Experimental Investigation on Role of Arc Foot Radius on Pollution Flashover Voltage of Porcelain Disc Insulators

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Abstract: *Most of mathematical models for pollution flashover are based on the Obenaus model, which consists of an arc in series with a residual resistance. To estimate the flashover voltage accurately, the calculation of residual resistance is of high importance. Residual resistance calculation is a very complex task due to the irregular shape of real insulators and the non-uniformity of the pollution layer. Wilkin's modelled the pollution layer resistance when the arc root is in contact with the pollution surface. Majority of flashover models have been using either Wilkin's or Rumeli formulations for their pollution resistance calculations. In this paper, an attempt is made to investigate influence of arc foot radius on flashover voltage of polluted porcelain disc insulators. Three rods of radii 2.1, 1.1, 0.61 mm with different lengths are used to mimic the size of arc root on the polluted surface and the propagated arc respectively. The investigations are carried out by conducting flashover experiments on porcelain disc insulators for different arc lengths at four levels of contamination for three arc root sizes. Three trials are taken for each arc length to verify the repeatability. The results of 1260 flashover experiments conducted on 5 insulators considered in the present study shows that the influence of the size of arc root on flashover voltage of polluted insulators for three arc foot radii mentioned above is less significant for the given contamination level.*

Keywords: *Arc foot radius, Critical arc length, flashover, Pollution, Porcelain disc insulator, surface arc foot*

I. INTRODUCTION

The performance of insulators used to overhead transmission lines and overhead distribution lines is one of the critical factors that govern the reliability of power delivery systems. Pollution induced flashover is the single largest reason of transmission and distribution line outages, next to lightning [1]. A major problem of polluted insulator is that it can repeatedly occur even at working voltages. Flashover of polluted insulators can occur when the surface is wet due to fog, dew, or rain. Development of local discharges on the insulator surface and propagation of these discharges over a period of time cause the leakage current to increase to its critical current on the insulator surface leading to a final flashover. This occurs in three stages. They are,

- The formation of electrolytic conductive film layer,
- The formation of dry bands and the starting of pre-discharges and
- The propagation of these pre-discharges.

The first two stages can occur frequently, however, the last stage does not occur as often as others do.

In the last decades, several flashover models, static and dynamic, mathematical and numerical, have been elaborated to determine the critical characteristics and to estimate flashover voltages on polluted insulators [2-14]. Majority of the flashover models used theoretical formulation to calculate the residual resistance on the pollution layer in series with the arc according to the Obenaus equivalent circuit [10]. This residual resistance remains one of the most influenced parameters in the flashover models as its calculation influences the accuracy of the FOV results significantly. The difficulty with the analytical formulation of residual resistance is to take into account the complexity of the insulator geometry as well as the non-uniformity of the leakage current distribution created by the presence of the arc root in contact with the polluted surface. Most of mathematical flashover models used the Wilkin's or Rumeli formulations [2-14].

Some researchers prefer using the Wilkin's [6] formulation as it takes into account the presence of the arc root in contact with the polluted surface [2, 7- 9]. But, Wilkin's [6] formulation is not adapted for complex geometries limiting its applicability to rectangular shapes.

To overcome such geometry limitation, Rumeli [12] has developed 2D AR model, whose length is equal to the leakage path of the given practical insulator. In this AR model, the residual resistance is calculated using the form factor of the insulator [3, 12-15]. However, as the form factor depends directly on the insulator geometry, flashover models must be adapted to each type of insulators and the formulation does not consider the presence of the arc root and current line constriction.

Further, Yujun Guo, et al. [16] model stated that due to the low air pressure at high altitude, the arc deviates from the surface of insulators with bending and rocking, shortening the arc distance. The earlier studies assumed the arc propagation to start from the pin and elongate toward the cap. However, according to [4-6] the pre-discharges not only elongate by starting from one point, but can also occur on several points at the same instant depending on the state of the dry bands.

