Prediction of flashover voltage of non-ceramic insulators under contaminated conditions

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ABSTRACT

This paper describes the development of a theoretical model to predict flashover voltage of nonceramic insulators. The model is based on reignition and arc constants that have been derived from electric field simulations and experimental data of flashover voltage and surface resistance measurements. New and field-aged silicone rubber and ethylene propylene diene monomer rubber samples were evaluated. A good correlation of the calculations from the model with experimental data has been demonstrated.

Index Terms — **Polymeric insulators, ceramic insulators, surface resistance, arc constant, reignition constant, flashover, ESDD.**

1 INTRODUCTION

FLASHOVER under contaminated conditions is a well known weakness of outdoor ceramic insulators (porcelain and glass). There are various types of contaminants that settle on the insulators. Insulators located near coastal regions encounter sodium chloride (*NaCl*), those located in inland areas are contaminated by industrial pollutants such as paper pulp, fly-ash, cement dust etc. Insulators in cold climates are contaminated with salts used for deicing the streets (brine, calcium chloride). These contaminants can include a mixture of soluble and insoluble materials. The term ESDD (Equivalent Salt Deposit Density) is used to indicate the contamination severity and is expressed in terms of mg of *NaCl* per unit surface area (cm^2) of the insulator. Contamination is of little significance under dry conditions. However in the presence of light rain, freezing rain, fog or dew the contaminants dissolve to form a conductive layer on the insulator surface initiating leakage current and partial arcs (dry band arcing) which can ultimately lead to flashover. The creation and propagation of the dry band arcing is aided by the hydrophilic or wettable nature of ceramic materials.

Users have handled this weakness of ceramic insulators by adopting conservative design rules that have been derived from field experience and laboratory tests. For new construction, relevant field experience may not be available and laboratory experiments are time consuming and expensive. A good theoretical model for simulating the flashover process is an asset as it helps to minimize experimental efforts. Theoretical models for calculating the flashover voltage of ceramic insulators under contaminated conditions were introduced in the 1950s and have undergone significant development. These models have helped manufacturers to optimize design and users to specify the right level of insulation required.

Nonceramic insulators (NCI) made from polymeric materials were introduced in the 1970s. This has helped users significantly as the flashover performance under contaminated conditions of these insulators is significantly better than the ceramic insulators. NCI are different from their ceramic counterparts in several respects. The housing materials are known to possess water repellent characteristics, commonly referred to as hydrophobicity, and is chiefly responsible for the improved performance under contaminated conditions. However the longevity of hydrophobicity is highly variable. It is short for some polymers such as ethylene propylene family of polymers and can be long for the silicone rubber family of polymers. Both types of materials are used presently for transmission and distribution lines.

Hydrophobicity is affected by surface contamination and aging of the material that occurs under various stresses (electrical, mechanical, chemical, environmental) encountered in service. NCI also differ significantly from ceramic insulators in the constructional aspect. For example, suspension NCI have no intermediate hardware (cap and pin), and this alters the electric field distribution significantly from ceramic insulators [1]. These differences are known to affect the flashover process. The phenomenon has not been studied adequately and hence modeling of the flashover process for NCI is still in its infancy.

2 REVIEW OF THEORETICAL MODELS

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FOR CERAMIC INSULATORS

Obenaus was the first to propose a model for contamination flashover of ceramic insulators [2, 3]. He modeled the flashover process as a discharge in series with a resistance, as shown in Figure 1.

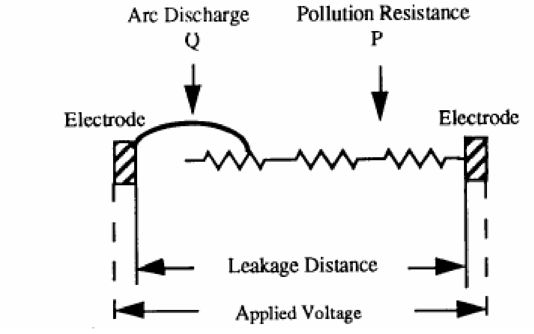

Figure 1. Obenaus model of polluted insulator [2, 3].

The discharge represents the arc bridging the dry band, and the pollution resistance represents the unbridged portion of the insulator. The voltage drop across the resistance is expressed as a function of current. The arc propagation criterion used is $E_p > E_{arc}$, that is, the electric field in the polluted layer should be greater than the arc gradient [3-5]. Flashover occurs when the arc propagates and ultimately bridges the insulator. Flashover voltage is plotted as a function of ESDD and such graphs obtained for various insulator geometries can be found in the literature [3].

