Evaluation of Station Post Porcelain Insulators with Room Temperature Vulcanized (RTV) Silicone Rubber Coatings

FInal Project Report

Power Systems Engineering Research Center

Empowering Minds to Engineer
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Evaluation of Station Post Porcelain Insulators with Room Temperature Vulcanized (RTV) Silicone Rubber Coating

Final Project Report

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Executive Summary

Several methods are presently available to improve performance of station insulators under contaminated conditions, of which the application of hydrophobic coatings (like grease, oils and room temperature vulcanized (RTV) silicone rubber material, fluorinated compounds) are attractive to utilities as it can be applied over existing installations. Of the hydrophobic coatings, RTV silicone rubber has proven to be the most popular type. The chief concerns with this method are the time of effectiveness of the coating, and insulator performance with time in service. This project describes the testing and analysis of porcelain post insulators that were coated with a room temperature vulcanized (RTV) silicone rubber material. The tests were performed in a fog chamber using the clean fog method and the insulators were artificially contaminated with different levels of contamination ranging from light to very heavy (as expressed by equivalent salt deposition density-ESDD).

It was found that the RTV coated insulators were able to withstand levels of contamination that are far higher than experienced in the SDG&E service territory. The adhesion of the coating to the porcelain was excellent even after many tests which involved substantial surface discharge activity.

Statistical analysis was performed to quantify the improvement provided by the RTV coating when it had completely lost its hydrophobicity. It was found to in the range of 15-40%, the higher number for 69 kV system voltage and the lower number for 230 kV system voltage. In practice, this number should be higher than these as the protected surface of the insulator sheds are usually hydrophobic.

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Nomenclature

AC	Alternating current
ASU	Arizona State University
B	Temperature factor
CIGRE	International Council for Large Electric Systems (in English)
Cl	Chlorine
Cm	Centimeter
DF	Degrees of Freedom
EPDM	Ethylene propylene diene monomer
ESDD	Equivalent Salt Deposit Density
F	Standard "F" Statistic
FOV	Flashover Voltage
HC	Hydrophobicity Classification
HLD	High Leakage Distance
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
K	Potassium
kV	Kilovolts
kVA	Kilovolt Amperes
kΩ/cm	Kilo-ohms per centimeter
LD	Leakage Distance
L-G	Line to ground
LMW	Low Molecular Weight
M	Meters
Mg	Magnesium
mg	Milligram
ml	Milliliters
MS	Mean sum of squares
N1,N2,N3	RTV coated Silicone Rubber Insulators designators
Na	Sodium
NaCl	Sodium chloride (common salt)
Obs	Observation number
P	Probability of testing the significance of null hypothesis
Perm	Permittivity of the material
R-Sq	Residual sum of squares
R-Sq(adj)	Adjusted Residual Sum of Squares
RTV	Room Temperature Vulcanized
S	Standard deviation
S_a	Salinity in µS/cm
SDG&E	San Diego Gas and Electric
SE Coef	Standard error coefficient
Seq SS	Sequential sum of squares
SS	Sum of squares
STRI	Swedish Technical Research Institute
T	Standard "T" Statistic

V	Volume in ml
θ_a	Advancing contact angle
θ_r	Receding contact angle
μg	Microgram
μS	micro Siemens
Ω	Ohm
θ	Temperature in degree Celsius
σ_{20}	Temperature at 20 ^{0}C
σ_{θ}	Temperature at θ degree Celsius
^{0}C	Degree Celsius

1. Introduction

The reliability of a power system is reduced whenever the flashover strength across an insulator falls below the breakdown strength of the air in its working environment. Mitigation of outages due to lightning or switching surges is a well discussed topic among the industrial and academic communities. However, contamination caused flashovers are still a major problem. Contamination flashover is a complex problem faced by utilities today which have a wide geographical working span. Different types of pollutants on the insulation equipment are encountered due to various environmental conditions. The outdoor insulation equipments used in substations, overhead transmission and distribution lines must withstand the over-voltages due to switching or lightning transients in addition to their service voltages. The performance of insulation in contaminated conditions is paramount for providing a reliable service to the end user.

The utilities are able to select the insulator type according to the system and design requirements. In order to improve the contamination flashover performance, the utilities need to opt for high leakage porcelain (HLD) units, which can be taller or have wider sheds than standard porcelain units. However, for an optimal design of substation insulation it is desirable to improve the contamination flashover without increasing the height or width of the unit.

