

# Mathematical Modeling on AC Pollution Flashover Performance of Glass and Composite Insulator

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**Abstract** – While considering the current scenario, in this world power demand goes on increases day by day. Frequent power outages occur in high voltage transmission line due to the deprived performance of polluted insulators; this affects overall operation of power system and may indirectly impinge on the growth of production sector. Many researchers are keenly taking efforts to provide highly reliable and stable power to neediest. In this paper, A.C pollution flashover performance of disc type glass insulator and composite long rod insulators investigation under various artificial pollutions by varying Equivalent Salt Density Deposition (ESDD) levels. Here, we use different types of pollution methods like binding method, dipping method and spraying methods with different types of pollutants concentration. Based on dimensional analysis, four different Mathematical models have been developed to predict the A.C pollution Flashover Voltage (FOV) of insulators. Both the experimental and mathematically modeled results are compared; it's observed that mathematical model 3 yields better results.

**Keywords:** A.C pollution flashover voltage, Pollution method, Modeling

## 1. Introduction

The two broad categories of insulators are ceramic and polymeric. The ceramic insulators are constructed from porcelain and glass. Polymeric insulators referred to as non-ceramic insulators. These are typically composed of a central rod made of fibre reinforced plastic and an outer weather shed made of silicone rubber or Ethylene Propylene Diene Monomer rubber (EPDM). The composite insulators replace porcelain insulators because of its excellent anti-pollution performance, economical maintenance, light weight and suitable for highly polluted areas [1-3]. To ensure the safe and reliable operation of ac transmission lines, a great number of research on ac flashover performance of polluted insulators have been conducted [1-15].

The environment in which an insulator is installed can have a significant impact on the unit's performance. When insulators are situated in areas where they are exposed to contaminate, their performance can deteriorate significantly. Natural dust, industrial waste, coastal fog etc... forms dry pollution layer on the surface of the insulators. It does not affect the operation of the insulators. While rain drops, moisture, fog etc... forms surface of insulators as wet, resistivity of the pollution layer reduced and leakage current increases exponentially and it leads to flashover of the insulator, which become an important problem for the

safe operation of transmission lines and the design of the external insulation [4-6].

In order to effectively assess the degree of contamination present on an insulator surface the dimensions of the insulator must taken into account. The relevant dimensions include creepage distance, diameter and height. The troublesome pollution comes in two forms. The soluble and nonsoluble components – e.g. salts from the sea and industrial gases that result in weak acids being formed, it produce an electrolyte when dissolved in water, this can be expressed as equivalent salt density deposition. And the nonsoluble materials, the nonsoluble part of the pollutant, can be expressed as the nonsoluble deposit density [7].

Artificial pollution testing on insulators classified into Salt Fog and Solid Layer methods. In this solid layer method is widely used because the contaminant conditions are significant for the selection of external insulation of transmission lines and substations in pollution regions. Test procedures of Solid Layer Method are described in IEC 60507 [9]. Table 1 shows different types of pollution test

**Table 1.** Overview of different pollution test methods applied for polymeric insulators (adopted from [8]).

| Method             | Conditioning required | Time consumption | CIGRÉ Strategy |
|--------------------|-----------------------|------------------|----------------|
| IEC 60507 Salt-Fog | Yes                   | Hours            | A              |
| Quick Salt-Fog     | Yes                   | Hours            | A              |
| Clean fog          | Yes                   | hours to day     | A              |
|                    | Natural pollution     | No               | hours to day   |
| Rapid clean-fog    | -                     | Hours            | A              |
| Dust cycle method  | No                    | Day              | B              |
| Dry-salt layer     | No                    | hours to day     | B              |

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methods for polymeric insulators.

Solid layer pollution methods are classified as Brushing Method (BM), Spraying Method (SM) and Dipping Method (DM) [10]. Researchers adopted different polluting methods in the pollution tests.

One of the key steps in the process of mathematical modeling is to determine the relationship between the variables. Dimensional analysis is a method to determine how variables are related for simplifying a mathematical model. Dimensional analysis alone does not give the exact form of an equation, but it can lead to a significant reduction of the number of variables. Units must be taken into consideration when collecting the data as well as when making the list of factors impacting the model and when testing the model. There is need to check that all the equations in a model are dimensionally consistent. [11-15]. This paper has been preceded with the proposed method which includes the experimental method of testing the insulators, developing the mathematical model with the different dimensionality functions and matching the accuracy of both the results obtained.