Numerous models were developed for ceramic insulators following the Obenaus model. However, the basic ingredients of the models are not very different. The models are based on different empirical values for the arc constant, reignition constant and the reignition exponent. Despite these efforts, the physical process is not completely understood. This can be attributed to the complexity of the flashover process.

The generic formulas for E_{arc} and E_p are given as;

$$E_{arc} = N \times I^{-n} \tag{1}$$

$$E_p = E_c = 10 * N \times (N - A)^{-n/_{n+1}} \times n^{n/_{n+1}} \times rpu^{n/_{n+1}} \Big/ n+1 \tag{2}$$

where, N- reignition constant
n- reignition exponent (typically 0.5)
A- arc constant (typically 0.15 * N)
I - current entering the pollution layer
rpu - average resistance per unit length

In order to investigate how close the predictions are by different authors, models proposed by several researchers were simulated using Matlab [3, 6-10]. The calculations were done for three widely used porcelain insulator geometries, a standard, fog type and deep rib porcelain bells with the dimensional details provided in Table 1.

Table 1. Dimensional details of samples.

Insulator geometry	Leakage distance (cm)	Unit spacing (cm)	Shed diameter (cm)
Standard	28.0	14.6	25.4
Fog type	43.2	14.6	25.4
Deep rib	54.5	18.0	32.0

The simulation results for ac voltage are given in Table 2, which shows that the variation in the predicted flashover voltage is quite large. Table 3 shows the formulas for E_{arc} and E_p used by different research groups.

In the present study, the basic Obenaus's model has been used as the starting point for NCI. However the arcing process for polymer can be different from porcelain and thus the arc constants may need to be changed.

Table 2. Predicted flashover voltage for various ac models.

ESDD (mg/cm^2)	Research group 1 [6]	Research group 2 [7]	Research group 3 [8]	Insulator Geometry
0.03	9.8	14.2	8.8	Standard
0.06	8.6	11.6	7.2	
0.12	7.6	9.4	6	
0.25	6.8	7.6	4.8	
0.05	12.2	16	9.8	Fog type
0.10	10.8	12.8	8	
0.15	10	11.4	7	
0.20	9.6	10.4	6.6	
0.10	12.8	14.8	9.2	Deep rib
0.20	11.2	12.0	7.4	

Table 3. E_p and E_{arc} used by different research groups.

	Research group 1	Research group 2	Research group 3
E_p (V/cm)	$58*rpu^{(0.4)}$	$103.3*rpu^{(0.33)}$	$63.4*rpu^{(0.333)}$
E_{arc} (V/cm)	$59*I^{(-0.5)}$	$80*I^{(-0.5)}$	$37.78*I^{(-0.5)}$

3 FLASHOVER MODEL DEVELOPMENT FOR NONCERAMIC INSULATORS

Flashover prediction based on ESDD measurement alone may not be the best method for NCI due to the hydrophobic nature of polymers. The ESDD measurement is made by cleaning a known area of the surface and dissolving the contents in water. A hydrophobic surface can have high levels of ESDD, yet the leakage current can be negligible due to the fact that the water formation on such a surface is in the form of discrete droplets as opposed to a continuous film. This issue has been discussed in detail in the IEEE Working Group on Insulator Contamination. An alternate method to characterize the electrical performance was introduced based on the measurement of surface resistance under wet conditions. The use of this parameter for predicting the flashover voltage is explored in this work. To date there has not been much work done in characterizing the values of surface resistance that would be indicative of either flashover or withstand. The type of fog and rate of wetting of the insulators affects the surface resistance of NCI [11, 12]. It is much easier to measure ESDD than surface resistance. Thus there is a need to determine the correlation between ESDD and surface resistance.

3.1 EXPERIMENTAL DETAILS

3.1.1 SAMPLES

Table 4 shows the dimensional details of the samples evaluated.

Table 4. Dimensional details.