Room temperature vulcanized (RTV) Silicone Rubber coated insulators is a practical option for improving the flashover performance in presence of the pollution without compromising on the mechanical aspects of the substation design. The motivation of this study is to compare the performance of bare and RTV Silicone Rubber coated porcelain insulators by performing accelerated aging tests in the laboratory. Overall assessment of several important aspects of the coating such as adhesion to porcelain, hydrophobicity, contamination flashover performance and weathering is provided in the study. A good theoretical model for predicting the flashover will be a desirable asset to the utilities, helping to improve the substation design in the future. The study aims to build a comprehensive model for predicting the flashover performance of the RTV coated insulators.

2. Sample Evaluation

Twelve 69 kV post insulators were provided by San Diego Gas and Electric (SDG&E). The insulator units were manufactured by NGK-Locke Inc. Eleven samples were coated with Room Temperature Vulcanized (RTV) Silicone Rubber by a private contractor also provided by SDG&E.

The RTV Silicone Rubber coating was applied in a dust-free spray booth facility available at the Arizona State University Campus. After, the coating, the samples were left to dry for one day before subjecting to laboratory tests.

Artificial contamination tests provide valuable information on the behavior of external insulation by simulating the service environment in lab conditions. The contaminants consist of a suspension prepared by mixing appropriate proportions of kaolin and common salt (NaCl) in de-mineralized water.

Figure 1: RTV coated insulator

Figure 2: Porcelain insulator

3. Contamination Level on Outdoor Insulators

In CIGRE Task Force 33.04.01 [1], the typical pollution environments are defined as follows.

- Marine environment, where proximity of the sea introduce Na, Cl, Mg, K and other marine salts into the atmosphere.
- Industrial environment include sources of soluble pollution from steel mills, refineries or sources of inert dust such as quarries and cement factories
- Agricultural environment includes pollutants from highly soluble fertilizers as well as insoluble dust and chaff
- Desert environment introduces pollutants like inert sand as well as salt in some areas.

The electrically conductive deposit on the surface of the insulators is expressed as an equivalent salt deposit density (ESDD) in units of mg or µg of sodium chloride (NaCl) per cm^2 of surface area.

According to IEC Standard 60815, 1986 values of 10 $\mu g/cm^2$ are considered light, while values above 400 $\mu g/cm^2$ are very heavy.

Figure 3 shows the classification of ESDD as well as NSDD levels in terms of severity of pollution [1].

The region of interest for the purpose of this study varies from medium to very high level of contamination i.e. ESDD level 0.1-0.5 mg/cm^2.

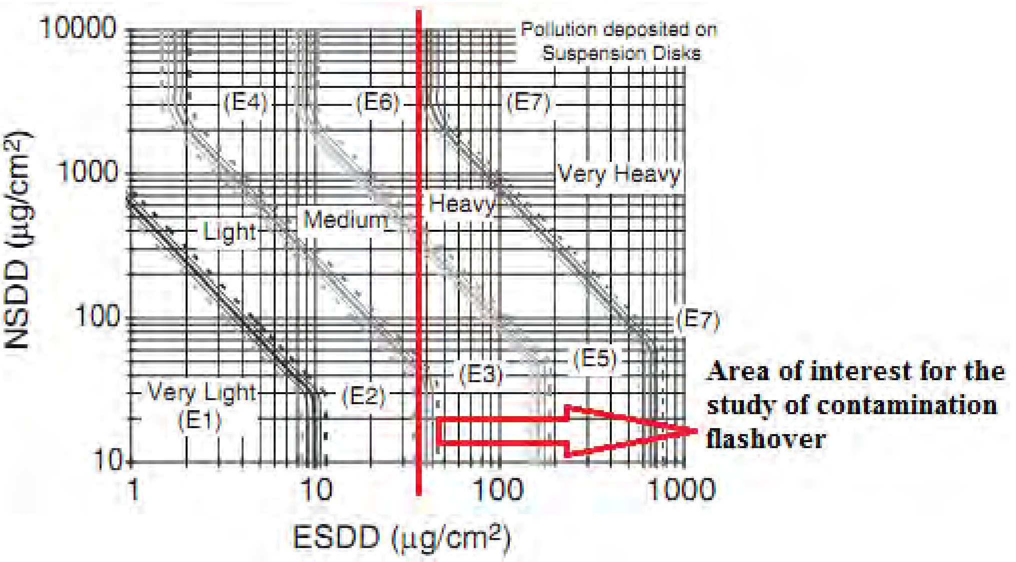

Figure 3: Zed curve approximation to IEC site pollution severity (SPS) guidelines [1]

Table 1 gives the range for the equivalent salt deposit density (ESDD) for various pollution levels [2].