The recent research [17] presents a self-consistent multi-arcs dynamic model for high voltage polluted insulator under impulse voltage. The model takes into account the instantaneous changes of discharges parameters and one of the discharge parameters, the discharge channel radius has been computed using Wilkins [6] equation $R = \sqrt{I/1.45\pi}$. In the paper [18], the DC flashover performance of an ice-covered insulator string in vertical and inclined positions under heavy icing conditions has been described by a new model in which pollution resistance has been calculated by considering the effect of arc foot radius. Also, the research [19] designed an improved Least Squares Support Vector Machines (LS-SVM) model based on Ant Colony Optimization (ACO) algorithm to estimate the critical flashover voltage on polluted insulators. This model has derived it's training data from the model [20] which has considered effect of both arc foot radius and form factor in the estimation of flashover voltage.

Thus, with above discussions, the proposed work has been carried out to investigate experimentally, the effect of the size of the arc foot radius on flashover voltage of a polluted porcelain disc insulator. The investigations were carried out by conducting flashover experiments on five polluted porcelain disc insulators for different arc lengths using three different size round rod electrodes of radii equal to 2.1 mm, 1.1mm and 0.61mm at four levels of contamination representing low, medium, high and very high pollution levels. In the proposed work, the round rods of different size and length have been used to mimic the size of arc foot and the propagated arc respectively on the surface of polluted porcelain disc insulator.

II. EXPERIMENTAL SETUP

The flashover experimental setup, the specimens used and flashover test procedure are explained in the following sections

a) TEST SPECIMENS

Five suspension porcelain disc insulators have been selected as test specimens. First four insulators are of standard type and the rest is Antifog type. They are designated as Type- A, Type- B, Type- C, Type-D and Type-E respectively. The geometrical parameters of the test specimens are shown in Table 2.1.

Table: 2.1 Geometrical parameters of Specimens

Type of insulator	D (cm)	H (cm)	L (cm)	Lp (cm)	form factor	No. of ribs
Type-A	25.5	14.6	31.8	21.0	0.57	4
Type-B	25.5	14.5	33.0	22.4	0.81	4
Type-C	28.0	14.6	38.1	25.4	0.65	5
Type-D	28.0	17.0	39.5	28.3	0.84	5
Type-E	30.5	17.0	50.1	36.0	0.90	4

b) TEST PROCEDURE AND TEST EQUIPMENT

The IEC-60507[21] recommended solid layer method is used to pollute the insulator specimens. The artificial contamination slurry is a mixture of commercial salt (NaCl), Kaolin and de-ionized water. The Equivalent Salt Deposit Density (ESDD) used in this study are 0.05, 0.10, 0.20 and 0.30 mg/cm^2 to represent low, medium, high and very high levels of pollution respectively. The cleaned insulator is dipped in the slurry and is dried artificially. The insulator with the known ESDD was mounted in the pollution chamber of dimension 3.0m X 3.0m X 3.0m as shown in Fig.2.1. In all the experiments, the required steam rate and humidity levels (98-99%) are maintained. AC voltage is applied gradually to the insulator through a pollution testing transformer of 415 V / 60kV, 60kVA with less than 5% impedance till flashover. The flashover voltage is noted. After the flashover test, the insulator is taken out and ESDD is measured. The schematic diagram of experimental set-up is given in Fig. 2.1.

According to the references [22,23] the radius of arc foot has been calculated using Wilkin's [6] equation. From [23] the maximum current attained for higher salinity is around 180mA and the arc foot radius for this current will be equal to 2.0 mm. In addition to this, most of the models in the literature have normally considered arc foot radius as equal to 2.0 mm [20,22]. Considering all this, in the present work, round rod electrode of radius equal to 2.1 mm (i.e., equal to a standard wire gauge of 8), the size of which represents the arc foot radius on the polluted surface of the insulators. Further, to verify the effect of size of the arc root, two more electrodes of radii equal to 1.1mm and 0.61mm have been used.

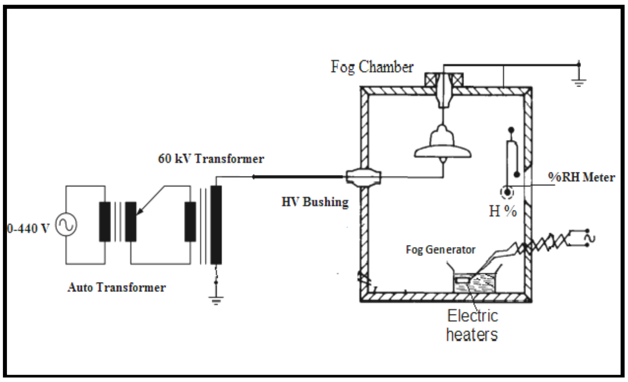

Fig.2.1 Schematic diagram of experimental setup

c) POLLUTION FLASHOVER TESTS ON INSULATORS.