## 2. Experimental Method

### 2.1 Test equipment

Experimental investigations are carried out in the artificial pollution chamber. Test power is supplied by 100 kV test transformer. Both the AC and DC voltage can be applied for the pollution tests. In this paper, the pollution tests are carried by using AC supply voltage and the artificial pollution chamber with a height and length of 60cm.

### 2.2 Test specimens

The samples of insulators used this paper are Disc type Glass insulator and Composite insulator. Their dimensions and profile are shown in Table 2 and Fig. 1 (a) and (b)

**Table 2.** Dimensions of insulators tested

| Types | Material  | Dimensions (mm) |     |     |
|-------|-----------|-----------------|-----|-----|
|       |           | D               | H   | L   |
| A     | Glass     | 254             | 146 | 292 |
| B     | Composite | 415             | 240 | 510 |



(a)



(b)

**Fig.1.** Profiles of insulator tested: (a) Type A; (b) Type B

dimensions used are D is the disc diameter, H is the configuration height, and L is the creepage distance of the insulators tested [7].

### 2.3 Preparation of samples

#### 2.3.1 Preconditioning of specimens

Before the pollution flashover tests are carried out, the specimens are carefully cleaned to ensure removing of all traces of dirt and grease and then dried naturally [16]. The specimen surfaces are coated with a very thin layer of dry kieselguhr to destroy the hydrophobicity. After one hour the completion of above procedures, surfaces of the specimens are contaminated with the suspension of sodium chloride and kieselguhr to acquire various equivalent salt deposit density levels 0.0103, 0.0319, 0.054 and 0.076 respectively, which simulate the electric and inert materials [17].

#### 2.3.2 Artificial pollution of insulators

Solid layer method can be employed to contaminate the surface of the insulators by three methods namely Brushing Method (BM), Dipping Method (DM) and Spraying Method (SM) [10].

### 2.4 Testing of samples

Flashover voltages of insulators without any pollution are measured as per reference [10] and results obtained are shown in Table 3.

**Table 3.** Flashover voltages of the insulators without pollution

| Insulator | Flashover voltage without pollution |
|-----------|-------------------------------------|
| Type A    | 71.5 kV                             |
| Type B    | 100 kV                              |

#### 2.4.1 Wetting

After polluting the insulator by one of the solid layer method above said, they are allowed for natural drying.

- The composite long - rod insulators are dried for 24 hours.
- The glass disc insulators are dried for 5 hours.

The insulators are positioned vertically at the centre of the artificial pollution chamber. Then they are completely wetted by spraying purified water with an angle of 45° before applying the test voltage. Now the pollution layer on the insulator surfaces is wetted, a series of flashover tests were carried out using AC supply.

#### 2.4.2 Flashover voltage evaluation

The test method used here is Even-Rising Voltage

Method. Using this method the flashover voltage and the standard deviation are calculated as follows:

Increase the voltage at a random rate till the flashover occurs. Record the flashover voltage,  $U_f$ . 1-2 minutes later, repeat the above procedure for five times. For the polluted specimen, the series of flashover voltage obtained by above procedure expressed as  $U_{f1}, U_{f2}, \dots, U_{fn}$  (n is the number of flashovers). The minimum flashover voltage of the polluted insulator is,

$$U_{fm} = \text{Min} (U_{f1}, U_{f2}, \dots, U_{fn}) \quad (1)$$

Concerning five effective flashover voltages, average flashover voltage for the each insulator is calculated as:

$$U_{av} = \sum_{i=1}^N U_{fm}(i) \quad (2)$$

where,  $U_{av}$  – average flashover voltage,  $U_{fm}$  – Minimum flashover voltage, N – Total times of effective tests and the standard deviation is calculated as:

$$\sigma(\%) = \sqrt{\frac{\sum_{i=1}^N (U_{fm}(i) - U_{av})^2}{N}} \quad (3)$$

where,  $(\sigma\%)$  – standard deviation  $U_{fm}(i)$  – minimum flashover voltage obtained from the test in the  $i^{\text{th}}$  time.