Type of material	Leakage distance (cm)	Shed diameter (cm)	Shed spacing (cm)
New silicone rubber	27.0	9.0	3.0
Aged silicone rubber	27.0	9.0	3.0
Aged EPDM	26.0	9.0	2.0
Porcelain	25.0	13	2.0

The samples included new and field-aged samples of insulators using silicone rubber and ethylene propylene diene monomer (EPDM) rubber as housing materials. The insulator shapes were identical. Porcelain line post insulators with a geometry as close to that of the NCI was used as a reference. The field-aged samples were removed after 5 years of exposure in the mid west USA. It is important that the period of field exposure and the service location be similar for comparison of different material types. The aged silicone samples were still hydrophobic but the EPDM samples had lost its initial hydrophobicity. The hydrophocity was assessed visually by using STRI guide 92/1. There was surface discoloration of the aged EPDM samples most likely from ultraviolet radiation in sunlight. There was no visible degradation on the aged samples.

3.1.2 EXPERIMENTAL SETUP

The experiments were carried out in a fog chamber. The high voltage (HV) supply was provided by a transformer rated 40 kVA/100 kV. A glass window (30 cm x 20 cm) was fitted on the door for visual observation. Ultrasonic nebulizers were used to generate fog. The size of the droplet generated by the nebulizer is very small typically 1 micron in diameter. These devices are easy to maintain, consume less power and minimize corrosion problems encountered with conventional fog generators like boiling water or salt spray. A relative humidity level of 100 % was achieved within 20 minutes of energizing the fog generators.

The contamination slurry was prepared by mixing 40 g of kaolin in one liter of deionized water. An appropriate amount of *NaCl* was added to the slurry depending on the level of ESDD to be obtained [13]. Using brush a uniform coating of contamination was applied on the insulator. There was several hours elapsed from the time the surface was dry to the time at which they were tested. This allowed recovery of hydrophobicity of silicone rubber to various degrees depending on the time elapsed. Samples were tested when the surface had no recovery of hydrophobicity (1 hour after drying), and visibly recovered its hydrophobicity (3 days after drying). Recovery was judged by spraying water and noting if the surface wetted out or beaded in to small drops and conclusions were made based on STRI guide 92/1. The EPDM samples were always hydrophilic and there was no visible recovery of the hydrophobicity with time.

3.1.3 SURFACE RESISTANCE MEASUREMENT

An ac voltage in the range of 2-4 kV was used depending on the insulator material and dimensions. The voltage was applied across aluminum tape electrodes that were placed in between the insulator hardware. The leakage distance of the insulators between the electrodes was typically 15 cm. The voltage applied should be adequate to establish a measurable leakage current but not high enough to initiate discharges. The insulators were mounted vertically in the chamber. Care is taken to ensure that the source of fog generation is not directly beneath the sample. The leakage current is measured as a voltage drop across the resistor connected in series with the sample. The surface resistance value is high initially and a steady value of surface resistance was obtained in 70-90 minutes after starting the fog generators. Figure 2 shows the schematic of testing in fog chamber.

3.1.4 FLASHOVER VOLTAGE MEASUREMENTS

The insulator is subjected to 80% of the probable flashover voltage (determined from previous trials) for 20 minutes after the relative humidity has reached 100%. If there is no flashover the voltage is raised in 10%, and each step is maintained for 5 minutes until flashover is obtained [14, 15]. This process is repeated for different levels of ESDD. The flashover voltage reported is the average of three measurements for the same ESDD. A different sample of the same type was used for different trials.

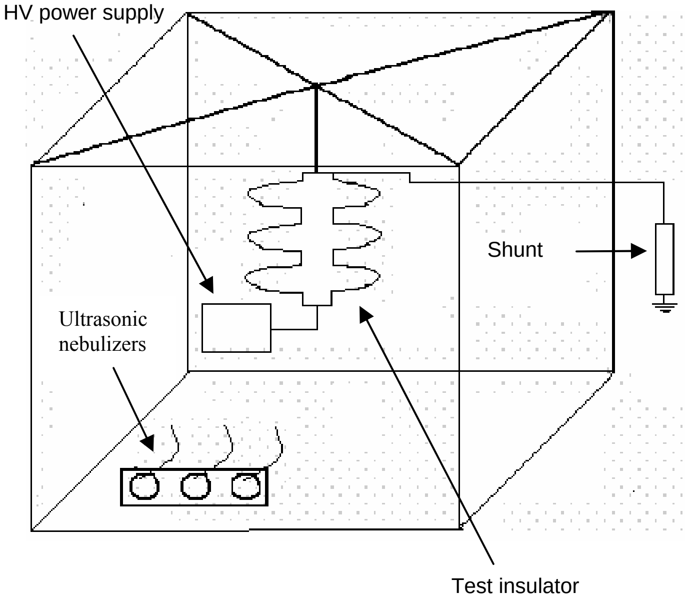

Figure 2. Schematic of testing in fog chamber.