In the present study, as mentioned above, three different size rods of different lengths are used to mimic the size of arc root form on polluted surface and the propagated arc respectively. The experiments are carried out at different arc lengths using three rods of radii 2.1mm, 1.1mm and 0.61mm for four levels of ESDD. In the first phase, experiments are conducted using a rod whose cross-sectional area mimic an arc root of radius equal to 2.1 mm. In the beginning, experiments are carried out on Type-A insulator for an arc length equal to 1% of its total creepage length. The arc length is simulated by shorting 1% of it's creepage length by the rod of radius 2.1 mm as shown in Fig. 2.2. This insulator with the pollution layer of ESDD equal to 0.05mg/cm^2 is mounted in the experimental chamber. The steam is allowed till the required humidity (90% - 95%) is reached. Now, the voltage is applied at a very low level and increased gradually till flashover. The flashover voltage is noted. This is carried out three times for each arc length at the same ESDD to check the repeatability. The above procedure is repeated for different arc lengths from 1% up to 80% of it's creepage. The same experiments are also conducted for ESDD levels equal to 0.1, 0.2 and 0.3mg/cm2 for all the five insulators.

In the next phases, flashover experiments are conducted using a rod of radius equal to 1.1 mm and 0.61 mm respectively on all five insulator specimens at different arc lengths and at four levels of contamination mentioned above.

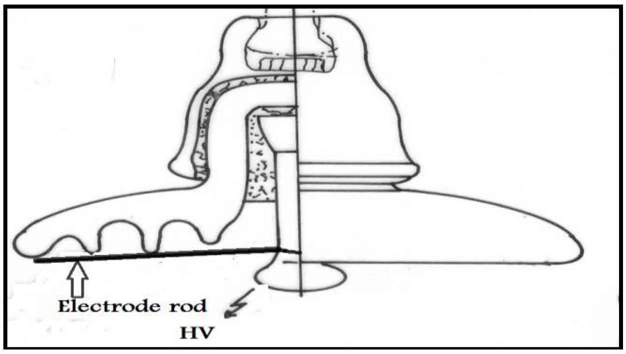

Fig.2.2 Electrode fixed from pin to last rib of the insulator

III. RESULTS AND DISCUSSIONS

The flashover voltages obtained from around 1260 flashover experiments with three different size arc root of radii equal to 2.1mm, 1.1mm and 0.61mm on all five test specimens at four ESDD levels and at different arc lengths are tabulated. The mean of flashover voltages is calculated for each arc length at given contamination level along with their standard deviations. The mean value of flashover voltages for Type A, B, C, D and E insulators for three different size arc root at four levels of contamination for different arc lengths along with standard deviations are presented in Tables 3.1a, 3.1b, 3.1c, 3.1d and 3.1e respectively. It is observed that the flashover voltages are quite consistent at given arc length and this is indicated by low value of standard deviation. The percentage standard deviation about the mean is under 5% in all the cases.

Further, flashover voltages have been plotted as a function of different arc lengths for three arc foot radii $R_{2.1}$=2.1mm, $R_{1.1}$=1.1mm and $R_{0.61}$= 0.61mm at four ESDDs for Type A, B, C, D and E insulators in the figures 3.1a, 3.1b, 3.1c, 3.1d and 3.1e respectively.

It can be observed from Fig.3.1a, that variation in flashover voltages for three different size arc roots at different arc lengths are almost negligible with a maximum standard deviation of 0.6kV.

Fig.3.1b shows results for Type-B insulator and one can observe the overlapping of the three flashover voltage curves at different arc lengths for three different size arc roots with a maximum deviation of 0.4kV between them.

It can also be observed from figures 3.1c, 3.1d and 3.1e for Type C, D and E insulators that the flashover voltages at different arc lengths tracks closely over three different size electrodes at four levels of contamination with a maximum standard deviation of 0.3kV, 0.3kV and 0.4kV respectively.