### 2.4.3 Measurement of ESDD

After flashover testing, the polluted insulators are dried under bright sunlight and dry pellets of NaCl sticking to the insulator surface are collected by brushing them off with a small paint brush. The collected deposits are then dissolved in 100 ml of distilled water. The conductivity measuring instrument is used to measure the conductivity of each collected salt solution. At the same time, the temperature is also recorded. The conductivities at different temperatures are converted to conductivity at 20°C using the formula:

$$\sigma = \sigma_{20^\circ C} (1 + b (\theta - 20^\circ C)) \quad (4)$$

where,  $\theta$  is the solution's temperature in degree Celsius,  $\sigma$  is the volume conductivity at the temperature  $\theta$ ,  $\sigma_{20}$  is the volume conductivity at temperature 20°C (S/m), and b is a temperature depend factor. (b=0.01905). Finally, the ESDD is determined as:

$$ESDD = \frac{S_a * Vol \text{ in } cm^3}{Area \text{ in } cm^2} \quad (5)$$

where, Vol is the volume of the solution in  $cm^3$ , A is the area of the cleaned surface in  $cm^2$ ,  $S_a$  is the salinity of the diluted liquid. It is given as:

$$S_a = (5.7 * \sigma_{20})^{1.03} \quad (6)$$

Thus the ESDD's at various pollution degrees are calculated and shown in Table 8.

## 3. Mathematical Modeling

Dimensional analysis discovers the relations among physical quantities by using their dimensions. This could be done by selecting the number of fundamental dimensions and standard magnitude for these dimensions. Four fundamental physical dimensions namely, length (L), mass (M), time (T) and current (A) are used to develop the relationship among the AC flashover voltage and other parameters that affects the flashover voltage in the outdoor environment. The calculation of FOV primarily depends on the ESDD, conductivity of pollution layer ( $\sigma_s$ ), surface area of the insulator (A), resistivity of the pollution layer ( $r_p$ ) and arc constant. In this paper, four models were developed and four parameters are taken for analysis in each model. In order to utilize the algebraic approach to dimensional analysis, it is convenient to display the dimensions of the respective variables in the matrix format. From the dimensional matrix homogenous algebraic equations are formed and solved. By applying Buckingham's  $\Pi$  theorem, the final dimension expression of FOV can be obtained.

### 3.1 Model 1:

In this model, FOV, ESDD, conductivity of the pollution layer ( $\sigma_s$ ) and arc constant ( $N_0$ ) are taken as the parameters for analysis. Therefore the relation among them can be written as:

$$U_{av} = f(ESDD, \sigma_s, N_0) \quad (7)$$

The dimensional matrix of the respective variables can be written and shown in Table 4.

**Table 4.** Dimensional matrix of Model – I

|   | $U_{av}$ (k1) | ESDD (k2) | $\sigma_s$ (k3) | $N_0$ (k4) |
|---|---------------|-----------|-----------------|------------|
| L | 2             | -2        | -2              | 1          |
| M | 1             | 1         | -1              | 1          |
| T | -3            | 0         | 3               | -3         |
| A | -1            | 0         | 2               | n-1        |

Homogeneous linear algebraic equations are formed and solved through the above dimensional matrix. The values of  $k_2$ ,  $k_3$  and  $k_4$  in terms of  $k_1$  (which represents the FOV) can be expressed as:

$$\begin{aligned} k_2 &= k_1/2 \\ k_3 &= n*k_1/(n+1) \\ k_4 &= -k_1/(n+1) \end{aligned} \quad (8)$$

By assigning  $k_1=1$  and Buckingham's  $\pi$  theorem, the

final dimensional expression describing AC FOV is obtained as:

$$\Pi = U_{av} * ESDD^{-1/2} * \sigma_S^{-n/(n+1)} * N_0^{1/(n+1)} \quad (9)$$

By applying Buckingham’s  $\pi$  theorem, the above equation can be written as:

$$U_{av} * ESDD^{-1/2} * \sigma_S^{-n/(n+1)} * N_0^{1/(n+1)} = dc \quad (10)$$

where dc is the dimensional constant. Therefore the final dimensional expression describing FOV can be written as:

$$U_{av} = dc * ESDD^{1/2} * \sigma_S^{n/(n+1)} * N_0^{-1/(n+1)} \quad (11)$$

The values of equation (11) is known, the FOV are calculated and shown in Table 10.

### 3.2 Model 2

In this model, FOV, ESDD, surface area of the insulator and arc constant are taken as the parameters for analysis. Therefore the relation among them can be written as:

$$U_{av} = f(ESDD, A, N_0) \quad (12)$$

The dimensional matrix of the respective variables can be written and shown in Table 5.

