging from 33°C to 42.5°C, and winters range from 8.2°C to 21.4°C. The rainy season in Faisalabad is intermittent, with an annual average rainfall of roughly 375 mm. Table 1 gives a description of the places as well as the possible types of pollution.

Table 1

Description of the Various Locations

No.	Location	Description
01	220 kV Transmission Line Gatti-Ludewala	Location outside of the city on the Chiniot bypass (dust, vehicular, and agricultural pollution).
02	220 kV Transmission Line Gatti-Bandala	Agricultural area near Shahkot.
03	220 kV Transmission Line Gatti-Yousafwala	Site extremely near to brick kilns at Khanuana bypass, Faisalabad (Dust, fly ash, low vehicular traffic, agricultural pollution)
04	220 kV Transmission Line Gatti-Nishatabad	Residential area at Nishatabad Bismillah colony, Faisalabad (No industry nearby, very little vehicular activity).

5. Sample Preparation

The tests were conceded utilizing disc insulators, which are often, utilized in overhead power transmission lines/networks in Pakistan. The unit is 254 mm in diameter, with 127 mm spacing and a 290 mm leaking distance [15]. Table 1 lists the sites where sample insulators were taken out. At the first week of December 2021, the investigation began with the collection of disc insulators in each of the four sites. Samples were taken to the high voltage laboratory at the end of the required exposure duration to be evaluated for the relevant parameters.


Fig. 1. Contaminated disc insulators

Fig. 2. Samples collected from specified locations.

6. Measurements

6.1 Voltage Measurement

Fig. 3 depicts a schematic of the experimental test setup used in this study. A testing transformer was used to produce high voltage rated value 150 kV, 50 Hz, single phase and 30 kVA. At maximal excitation, the testing transformer's short circuit current is 15 A. For measurement of voltage, primary side of the transformer was connected to a volt meter (accuracy $\pm$1 percent), which measure low voltage side [16].

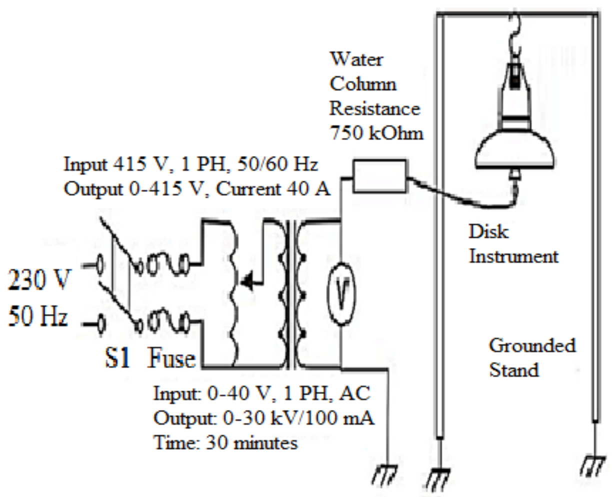

Fig. 3. Experimental setup to determine the flashover voltage under different polluted conditions.

The test sample with the pollution layer was mounted in the experimental chamber. The high voltage was applied through a high voltage transformer at a very low level and increased gradually until the flashover occurred. The flashover voltage during the arc initiation and at the end of flashover process was recorded.

6.2 Measurement of pH

The pH of a liquid determines whether it is acidic or basic. The scale runs from 0 to 14, with seven serving as the neutral number [13]. A pH less than 7 implies acidity, while a pH greater than seven suggests base. The relative number of free hydrogen and hydroxyl ions present in a liquid is measured by its pH. Free hydrogen ions are more abundant in acidic liquids, while free hydroxyl ions are more abundant in basic liquids [17].

After removing the accumulated salt on the sample, the pH value of the contaminant was determined using a LI 120 pH metre with a range of 0-14. The solution sample was poured in the cup, and the retractable arm's glass probe was inserted into the solution. Two electrodes measuring voltage at the end of the probe were housed within the thin glass bulb. One electrode is submerged in a liquid with a predetermined acidity level, or pH. The acidity of the solution sample is detected by the other electrode. The difference between the voltages of the two electrodes is measured by a voltmeter in the probe. After that, the voltage difference is converted to pH and is shown on the meter box's small screen.