Table 1: ESDD values as per IEC 60815 [2]

Class	**ESDD**	**Pollution Level**
I	0.03-0.06	Light
II	0.1-0.2	Medium
III	0.3-0.6	Heavy
IV	0.6	Very Heavy

4. Hydrophobicity Classification

STRI 92/1 Standard is used to classify the hydrophobicity of the insulator surface.

Criteria: The receding contact angle (θ_r) is the most important parameter in evaluation of the wetting properties of an insulator [3].

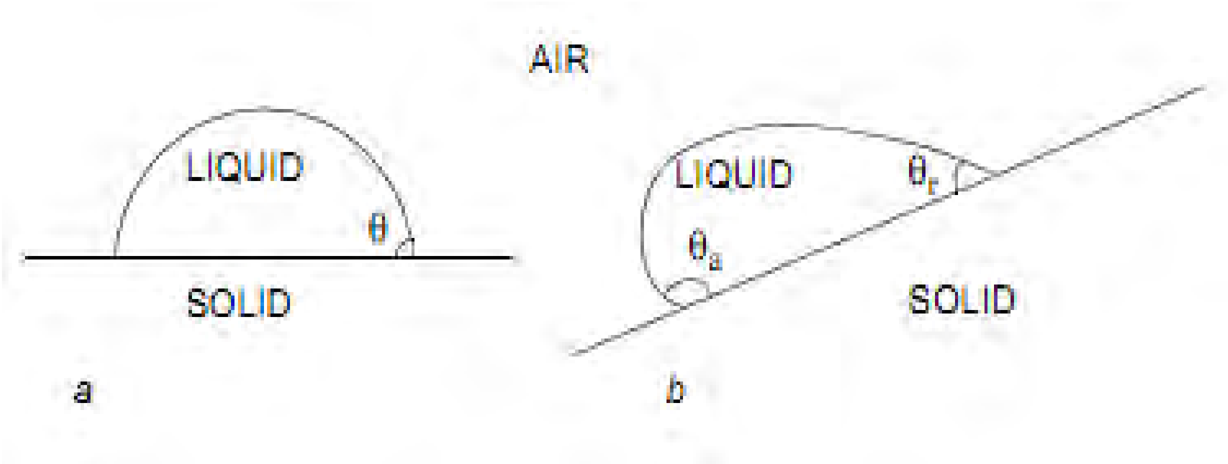

Figure 4: Definition of contact angles [3]

Figure 4 shows a water drop on a horizontal surface and on an inclined plane. θ_a is the advancing angle and θ_r is the receding angle. The actual wetting appearance on the insulator has to be identified with one of the seven hydrophobicity classes as shown in Figure 5.

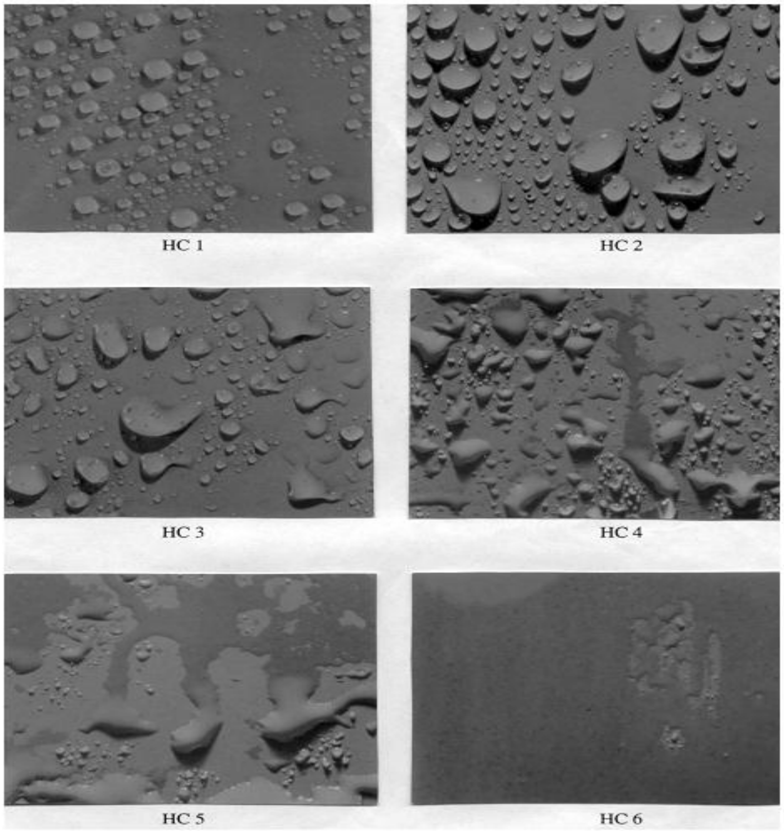

Figure 5: Typical examples of surfaces with HC from 1 to 6 [3]