4 RESULTS AND DISCUSSION

4.1 EFFECT OF HYDROPHOBICITY ON FLASHOVER VOLTAGE AND SURFACE RESISTANCE OF NCI

The experiments were performed for a wide range of ESDD from 0.08 - 0.34 mg/cm^2. Figure 3 shows the variation of ESDD with flashover voltage for all the different samples.

It can be seen that for the same level of ESDD the flashover voltage for an aged silicone rubber is about 12% less compared to new silicone rubber. The aged EPDM has a flashover voltage of about 16% lower than aged silicone rubber, whereas porcelain has a flashover voltage of about 16% lower than aged EPDM. These differences in the flashover voltage are indicative of inherent differences in the materials' ability to resist water filming.

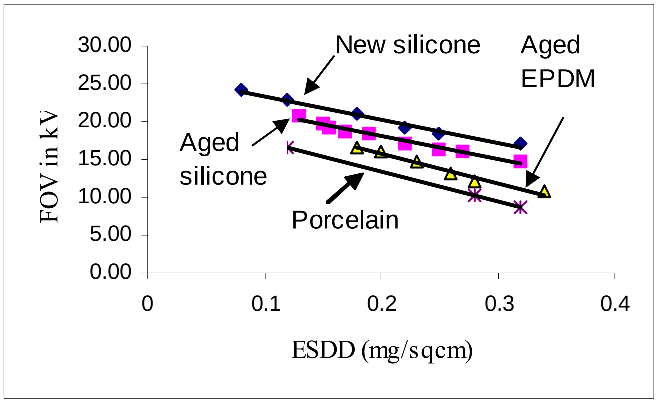

Figure 3. Variation of flashover voltage to ESDD for different materials.

The surface resistance of aged silicone rubber and EPDM was measured for different levels of ESDD. From Figure 4 it can be observed that for the same ESDD the surface resistance values are much lower for field aged EPDM than field aged silicone rubber and this is due to the hydrophobic property of silicone rubber. For silicone rubber the dynamics of the hydrophobic surface results in a much higher value of surface resistance than EPDM [14-16]. A comparison of experimental results of surface resistance for a constant ESDD is shown in Figure 5 for field-aged silicone rubber with and without recovery, new and field aged EPDM and porcelain. The data in Figures 4 and 5 illustrate the role played by the silicone rubber material towards improving the contamination performance, as the surface resistance is always higher than that of EPDM and porcelain.

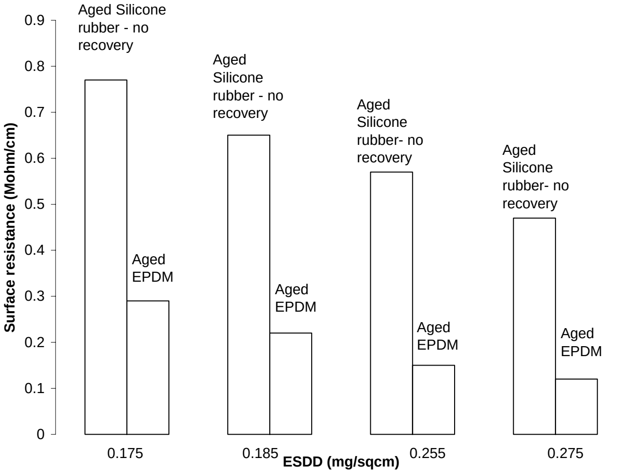

Figure 4. Comparison of experimental results of surface resistance vs. ESDD for aged silicone rubber and aged EPDM.