6.3 Measurement of Conductivity

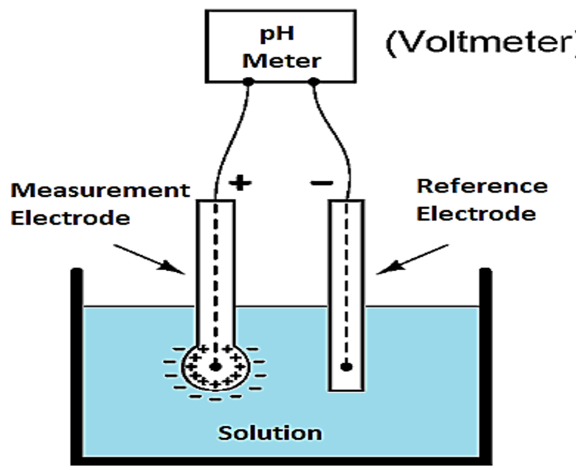

Fig. 4. pH measurement setup

A conductivity meter (CM 180) was used to evaluate the parameter conductivity of the contaminants accumulated on the surfaces of the insulators. The meter used in this setup has cell constant of 0.2 to 1 and a conductance range of 18 PS to 200 ms.

Following the removal of the sample's deposited salt, the EC value of the pollutant was determined using a CM 180 meter. Collected sample in a glass container. Then its solution sample was placed in a cup and probe inserted in the solution. The meter then displays EC value on the small screen on the main box.

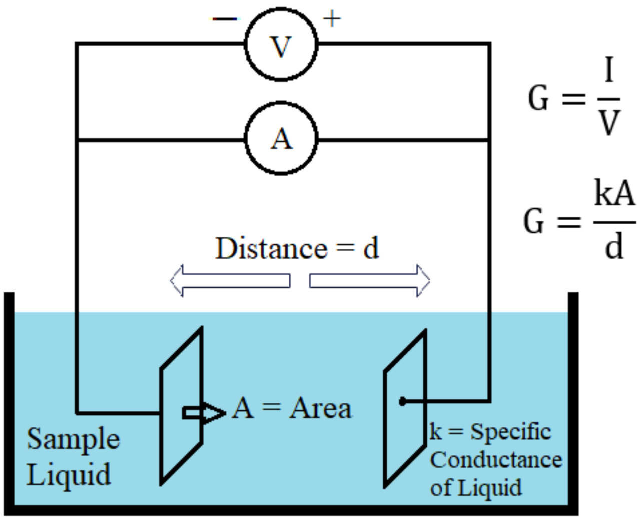

Fig. 5. Conductivity measurement setup

Fig. 6. Measuring electrical conductivity of different samples

6.4 ESDD Calculation

The amount of soluble material that has the potential to conduct electricity is traditionally expressed by an equivalent amount of NaCl or equivalent salt deposit density (ESDD), because ionic transmission in aqueous salt solution causes the electrical condition along contaminated surfaces. Volume conductivity, solution temperature, and wash water solution volume were used to get the ESDD value [18].

7. Results and Discussion

The polluted insulators were subjected to high voltage afterwards exposed to natural conditions, to measure flashover voltage. Tables 4-7 provide the observed values of FOV per unit insulation distance (FOVUID), pH and conductivity.

Table 2

Location 1 (Highway) December 2021

Sample #	pH	σ (μs/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.92	92.30	0.037	3.10
2	6.90	94.00	0.038	3.10
3	6.88	96.12	0.040	3.060
4	6.85	99.30	0.045	3.045
5	6.80	102.4	0.048	3.020
6	6.75	106.2	0.051	3.010
7	6.70	110.0	0.053	3.0
8	6.50	121.0	0.057	2.8

Table 3

Location 2 - (Agricultural Area) December 2021

Sample	pH	σ (μs/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.98	80.00	0.027	3.20
2	6.96	80.60	0.028	3.23
3	6.95	83.22	0.030	3.16
4	6.94	84.30	0.030	3.14
5	6.93	85.00	0.030	3.13
6	6.91	87.40	0.0311	3.10
7	6.90	89.20	0.0312	3.11
8	6.88	93.2	0.0313	3.05

Table 4

Location 3 - (Brick Kilns) December 2021

Sample	pH	σ (μS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.24	150.20	0.0624	2.81
2	6.18	158.10	0.0779	2.76
3	6.10	167.20	0.0884	2.74
4	6.00	160.10	0.089	2.70
5	5.95	176.40	0.143	2.70
6	5.91	180.06	0.210	2.66
7	5.80	183.10	0.180	2.60
8	5.50	188.20	0.224	2.81

Table 5

Location IV (Residential Area) December 2021

Sample	pH	σ (µS/cm)	ESDD (mg/cm^2)	FOVUID (kV/cm)
1	6.95	107.20	0.027	3.25
2	6.94	109.18	0.028	3.22
3	6.93	110.15	0.029	3.21
4	6.91	111.22	0.029	3.19
5	6.90	109.10	0.030	3.19
6	6.88	114.17	0.030	3.16
7	6.87	117.06	0.0313	3.14
8	6.82	125.15	0.0316	3.00

7.1 Variation of FOVUID and pH

Fig. 7 to 10 below shows the fluctuation in FOVUID and pH values of the pollutants for various locations.