Homogeneous linear algebraic equations are formed and solved through the above dimensional matrix. The values of  $k_2, k_3$  and  $k_4$  in terms of  $k_1$  (which represents the FOV) can be expressed as:

**Table 5.** Dimensional matrix of Model – II

|   | Uav (k1) | p (k2) | ESDD (k3) | N <sub>0</sub> (k4) |
|---|----------|--------|-----------|---------------------|
| L | 2        | -2     | -2        | 1                   |
| M | 1        | 1      | 1         | 1                   |
| T | -3       | 0      | 0         | -3                  |
| A | -1       | 0      | 0         | n-1                 |

$$\begin{aligned} k_2 &= (-n/n-1) * k_1 \\ k_3 &= -(4n-1/2n-2) * k_1 \\ k_4 &= (1/n-1) * k_1 \end{aligned} \quad (13)$$

By assigning  $k_1=1$  and Buckingham’s  $\pi$  theorem, the final dimensional expression describing FOV is obtained as:

$$\Pi = U_{av} * ESDD^{n/(n+1)} * A^{(4n-1/2n-2)} * N_0^{(-1/n-1)} \quad (14)$$

By applying Buckingham’s  $\pi$  theorem, the above equation can be written as:

$$U_{av} * ESDD^{n/n+1} * A^{(4n-1/2n-2)} * N_0^{(-1/n-1)} = dc \quad (15)$$

The final dimensional expression describing FOV can be written as:

$$U_{av} = dc * ESDD^{(n/n+1)} * A^{(4n-1/2n-2)} * N_0^{(-1/n-1)} \quad (16)$$

The values of equation (16) is known, the FOV are calculated and shown in Table 10.

### 3.3 Model 3

In this model, FOV, Pollution severity factor (p), ESDD and arc constant (N<sub>0</sub>) are taken as the parameters for analysis. Therefore the relation among them can be written as:

$$U_{av} = f(p, ESDD, N_0) \quad (17)$$

The dimensional matrix of the respective variables can be written and shown in Table 6.

**Table 6.** Dimensional matrix of Model – III

|   | Uav (k1) | ESDD (k2) | A (k3) | N <sub>0</sub> (k4) |
|---|----------|-----------|--------|---------------------|
| L | 2        | -2        | 2      | 1                   |
| M | 1        | 1         | 0      | 1                   |
| T | -3       | 0         | 0      | -3                  |
| A | -1       | 0         | 0      | n-1                 |

Homogeneous linear algebraic equations are formed and solved through the above dimensional matrix. The values of  $k_2, k_3$  and  $k_4$  in terms of  $k_1$  (which represents the FOV) can be expressed as:

$$\begin{aligned} k_2 &= (4n-1/2n-2) * k_1 \\ k_3 &= -(n/n-1) * k_1 \\ k_4 &= 1/(n-1) * k_2 \end{aligned} \quad (18)$$

By assigning  $k_1=1$  and applying Buckingham’s  $\pi$  theorem, the final dimensional expression describing FOV is obtained as:

$$\Pi = U_{av} * P^{(4n-1/2n-2)} * ESDD^{-(n/n-1)} * N_0^{1/(n-1)} \quad (19)$$

By applying Buckingham’s  $\pi$  theorem, the above equation can be written as:

$$U_{av} * P^{(4n-1/2n-2)} * ESDD^{-(n/n-1)} * N_0^{1/(n-1)} = dc \quad (20)$$

The final dimensional expression describing FOV can be written as:

$$U_{av} = dc * P^{(4n-1/2n-2)} * ESDD^{n/(n-1)} * N_0^{-1/(n-1)} \quad (21)$$

The values of equation (21) is known, the FOV are calculated and shown in Table 10.

### 3.4 Model 4

In this model, FOV, Resistance of the pollution layer ( $r_p$ ), Surface area of the insulator (A) and arc constant (N<sub>0</sub>) are taken as the parameters for analysis. Therefore the relation

**Table 7.** Dimensional matrix of Model – IV

|   | U <sub>av</sub> (k1) | r <sub>p</sub> (k2) | A (k3) | N <sub>0</sub> (k4) |
|---|----------------------|---------------------|--------|---------------------|
| L | 2                    | -2                  | -2     | 1                   |
| M | 1                    | 1                   | 1      | 1                   |
| T | -3                   | 0                   | 0      | -3                  |
| A | -1                   | 0                   | 0      | n-1                 |

among them can be written as:

$$U_{av} = f(r_p, A, N_0) \tag{22}$$

The dimensional matrix of the respective variables can be written and shown in Table 7.