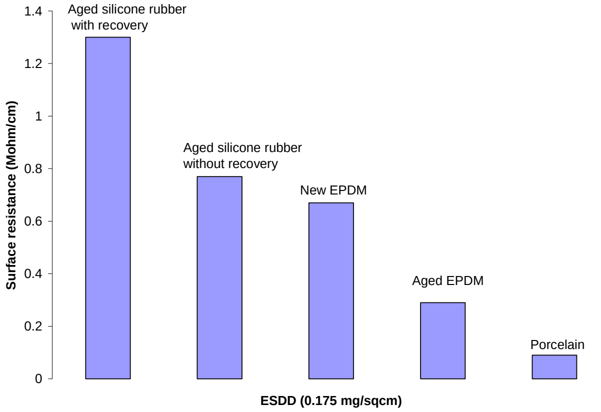

Figure 5. Comparison of experimental results of surface resistance for a constant ESDD for aged silicone rubber with and without recovery, aged EPDM and porcelain.

4.2 RECOVERY ASPECTS OF SILICONE RUBBER AND EPDM

The surface resistance measurement was done on aged silicone rubber samples, as well as aged EPDM samples with and without recovery, for the same ESDD (0.175 mg/cm^2). The recovery period was typically for three days on the roof of the laboratory where maximum day time temperatures of 45^{o}C are common. From Figure 6 it is quite evident that the recovery exerts little influence on the electrical performance of EPDM insulators due to material characteristic and hydrophilic nature. Figure 7 shows the recovery aspects of silicone rubber.

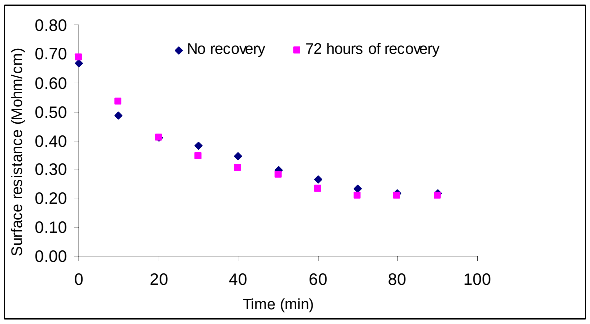

Figure 6. Variation of surface resistance vs. time for aged EPDM sample with and without recovery.

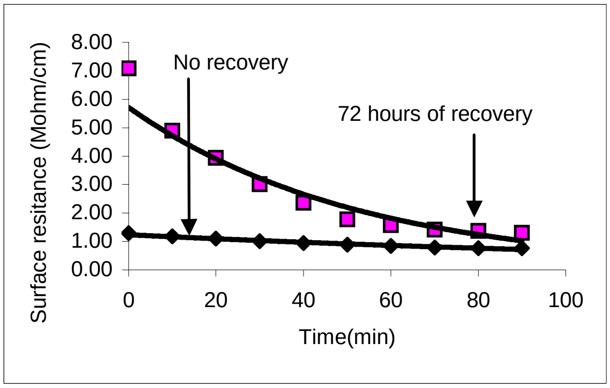

Figure 7. Variation of surface resistance vs. time for aged silicone rubber sample with and without recovery.

From Figure 7 it can be seen that for silicone rubber insulators the recovery process plays a significant role in improving the contamination performance Experimental evidence has indicated that the recovery of hydrophobicity in silicone rubber insulators is a progressive superposition of (low molecular weight silicone polymer) silicone oil layers with time that beads up water droplets. This transfer of silicone oil to the contaminated layer will prevent a complete dissolution of conductive material in wet conditions. Hence, there is a considerable decrease in contamination layer thickness. Therefore, the net effect of recovery can be viewed as a process in which there is a gradual reduction of effective contamination layer thickness. This reduction of the effective contamination layer can explain to some extent how a seemingly wettable silicone rubber insulator is able to withstand higher flashover voltage [14, 16-18].

4.3 EFFECT OF LEAKAGE DISTANCE ON FLASHOVER VOLTAGE

It is known that the flashover voltage will increase with leakage distance [3, 15]. However the improvement obtained in the flashover voltage for various materials for the same ESDD and leakage distance is not known. This information is useful to determine insulator dimensions as a function of material type. The ESDD level selected for comparison was 0.13 mg/cm^2, which represents heavy contamination. Figure 8 shows the graph that compares silicone rubber and EPDM performance.

The following can be inferred from Figure 8,

- When compared to EPDM for the same leakage distance, contamination severity (ESDD) and field aging, the use of silicone rubber provides up to a 30% improvement in flashover voltage if the surface hydrophobicity has recovered. If there is no hydrophobicity recovery, the improvement is about 10%.
- New silicone rubber housing is capable of providing the same flashover voltage as a new EPDM with 74% less leakage distance. With aging of the silicone rubber material and complete loss of hydrophobicity, the same flashover voltage is obtained with a reduction of 20% when compared to the aged EPDM material.