The comparison of flashover voltages for different arc foot radii at different arc lengths for all the five insulators considered in the present study with varying salinity show that the role of size arc foot radius on flashover voltages of polluted porcelain disc insulators is less significant.

IV. CONCLUSIONS

In the present work, experimental investigation has been carried out by conducting flashover experiments on the 5 selected insulator specimens at four ESDD levels with three electrodes of radii 2.1mm, 1.1mm and 0.61mm whose size and length represents size of arc foot radius form on polluted surface and propagated arc respectively. Around 1260 experiments are conducted and the flashover voltages obtained are tabulated and analysed. Based on the experimental results it can be observed that the variation in flashover voltages of the polluted insulators with three different size arc foot radius at given pollution level varies between 0.3 to 0.6 kV. Hence, it is concluded that the influence of size of the arc foot radius (form on polluted surface) on flashover voltage of polluted porcelain disc insulators considered in the present study is less significant.

The proposed conclusion may help in reducing the complexity involved in the formulations of pollution resistance due to the arc foot radius without loss of much accuracy in the estimation of flashover voltage.

Table 3.1a: Average Experimental Flashover voltages obtained for three electrodes representing arc root radii R =2.1, 1.1 and 0.61 mm of Type-A insulator at four ESDD levels

Arc Length in cm for Type-A insulator	ESDD = 0.05 mg/cm2				ESDD = 0.1 mg/cm2				ESDD = 0.2 mg/cm2				ESDD =0.3 mg/cm2			
	FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii			
	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean
0.3	14.5	15.0	15.0	0.2	12.5	12.5	12.5	0.0	9.5	9.5	9.5	0.0	7.0	7.2	8.0	0.4
4.2	9.8	10.0	9.8	0.1	9.0	8.7	8.9	0.1	7.5	7.0	7.0	0.2	5.5	5.5	5.5	0.0
9.3	7.0	6.7	6.8	0.1	5.3	6.2	6.2	0.4	5.5	5.3	5.0	0.2	4.3	4.2	4.0	0.1
15.9	5.5	5.5	5.5	0.0	4.3	4.3	4.1	0.1	4.5	4.2	4.0	0.2	3.8	3.3	3.3	0.2
21.7	5.0	4.8	4.7	0.1	4.0	3.8	3.7	0.1	4.0	3.5	3.5	0.2	3.5	3.1	3.0	0.2
23.6	4.6	4.5	4.3	0.1	3.5	3.5	3.6	0.0	3.5	3.5	3.2	0.1	3.1	3.0	3.0	0.0
25.3	3.8	3.9	3.8	0.0	3.5	3.5	3.4	0.0	3.3	3.0	3.0	0.1	3.0	3.0	3.0	0.0
27.0	3.2	3.2	3.3	0.0	3.0	3.3	3.2	0.1	3.0	3.0	3.0	0.0	3.0	3.0	3.0	0.0

Table 3.1b: Average Experimental Flashover voltages obtained for three electrodes representing arc root radii R =2.1, 1.1 and 0.61 mm of Type-B insulator at four ESDD levels

Arc Length in cm for Type-B insulator	ESDD = 0.05 mg/cm2				ESDD = 0.1 mg/cm2				ESDD = 0.2 mg/cm2				ESDD =0.3 mg/cm2			
	FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii			
	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad = 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad = 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad = 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean
0.4	18.0	18.3	18.0	0.1	16.0	16.3	16.1	0.1	13.5	13.2	13.5	0.1	10.5	10.3	10.5	0.1
4.2	11.5	11.5	11.0	0.2	11.3	11.2	11.2	0.0	8.7	9.2	9.2	0.2	6.8	7.2	7.0	0.1
9.3	8.0	8.0	8.3	0.1	7.5	7.8	7.8	0.1	6.8	6.5	6.8	0.1	5.5	5.0	5.0	0.2
15.9	7.0	6.5	6.3	0.3	5.5	5.2	5.0	0.2	5.0	5.2	5.5	0.2	4.5	4.3	4.3	0.1
21.7	5.5	5.3	5.0	0.2	5.0	4.6	4.8	0.1	4.0	4.3	4.5	0.2	3.5	3.5	3.5	0.0
23.6	5.3	5.2	5.0	0.1	4.8	4.5	4.8	0.1	3.8	4.0	4.3	0.2	3.5	3.5	3.5	0.0
25.3	5.1	5.1	5.0	0.0	4.7	4.5	4.7	0.1	4.0	4.1	4.2	0.1	3.5	3.5	3.5	0.0
27.0	5.0	5.2	5.1	0.1	4.6	4.5	4.8	0.1	4.0	4.1	4.2	0.1	3.5	3.5	3.5	0.0