Homogeneous linear algebraic equations are formed and solved through the above dimensional matrix. The values of k<sub>2</sub>, k<sub>3</sub> and k<sub>4</sub> in terms of k<sub>1</sub> (which represents the FOV) can be expressed as:

$$\begin{aligned} k_2 &= -(n/n+1) * k_1 \\ k_3 &= -1/2 * k_1 \\ k_4 &= -1/(n+1) * k_1 \end{aligned} \tag{23}$$

By assigning k<sub>1</sub>=1 and applying Buckingham’s π theorem, the final dimensional expression describing FOV is obtained as:

$$\Pi = U_{av} * r_p^{-n/(n+1)} * A^{-1/2} * N_0^{-1/(n+1)} \tag{24}$$

By applying Buckingham’s π theorem, the above equation can be written as:

$$U_{av} * r_p^{-n/(n+1)} * A^{-1/2} * N_0^{-1/(n+1)} = dc \tag{25}$$

The final dimensional expression describing FOV can be written as:

$$U_{av} = dc * r_p^{n/(n+1)} * A^{1/2} * N_0^{1/(n+1)} \tag{26}$$

The values of equation (26) is known, the FOV are calculated and shown in Table 10.

#### 4. Results and Discussion

##### 4.1. Experimental analysis

The experimental investigation on the pollution flashover performance of composite long rod insulator and Disc type Glass insulator has been carried out. The average FOV U<sub>av</sub> (in kV) and standard deviation (%) are shown in Table 8. for three pollution methods (BM, SM and DM) with different ESDD’s 0.0103, 0.0319, 0.054 and 0.076 mg/cm<sup>2</sup>.

While comparing the FOV of pure insulators and artificially polluted insulator for various ESDD’s, pure insulators shows high withstand ability than polluted

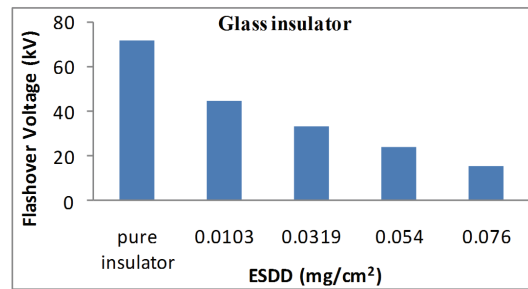
**Table 8.** Flashover voltages of samples using various polluting methods.

| TYPE | ESDD (mg/cm <sup>2</sup> ) | BM                   |      | SM                   |      | DM                   |      |
|------|----------------------------|----------------------|------|----------------------|------|----------------------|------|
|      |                            | U <sub>av</sub> (kV) | σ(%) | U <sub>av</sub> (kV) | σ(%) | U <sub>av</sub> (kV) | σ(%) |
| A    | 0.0103                     | 44.5                 | 3.62 | 41                   | 1.99 | 39.5                 | 1.03 |
|      | 0.0319                     | 33.3                 | 2.6  | 28                   | 1.46 | 26                   | 1.57 |
|      | 0.054                      | 23.8                 | 3.57 | 20                   | 2.04 | 19                   | 2.15 |
|      | 0.076                      | 15.5                 | 1.08 | 14                   | 2.91 | 13.5                 | 3.02 |
| B    | 0.0103                     | 91.5                 | 1.18 | 86                   | 0.99 | 82                   | 0.99 |
|      | 0.0319                     | 74.8                 | 1.14 | 71                   | 1.15 | 68                   | 1.2  |
|      | 0.054                      | 61                   | 1.34 | 55.5                 | 0.74 | 54                   | 1.5  |
|      | 0.076                      | 45.8                 | 1.85 | 40.5                 | 1.01 | 38                   | 2.15 |

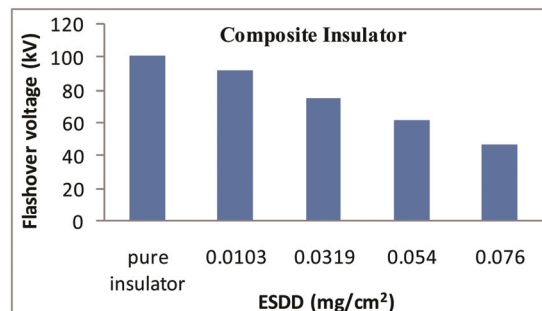
insulators shown in Fig. 2 (a) and (b). FOV of pure Type B insulator is 100 kV and the FOV of polluted Type B insulator with ESDD 0.0103 mg/cm<sup>2</sup>, 0.0319 mg/cm<sup>2</sup>, 0.054 mg/cm<sup>2</sup>, and 0.076 mg/cm<sup>2</sup> is 91.5 kV, 74.8 kV, 61 kV and 45.8 kV respectively. Increase in pollution level on surface of insulators, FOV decreases. The chief cause behind this decrease in FOV is, pollution layer act as a conductor (i.e) it forms a conduction layer on surface of the insulator and it leads to immediate flashover.