In the field, complete loss of hydrophobicity is rare. So the average improvement obtained in the contamination performance is somewhere in between the two extremes mentioned above.

In order to predict flashover voltage (FOV) for aged EPDM, a regression model using statistical technique was developed based on surface resistance values (SR) , and is given as.

$$FOV = 7.00 + 41.7\ SR \tag{3}$$

The model is valid only when certain assumptions are satisfied and is applicable for a range of surface resistance values. The basic assumptions are as follows [19]

- Errors are normally distributed. This aspect is checked through normal probability plot of residuals.
- Errors have zero mean and constant variance. This is validated by plot of residuals vs. predicted data.
- Errors are uncorrelated, which is demonstrated by plotting residuals and runorder.

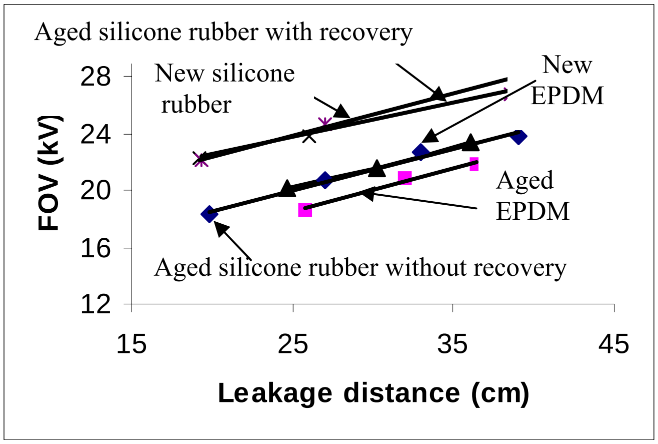

Figure 8. Variation of flashover voltage with leakage distance for silicone rubber and EPDM.

With regard to normal probability plot of residuals, the residuals should lie approximately in a straight line. If that is so, then it can be inferred that there is no considerable deviation from normality. Typically, a random scatter of points is obtained when the assumption of constant variance is satisfied. That is, the plot between the residuals and predicted values should not indicate any specific shape. In the plot, between residuals and runorder there should not be any trend discernable from the plot. If so, the assumption of independence of errors is not violated. All the assumptions were checked and found to be satisfied and hence the developed model is a valid model [19].

The details of statistical results are given in Table 5.

Table 5. Details of statistical results.

Predictor	Coef	SE Coef	T	P
Constant	7.0000	0.4980	14.06	0.000
Surface resistance	41.667	4.066	10.25	0.000
R-Sq = 93.8% R-Sq(adj) = 92.9% R-Sq(pred) = 89.65% From ANOVA; F = 105 P = 0.000				

Where,

SE coef – Standard error coefficient

T –Standard “T” Statistic

P– Probability of testing the significance of null hypothesis

F- Standard “F” statistic

R^2 – Residual sum of squares

R^2 (adj) –Adjusted residual sum of squares

R^2 – (pred) - Predicted residual sum of squares

A few comments can be made from Table 5. Since the values of R^2 and R^2 *(adj)* do not differ dramatically it confirms no non-significant terms have been included in the model. A high value of R^2*(pred)* indicates the good capability in predicting the variability in new observations. A high "*F*" ratio and low "*p*" value indicates that the model is highly significant. Figure 9 shows pictorially the validation of model at 95% prediction interval. *LL* and *UL* represent the lower and upper prediction interval. *M* represents the mean of *LL* and *UL*. *E* is the experimentally obtained value for flashover voltage.

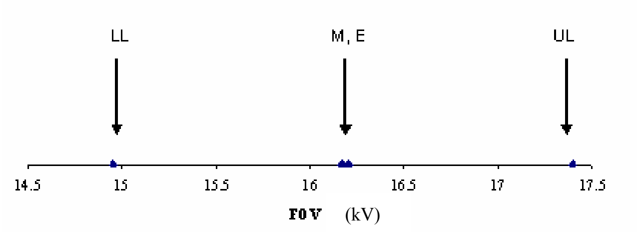

Figure 9. Pictorial representation of model validation (95% PI) at a surface resistance of 0.22 *MΩ/cm* and ESDD of 0.2 *mg/cm*^{2}.