Table 2: Criteria for the hydrophobicity classification [3]

HC	Description
1	Only discrete drops are formed. $\theta_r \approx 80^0$ or larger for the majority of droplets
2	Only discrete drops are formed. $50^0 < \theta_r < 80^0$ for majority of droplets
3	Only discrete drops are formed. $20^0 < \theta_r < 50^0$ for majority of droplets. Usually they are no longer circular
4	Both discrete droplets and wetted traces from the water runnels are observed (i.e. $\theta_r = 0^0$). Completely wetted areas < 2 cm^2. Together they cover 90% of the tested area.
5	Some completely wetted areas > 2cm^2, which cover < 90% of the tested area.
6	Wetted areas cover > 90%, i.e. small un-wetted areas (spots/traces) are still observed.
7	Continuous water film over the whole tested area.

(a) (b)

Figure 6: (a) RTV silicone rubber coated porcelain insulator hydrophobicity classification HC-1. (b) Bare porcelain insulator hydrophobicity classification HC-4

The polar molecules on the surface of bare porcelain are replaced by non-polar molecular groups; therefore, the surface becomes hydrophobic. Low molecular weights (LMW) components are responsible for the hydrophobic surface of the coating [4].

Bare Porcelain has high surface energy making it highly wettable [4].

5. Sample Preparation

5.1 Flashover phenomena on outdoor insulators

Flashover for an insulator is defined as a disruptive discharge over the surface of a solid insulation in a gas or liquid [5]. Outdoor insulators are subjected to various conditions in their working environment. During the service, contaminants accumulate on the insulator surface. Contamination on the surface increases the risk of a flashover under wet conditions such as light rain, fog or dew. When the surface of the insulator is wet, the contaminants dissolve to form a conducting film. As a result, leakage current flows on the surface which leads to the formation of dry band regions.

The sequence of events for contamination flashover:

- Deposition of conducting salts and moisture
- Dry band formation
- Electrical breakdown of dry-bands
- Propagation of the discharge across the film, bridging the insulator

5.2 Artificial contamination procedure

The pollution layer in the laboratory is achieved by artificially contaminating the insulators prepared by mixing kaolin and common salt in water. Fixed proportions of salt and kaolin are used to achieve contamination at various ESDD levels. The test object is carefully cleaned, so that all traces of dirt is removed. The contamination slurry is then applied to the insulator surface using a brush. Drying period for the insulator was about 10 hours before putting it to test under high voltage.

5.3 Measurement of insulator contamination level

Equivalent Salt Deposit Density (ESDD) is the standard measure for the contamination level on the insulator surface. It is expressed in mg/cm^2. The technique used to measure ESDD level in the laboratory is known as the rag-wipe method. A clean cloth/ cotton is rinsed in a fixed volume of deionized water. A fixed area on the shed is wiped using the cloth/cotton. The cloth is then rinsed in the deionized water. Conductivity (σ_θ) of the rinsed solution is then measured using a Horiba conductivity meter at temperature Θ (^{0} C). Then the value σ_{20} is obtained from σ_Θ by the following relationship:

$$\sigma_{20} = \sigma_\theta * [1 - b * (\theta - 20)] \qquad 1$$

$\sigma_{20}$is the layer conductivity at a temperature of 20^0 C in S/m

σ_θ is the layer conductivity at a temperature of Θ (^{0} C) in S/m

b is a factor depending on the temperature as given in Table 3 show below [5].

Table 3: Factor b values at various temperatures [5]

Θ	**b**
5	0.03156
10	0.02817
20	0.02277
30	0.01905

The salinity S_a is then measured by using the formula,

$$S_a = (5.7 * \sigma_{20})^{1.03} \qquad 2$$

The equivalent salt deposit density (ESDD) in mg/cm^2 is then obtained by the following formula

$$ESDD = S_a * \frac{V}{A} \qquad 3$$

Where 'V' is the volume of the rinsed solution in ml and 'A' is the area of the cleaned surface of the sample in cm^2 [5].