The average pollution FOV of various insulators decreases with increase in ESDD. For example, BM with the value of ESDD is 0.0103 mg/cm<sup>2</sup>, 0.0319 mg/cm<sup>2</sup>, 0.054 mg/cm<sup>2</sup>, and 0.076 mg/cm<sup>2</sup>, the U<sub>av</sub> of Type A insulator is 44.5 kV, 33.3 kV, 23.8 kV and 15.5 kV respectively. From the data above we can see that U<sub>av</sub> decreases by respectively when the ESDD increases.

Average pollution FOV of various insulators is affected by different types of polluting methods. The polluting

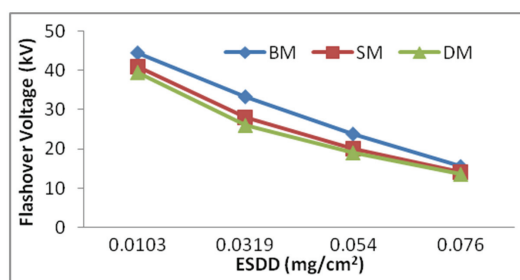


(a)

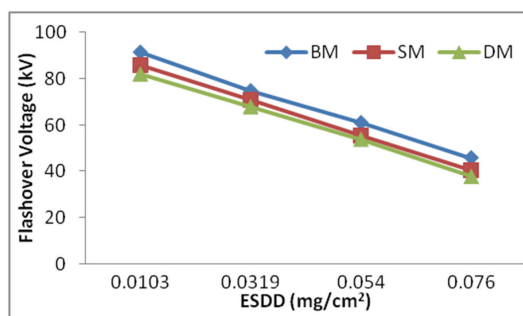


(b)

**Fig. 2.** Flashover voltage Vs ESDD for insulators Type A & B: (a) Type A insulator; (b) Type B insulator



(a)



(b)

**Fig. 3.** Flashover voltage Vs ESDD for different polluting methods: (a) Type A insulator; (b) Type B insulator

methods are BM, SM and DM, and the  $U_{av}$  values of Type A insulator is 44.5 kV, 41 kV, 39.5 kV respectively for ESDD 0.0103 mg/cm<sup>2</sup>, this inferred that the  $U_{av}$  values of BM with various ESDD is higher than that of SM and DM pollution methods. Similarly for Type B insulator  $U_{av}$  values of BM is higher than that of SM and DM pollution methods and shown in Fig. 3 (a) and (b).

Authors witnessed standard deviation  $\sigma$  (%) of  $U_{av}$  of three pollution methods BM, SM and DM for Type A and B insulator are 1.08% – 3.62%, 0.99% – 2.91% and 0.99% – 3.02% respectively. In these, standard deviation of BM is large compared to that of SM and DM, because of non-uniform pollution layer on the surface of the insulator and this is the main drawback while applying BM pollution on the surface of the insulator. The advantage is, it's easy and simple.

Based on Table 8, relative deviation between BM, SM, and DM pollution methods are calculated and shown in Table 9. The relative deviation of FOV depends on type of insulator. Deviation range of  $\Delta 1$  % and  $\Delta 2$  % vary from 1.308% – 19% and (-2.702%) – (-7.142%) respectively for Type A and B. The  $\Delta 1$ % and  $\Delta 2$ % will vary at different ESDDs for the same type of insulator. For example, Type A insulator ESDD is 0.0103-0.076 mg/cm<sup>2</sup>, the relative deviation of FOV for  $\Delta 1$ % and  $\Delta 2$  % from are 8.292% – 19% and (-3.571%) – (-7.142%), respectively.