Table 3.1c: Average Experimental Flashover voltages obtained for three electrodes representing arc root radii R =2.1, 1.1 and 0.61 mm of Type-C insulator at four ESDD levels

Arc Length in cm for Type-C insulator	ESDD = 0.05 mg/cm2				ESDD = 0.1 mg/cm2				ESDD = 0.2 mg/cm2				ESDD =0.3 mg/cm2			
	FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii			
	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean
0.5	21.1	20.8	21.0	0.1	17.9	17.8	18.0	0.1	14.0	13.8	14.0	0.1	11.0	11.0	11.5	0.2
3.2	17.3	17.7	17.5	0.1	15.5	15.0	15.5	0.2	11.7	12.3	11.7	0.3	9.8	9.7	9.5	0.1
7.6	10.0	10.2	10.5	0.2	9.5	9.0	9.0	0.2	6.7	7.3	6.7	0.3	5.3	5.5	5.5	0.1
14	5.7	5.9	6.0	0.1	5.3	5.0	5.5	0.2	4.0	4.3	4.0	0.1	4.0	3.5	3.5	0.2
20.0	5.3	5.0	5.3	0.1	4.5	4.3	4.3	0.1	3.7	4.0	3.7	0.1	3.7	3.3	3.3	0.2
25.8	4.8	4.5	4.5	0.1	4.3	4.0	4.0	0.1	3.3	3.8	3.3	0.2	3.5	3.2	3.0	0.2
29.9	4.5	4.5	4.3	0.1	4.2	4.0	4.0	0.1	3.3	3.8	3.3	0.2	3.5	3.2	3.0	0.2
35.0	4.5	4.5	4.5	0.0	4.0	4.0	4.0	0.0	3.3	3.5	3.3	0.1	3.5	3.2	3.0	0.2

Table 3.1d: Average Experimental Flashover voltages obtained for three electrodes representing arc root radii R =2.1, 1.1 and 0.61 mm of Type-D insulator at four ESDD levels

Arc Length in cm for Type-D insulator	ESDD = 0.05 mg/cm2				ESDD = 0.1 mg/cm2				ESDD = 0.2 mg/cm2				ESDD =0.3 mg/cm2			
	FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii			
	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean
0.5	22.0	21.8	21.9	0.1	16.0	16.0	16.5	0.2	13.9	13.8	14.0	0.1	10.9	10.7	11.0	0.1
3.2	18.0	18.5	18.0	0.2	13.5	14.0	14.0	0.2	12.0	12.5	12.5	0.2	9.0	9.5	9.3	0.2
7.6	13.5	13.7	13.7	0.1	11.0	11.0	11.0	0.0	9.0	9.0	9.0	0.0	7.0	7.3	7.0	0.1
14	8.3	8.0	8.5	0.2	7.3	7.0	7.5	0.2	6.5	6.0	6.5	0.2	5.3	5.3	5.0	0.1
20.0	5.5	5.2	5.5	0.1	5.3	5.0	5.0	0.1	5.0	5.0	5.1	0.0	4.3	4.2	4.5	0.1
25.8	4.8	5.1	5.0	0.1	4.7	5.0	5.0	0.1	4.7	4.4	4.5	0.1	4.0	3.9	4.0	0.0
29.9	4.7	5.0	5.0	0.1	4.5	4.5	4.5	0.0	4.5	4.3	4.3	0.1	3.9	3.9	3.9	0.0
35.0	4.7	4.7	4.7	0.0	4.5	4.5	4.5	0.0	4.0	4.0	4.0	0.0	3.8	3.8	3.8	0.0