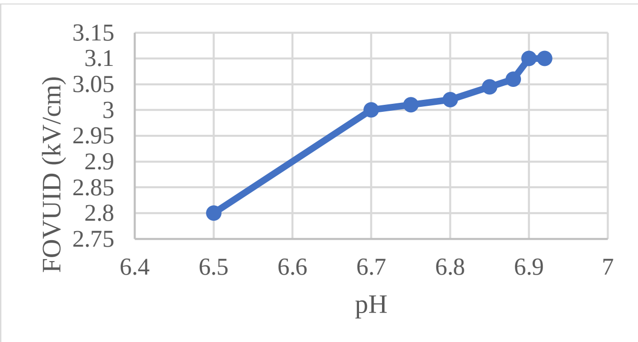

Fig. 7. Variation of FOVUID with pH at Location 1 (Highway)

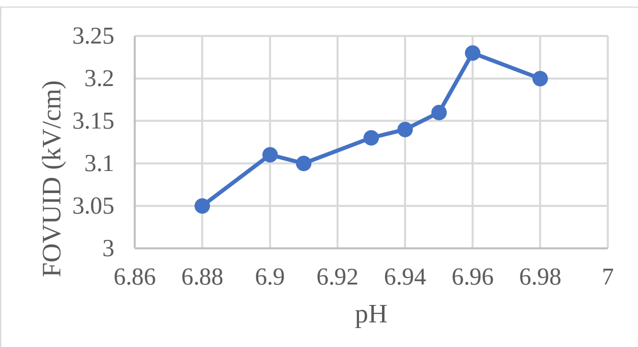

Fig. 8. Variation of FOVUID with pH at Location 2 (Agricultural Area)

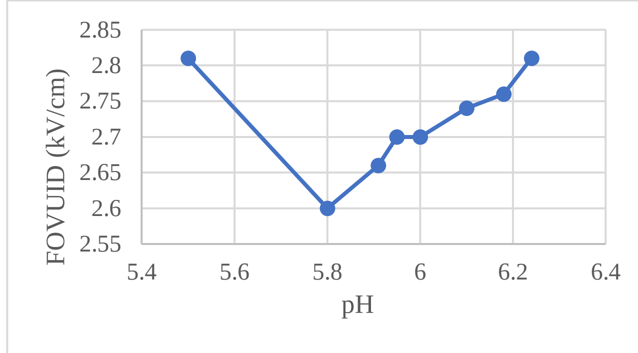

Fig. 9. Variation of FOVUID with pH at Location 3 (Brick Kilns)

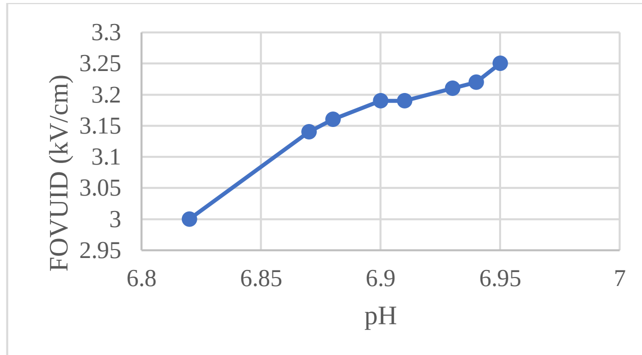

Fig. 10. Variation of FOVUID with pH at Location 4 (Residential Area)

Fig. 7 to 10 above illustrates, as the pH of the contaminants rises, the FOVUID values rise as well. As pH rises, the concentration of hydrogen ion is reduced, meaning that the electrolytic solution is little acidic. It may also be deduced, despite the fact that the three places are isolated by around 20 km; there is a difference in the contaminant's pH value. This could be owing to the different types of deposits found at the three locations. Dust, microscopic carbon particles, ash, and oil generated by incomplete fuel combustion make up the deposit at site one. In addition to dust, insulators near thermal plants are vulnerable to fly ash deposits, which primarily consist of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, P_2O_5, carbon, and carbonate ions [19].

7.2 Variation of FOVUID and ESDD

Fig. 11 to 14 below shows the decrease in FOVUID with increase in ESDD for various locations.