The developed regression equation is valid for surface resistance that ranges from 0.05 to 0.30 MΩ/cm. From Figures 4 and 5, this range represents a fairly large range in terms of ESDD or contamination severity. Similar regression models could be developed for silicone rubber insulators. However, such models are of limited use as one needs to measure the surface resistance in order to calculate the flashover voltage. With different insulator dimensions new equations need to be developed. There is a need to develop a more generic model for calculating flashover voltage for wider application.

4.4 THEORETICAL MODEL FOR NCI

A dynamic model described in [3] was used as the basis for the model proposed in this paper. This model takes into account the profile of the insulator and the dynamic change in the arc resistance as it traverses along the leakage length of the insulator. In order to determine the reignition constant that could be used for silicone rubber, electric-field simulations were performed using "*Electro"* software [20]. This package offers two choices - rotationally symmetric or two dimensional modeling. The latter was chosen for this work as the geometry modeled is a flat plate. The computation error was less than 5% (determined by the difference of the integral of the axial electric field from the applied voltage). Two identical slabs of dimension 20 cm x 20 cm with parallel plate electrodes were considered as shown in Figures 10 and 11. The flow of water is modeled as a triangle. As porcelain surface is wettable, the water path is assumed to have a large base when compared to silicone rubber (dotted lines) where the water path is approximated as a filament. A series of simulations were performed by varying the area of the water channel and the distance of the tip of the channel from the HV end. The electric field at the tip of the water channel was calculated for various combinations of area (water channel) and distance (tip from HV).

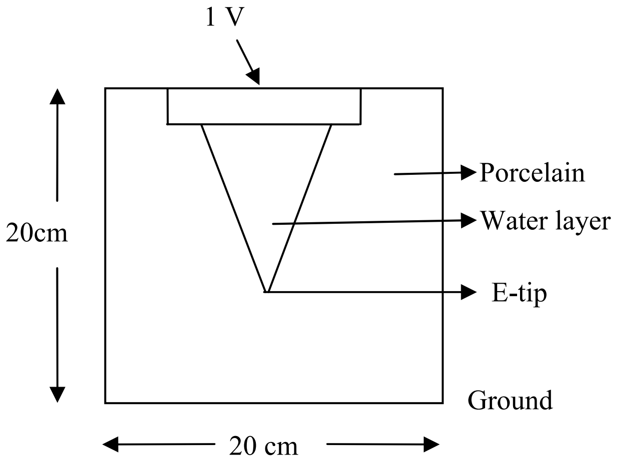

Figure 10. Simulation model considered for porcelain.

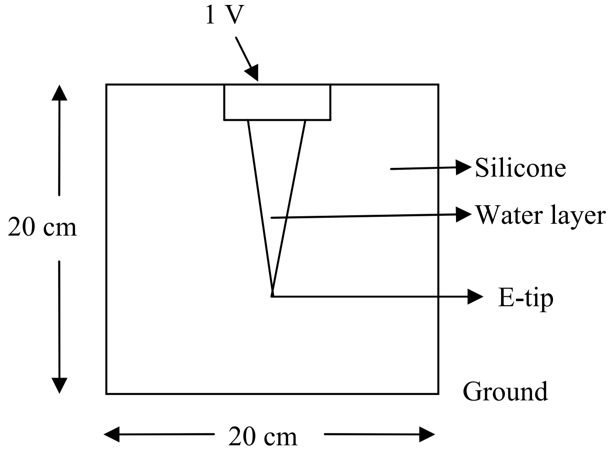

Figure 11. Simulation model considered for silicone rubber.

$$E\ field\ (porcelain) = K1*(A*D) + C1 \tag{4}$$
$$E\ field\ (silicone) = K2*(A*D) + C2 \tag{5}$$

Here K1, C1, (for porcelain) and, K2, C2 (for silicone) are numerical constants obtained from a linear regression fit (statistical) of the electric field data to the product of area and distance. The ratio of K2/K1 is 5.8. The electric field simulation results are given in Tables 6 and 7. The statistical results obtained using regression analyses are given in Tables 8 and 9. Statistical inferences that can be drawn from Tables 8 and 9 are the same as that was done from Table 5. The values of constants derived from the simulations are given in Table 10. It is to be expected that the aged silicone rubber which shows better flashover performance than porcelain will have the reignition constant value higher than porcelain and lower than new silicone rubber. For aged silicone rubber that has no recovery and behaves like a new EPDM material, and for aged EPDM the values of different constants that provide a good fit to experimental data are also given in Table 10. The value of constant to be used for silicone rubber samples with varying degree of hydrophobicity recovery is a subject for further research.