Table 3.1e: Average Experimental Flashover voltages obtained for three electrodes representing arc root radii R =2.1, 1.1 and 0.61 mm of Type-E insulator at four ESDD levels

Arc Length in cm for Type-E insulator	ESDD = 0.05 mg/cm2				ESDD = 0.1 mg/cm2				ESDD = 0.2 mg/cm2				ESDD =0.3 mg/cm2			
	FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii				FOV in kV for 3 arc root radii			
	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean	Rad= 2.1 mm	Rad= 1.1 mm	Rad= 0.61 mm	SD about mean
0.5	28.0	27.8	28.5	0.3	23.5	23.5	24.0	0.2	18.5	18.3	18.5	0.1	14.0	13.5	14.0	0.2
7.2	24.0	24.3	24.3	0.1	20.0	20.5	20.0	0.2	15.0	15.5	15.0	0.2	11.5	11.8	11.5	0.1
12.5	20.0	20.8	20.5	0.3	17.0	17.5	17.0	0.2	13.5	13.0	13.7	0.3	10.0	9.8	10.0	0.1
23.4	10.5	10.3	10.8	0.2	9.2	9.2	9.0	0.1	7.0	7.5	7.7	0.3	5.0	5.0	5.0	0.0
33.0	5.5	5.3	5.2	0.1	5.2	5.5	5.0	0.2	4.8	5.0	4.8	0.1	4.5	4.5	4.5	0.0
34.2	5.3	5.3	5.2	0.0	5.2	5.2	5.0	0.1	4.5	4.5	4.8	0.1	4.5	4.5	4.5	0.0
39.1	5.3	5.3	5.2	0.0	5.2	5.2	5.0	0.1	4.5	4.5	4.8	0.1	4.3	4.3	4.3	0.0

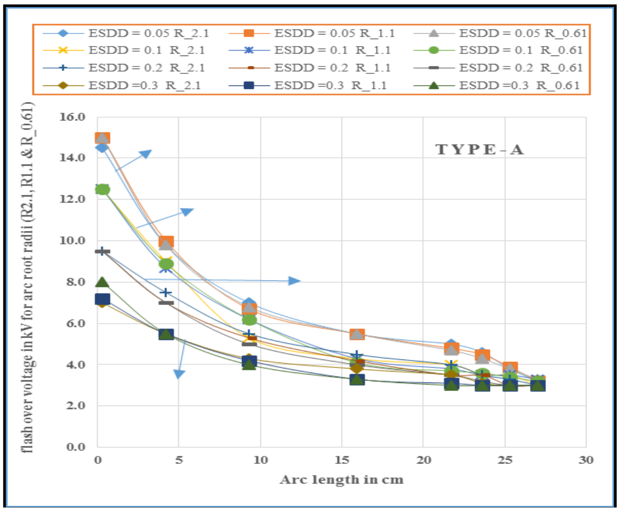

Fig. 3.1a Comparison of Flashover Voltages of three electrodes representing the arc root radii R=2.1mm, R-1.1mm and R=0.61mm at different arc lengths of insulator Type-A at four ESDD levels

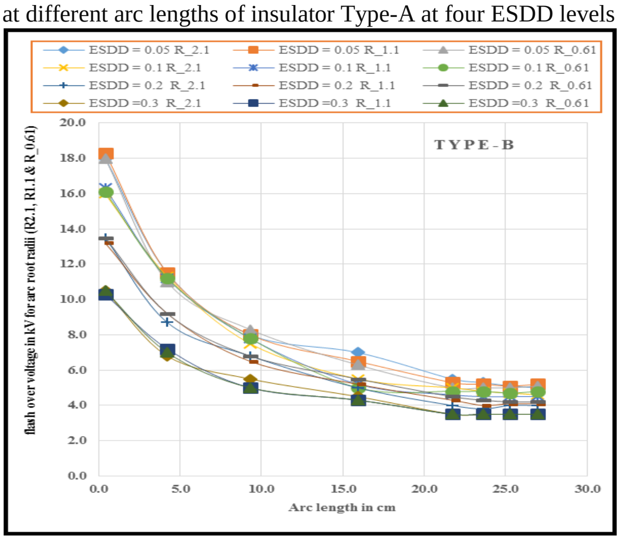

Fig. 3.1b Comparison of Flashover Voltages of three electrodes representing the arc root radii R=2.1mm, R-1.1mm and R=0.61mm at different arc lengths of insulator Type-B at four ESDD levels