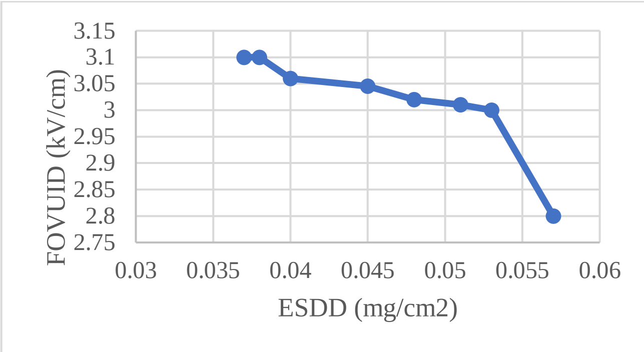

Fig. 11. Variation of FOVUID with ESDD (mg/cm^2) at Location 1 (Highway)

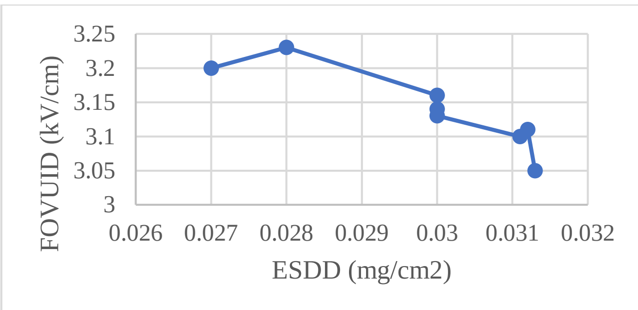

Fig. 12. Variation of FOVUID with ESDD (mg/cm^2) at Location 2 (Agricultural Area)

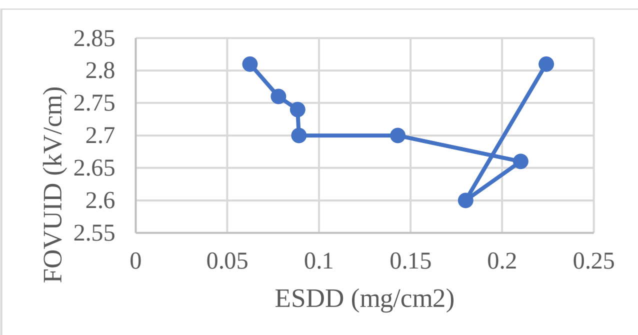

Fig. 13. Variation of FOVUID with ESDD (mg/cm^2) at Location 3 (Brick Kilns)

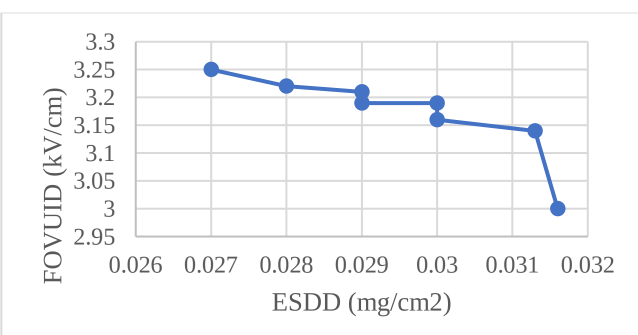

Fig. 14. Variation of FOVUID with ESDD (mg/cm^2) at Location 4 (Residential Area)

While the three locations are all in the low-to-moderate pollution category, the decrease in FOVUID at position three is the smallest, indicating that it is the least polluted. Even though location two samples have a greater ESDD for the whole experiment, the values of FOVUID are nearly identical to those of site one. This is owing to the properties of the inactive ash accumulated on the surface of the samples, which produces an inactive matrix that obstructs leakage current passage.

Greater relative humidity, in addition to a high ESDD, plays an important effect in reducing the voltage which puts the insulator to flashes-over, because the availability of dissociated water ions rises at higher relative humidity [1].

8. Conclusion

The pH and conductivity (ESDD) of contaminants play a significant role in determining the insulator's flashover voltage. It is determined by the surrounding atmospheric conditions. The insulation required must match to the requirements. A considerable increase in FOV occurs when the pH of the pollutant rises. As the ESDD increases, the flashover voltage decreases significantly. The pH variation is due to the composition of the deposit. Flashover voltage may vary even for the same ESDD, due to the presence of main non soluble components in scattered contaminants. Relative humidity is important in determining flashover characteristics. Constant monitoring of conductivity and pH, which indicate the severity of pollutants accumulating on insulators, can be utilized to develop a preventive maintenance program and as an analytic tool to assess a maintenance schedule as the pH of a common pollutant reaches a specified value.

9. Acknowledgement

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