Table 6. Electric field simulation results for porcelain model.

Area (cm^2)	Distance (cm)	A*D	E-tip (V/cm)
5.22	0.78	4.08	0.061
11.00	1.64	18.08	0.057
14.25	2.24	31.88	0.053
14.97	2.24	33.49	0.052
22.19	3.32	73.59	0.044

Table 7. Electric field simulation results for silicone rubber model.

Area (cm^2)	Distance (cm)	A*D	E-tip (V/cm)
10.74	8.40	90.20	0.357
12.25	9.57	117.18	0.306
13.26	10.36	137.43	0.278
13.86	10.83	150.07	0.264
14.76	11.54	170.33	0.244

Table 8. Statistical results for E-field vs. (area*distance) for porcelain.

The regression equation is Efield = 0.0612 - 0.000242 A*D				
Predictor	Coef	SE Coef	T	P
Constant	0.0612063	0.0006914	88.52	0.000
A*D	-0.00024225	0.00001740	-13.92	0.001
R-Sq = 98.5% R-Sq(adj) = 98.0 % R-Sq(pred) = 88.57 % From ANOVA; F = 193.88 P = 0.001				

Table 9. Statistical results for E-field vs (area*distance) for silicone rubber.

The regression equation is Efield = 0.477 - 0.00141 A*D				
Predictor	Coef	SE Coef	T	P
Constant	0.47724	0.01636	29.17	0.000
A*D	-0.0014089	0.0001204	-11.70	0.001
R-Sq = 97.9 % R-Sq(adj) = 97.1 % R-Sq(pred) = 89.07 % From ANOVA; F = 136.84P = 0.001				

Table 10. Recommended values of various constants for different materials.

Material	Reignition constant (*N*)	Reignition exponent (*n*)	Arc constant (*A*)
New silicone rubber/Aged silicone rubber with recovery	340	0.5	50
Aged silicone rubber with no recovery/ New EPDM	300	0.5	50
Aged EPDM	250	0.5	35

4.5 COMPARISON OF SIMULATED AND EXPERIMENTAL RESULTS

In order to compare the simulated and the experimental values, simulations were performed with the developed new set of constants and compared with the experimental results that were obtained for new and aged silicone rubber. Experimental results show that the flashover performance of a new silicone rubber is similar to that of aged silicone rubber that has been allowed to recover its hydrophobicity. Without recovery, this sample behaves like a new EPDM. it can be inferred from Figure 12 that the experimental and theoretical simulation matches very closely. This proves the validity of the model proposed.

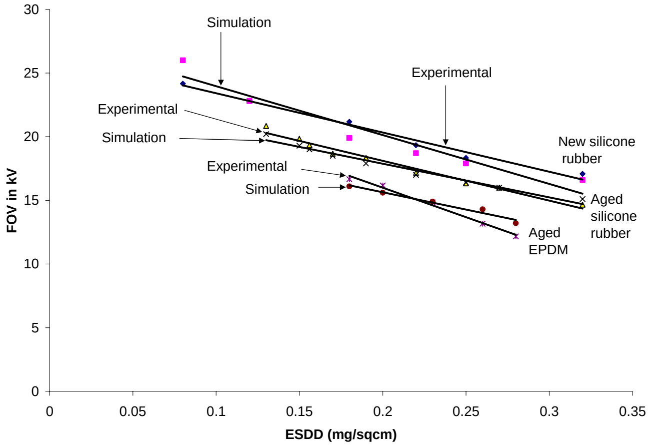

Figure 12. Graphical representation to show simulated flashover voltage and experimental flashover voltage for new and aged silicone rubber.

5 CONCLUSIONS

For traditional porcelain and glass insulators, there is a wide range in the predicted values of flashover voltage under contaminated conditions, indicating the rather poor understanding of the flashover process. This situation is more complicated for nonceramic insulators. The theoretical model proposed in this work shows good correlation with experimental results. The model can be used to predict the flashover voltage of silicone rubber and EPDM and also considers the hydrophobic nature of the surface.

ACKNOWLEDGMENT

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