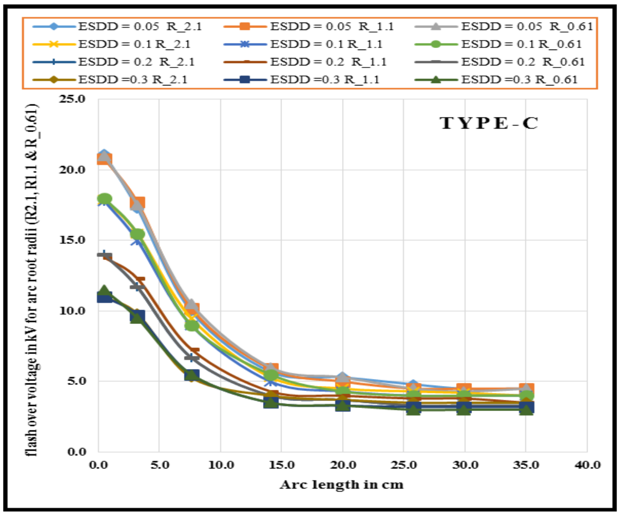

Fig. 3.1c Comparison of Flashover Voltages of three electrodes representing the arc root radii R=2.1mm, R-1.1mm and R=0.61mm at different arc lengths of insulator Type-C at four ESDD levels

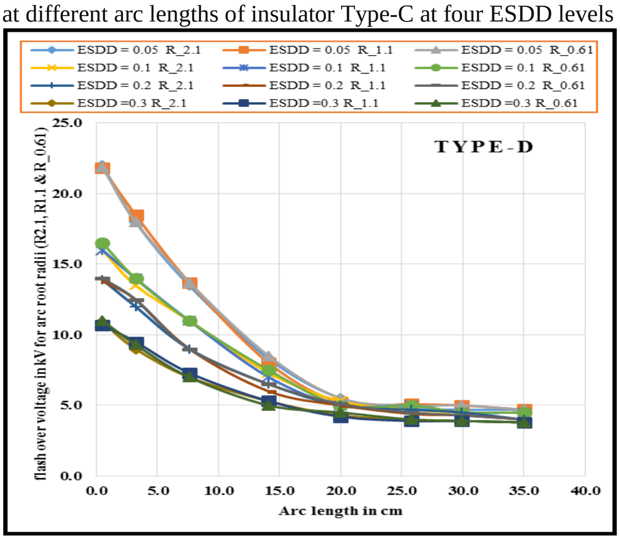

Fig. 3.1d Comparison of Flashover Voltages of three electrodes representing the arc root radii R=2.1mm, R-1.1mm and R=0.61mm at different arc lengths of insulator Type-D at four ESDD levels

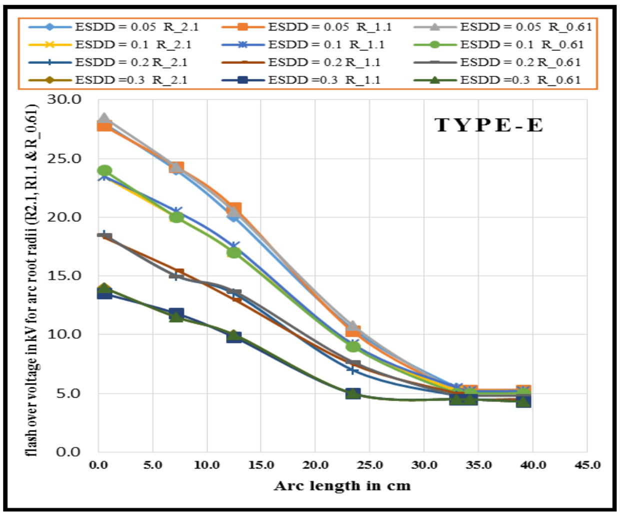

Fig. 3.1e: Comparison of Flashover Voltages of three electrodes representing the arc root radii R=2.1mm, R-1.1mm and R=0.61mm at different arc lengths of insulator Type-E at four ESDD levels

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