Maximum standard deviation  $\sigma$  (%) of  $U_{av}$  is only 3.62. but the deviations  $\Delta 1$  % of  $U_{av}$  between BM and SM is up to 19% at various ESDD's for Type A and B insulators. This deviation is not acceptable one.  $U_{av}$  between DM and SM is less than -2.702, this deviation is acceptable and it

**Table 9.** Results of deviations in polluting methods.

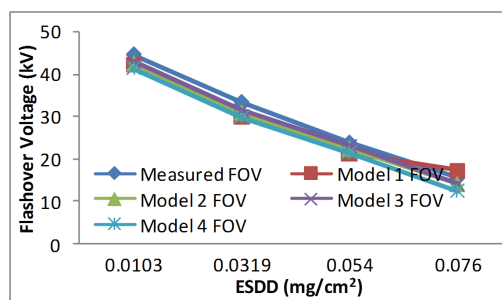
| Type | Difference (%) | ESDD   |        |        |        |
|------|----------------|--------|--------|--------|--------|
|      |                | 0.0103 | 0.0319 | 0.054  | 0.076  |
| A    | $\Delta 1$ %   | 8.292  | 18.928 | 19     | 10.71  |
|      | $\Delta 2$ %   | -3.658 | -7.142 | -5     | -3.571 |
| B    | $\Delta 1$ %   | 6.395  | 5.352  | 9.909  | 1.308  |
|      | $\Delta 2$ %   | -4.651 | -4.225 | -2.702 | -6.172 |

could be negligible.

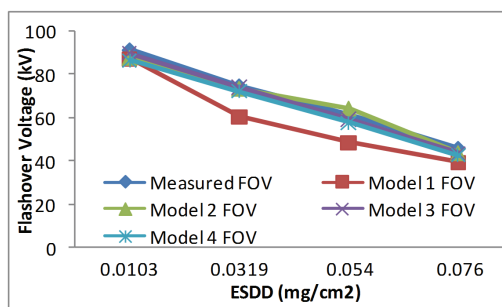
#### 4.2. Mathematical analysis

While comparing the mathematical models (1 to 4) results with experimental results of Type A insulator, mathematical models (1 to 4) results are lesser than experimental results. For example, the experimentally attained FOV of Type A insulator with ESDD 0.0103 mg/cm<sup>2</sup> is 44.5 kV and mathematical models (1 to 4) results for same ESDD is 42.07 kV, 42.25 kV, 42.83 kV and 41.36 kV respectively.

Much attention is given to compare the factor that affects the FOV is mathematical models (1 to 4). The experimentally attained FOV of Type A insulator with ESDD 0.0103 mg/cm<sup>2</sup> is 44.5 kV and mathematical models (1 to 4) FOV for same ESDD is, 42.07 kV, 42.25 kV, 42.83 kV and 41.36 kV respectively. The experimentally attained FOV of Type B insulator with ESDD 0.0103 mg/cm<sup>2</sup> is 91.5 kV and mathematical models (1 to 4) FOV for same ESDD is 87.34 kV, 87.7 kV, 89.63 kV and 86.54 kV respectively. It's inferred that experimentally attained FOV



(a)



(b)

**Fig. 4.** Mathematical Models (1 to 4) results VS Experimental results of Type A & B insulator Type A insulator; (b) Type B insulator.

**Table 10.** Comparison of calculated results with experimental results of type A Insulator

| ESDD (mg/cm <sup>2</sup> ) | Experimental FOV | Type A (Calculated Results) |             |             |             | Experimental FOV | Type B (Calculated Results) |             |             |             |
|----------------------------|------------------|-----------------------------|-------------|-------------|-------------|------------------|-----------------------------|-------------|-------------|-------------|
|                            |                  | Model 1 FOV                 | Model 2 FOV | Model 3 FOV | Model 4 FOV |                  | Model 1 FOV                 | Model 2 FOV | Model 3 FOV | Model 4 FOV |
| 0.0103                     | 44.5             | 42.07                       | 42.25       | 42.83       | 41.36       | 91.5             | 87.34                       | 87.7        | 89.63       | 86.54       |
| 0.0319                     | 33.33            | 29.88                       | 30.75       | 31.27       | 29.71       | 74.8             | 60.34                       | 73.517      | 73.97       | 72.18       |
| 0.054                      | 23.83            | 21.29                       | 22.24       | 22.86       | 21.43       | 61               | 48.57                       | 64.43       | 59.38       | 57.73       |
| 0.076                      | 15.5             | 17.2                        | 14.03       | 13.97       | 12.38       | 45.83            | 39.37                       | 43.98       | 43.85       | 42.63       |

**Table 11.** Deviation of mathematical models (1 to 4) FOV from experimental FOV in (%)

| ESDD (mg/cm <sup>2</sup> ) | Type A  |         |         |         | Type B  |         |         |         |
|----------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
|                            | Model 1 | Model 2 | Model 3 | Model 4 | Model 1 | Model 2 | Model 3 | Model 4 |
| 0.0103                     | -5.78%  | -5.36%  | -3.89%  | -7.59%  | -4.76%  | -4.33%  | -2.08%  | -5.73%  |
| 0.0319                     | -11.55% | -8.39%  | -6.57%  | -12.18% | -23.96% | -1.74%  | -1.12%  | -3.62%  |
| 0.054                      | -11.93% | -7.13%  | -4.26%  | -11.19% | -25.59% | 5.32%   | -2.73%  | -5.66%  |
| 0.076                      | 9.88%   | -10.47% | -10.94% | -25.20% | -16.40% | -4.21%  | -4.52%  | -7.51%  |

**Table 12.** Accuracy of mathematical models (1 to 4) FOV from experimental FOV in (%)

| ESDD (mg/cm <sup>2</sup> ) | Type A  |         |         |         | Type B  |         |         |         |
|----------------------------|---------|---------|---------|---------|---------|---------|---------|---------|
|                            | Model 1 | Model 2 | Model 3 | Model 4 | Model 1 | Model 2 | Model 3 | Model 4 |
| 0.0103                     | 94.54%  | 94.94%  | 96.25%  | 92.94%  | 95.45%  | 95.85%  | 97.96%  | 94.58%  |
| 0.0319                     | 89.65%  | 92.26%  | 93.38%  | 89.13%  | 80.67%  | 98.29%  | 98.89%  | 96.49%  |
| 0.054                      | 89.43%  | 93.37%  | 95.93%  | 89.93%  | 79.62%  | 105.62% | 97.34%  | 94.64%  |
| 0.076                      | 110.97% | 90.52%  | 90.13%  | 79.87%  | 85.90%  | 95.96%  | 95.68%  | 93.01%  |

is higher than that of mathematically attained FOV; Model 3 with ESDD 0.076 mg/cm<sup>2</sup> is greater than experimental FOV for Type B insulator, similarly Model 1 with same ESDD and shown in Table 10. FOV of Model 3 is nearly same with experimental FOV for both type A & B insulator and Fig. 4 (a) and (b) shows comparison of results of mathematical models (1 to 4) with experimental results of Type A insulator.

Table 11 shows the deviation of mathematical models (1 to 4) FOV from experimental FOV. In this FOV deviation with ESDD 0.0103 mg/cm<sup>2</sup> is (-5.78%), (-5.36%), (-3.89%) and (-7.59%) respectively for Type A insulator. Model 1 for ESDD 0.076 mg/cm<sup>2</sup> is 9.88%, this ESDD show positive deviation and all other ESDD's shows negative deviation for Type A insulator. Similarly for Type B insulator FOV with ESDD 0.0103 mg/cm<sup>2</sup> is (-4.76%), (-4.33%), (-2.08%) and (-5.73%) respectively. Model 2 for ESDD 0.054 mg/cm<sup>2</sup> is 5.32%, this ESDD show positive deviation and all other ESDD's shows negative deviation for Type B insulator.

Accuracy of mathematical models (1 to 4) FOV compared with experimental FOV shown in Table 12. For Type A insulator, accuracy of FOV for model 3 is high compared to other models. For example, accuracy of model 3 with ESDD 0.0103 mg/cm<sup>2</sup>, 0.0319 mg/cm<sup>2</sup>, 0.054 mg/cm<sup>2</sup>, and 0.076 mg/cm<sup>2</sup> for Type A insulator is 96.25%, 93.38%, 95.93% and 90.13% respectively, except model 1 with an accuracy of 110.97% for ESDD 0.076 (mg/cm<sup>2</sup>). For Type B insulator, accuracy of FOV for model 3 is high compared to other models.

### 5. Conclusion

From the above pollution flashover tests and analysis, some conclusions are obtained as follows:

- 1) FOV decreases with increase in pollution severity in terms of Equivalent Salt Density Deposition (ESDD).
- 2) The AC pollution FOV of polluted insulators using brushing method is greater than using spraying method and dipping method.
- 3) Mathematical model 3 yields better results than other methods for both Type A and B insulators.
- 4) Relative deviation between BM and SM is not acceptable by engineering applications because the deviation is beyond tolerance limit.
- 5) While considering accuracy of the Mathematical models (1 to 4), Model 3 shows higher accuracy compared with other Models in both Type A and B insulators.

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