6. Laboratory Experiments

The samples were subjected to high voltages in a fog chamber available in the Arizona State University High Voltage Laboratory. Two types of experiments were carried out on each samples viz. 1. Surface Resistance Measurement Test and 2. Flashover Test.

The fog chamber used for these experiments is made of stainless steel with a volume of approximately 27 m^3. A 40 kVA/ 100 kV transformer adjacent to the chamber provides the high voltage (HV) supply. The fog is generated using ultrasonic nebulizers placed in a water tub inside the chamber. Figure 7 gives the schematic of the fog chamber set available at Arizona State University [6].

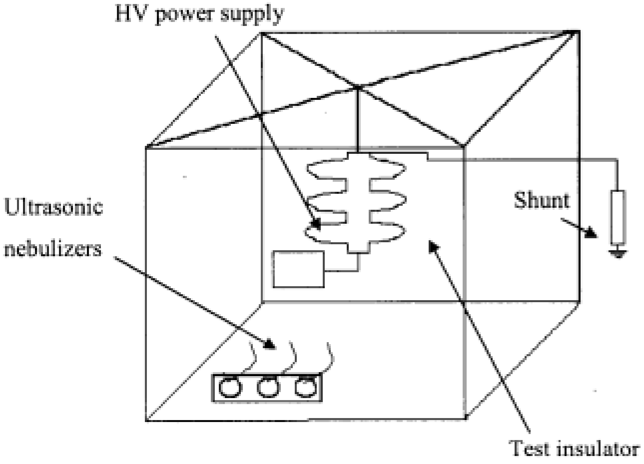

Figure 7: Schematic of testing in fog chamber for surface resistance measurement [6]

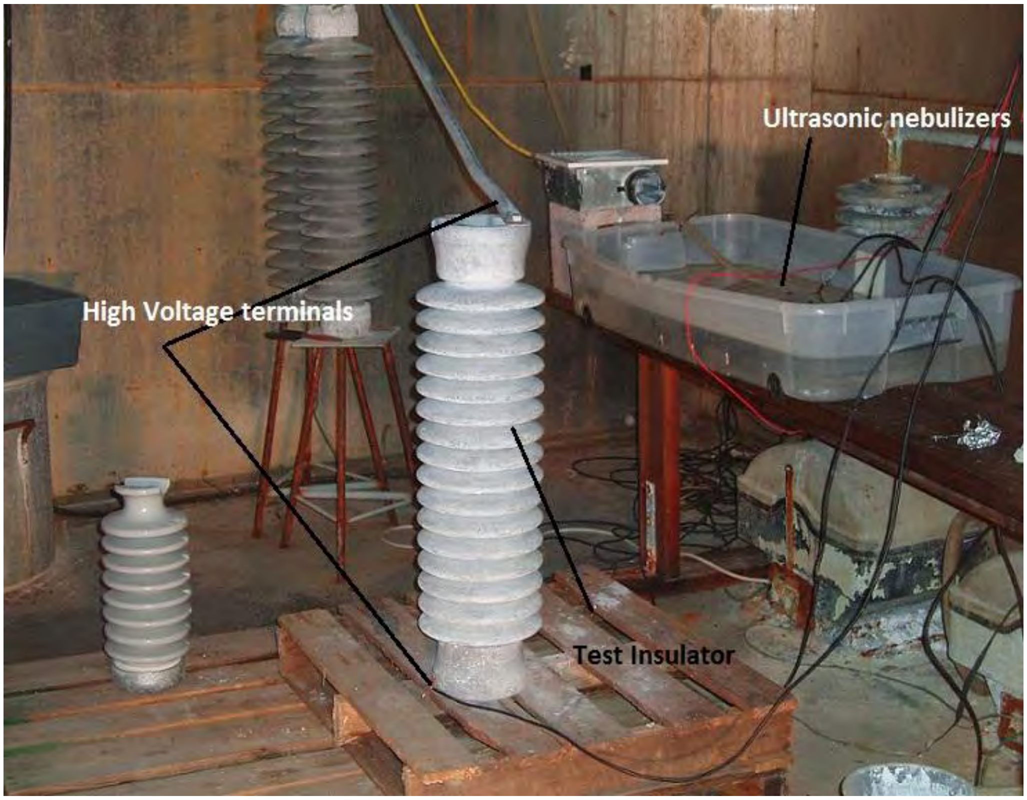

Figure 8: Experimental set up in the fog chamber for testing the RTV silicone rubber coated insulator.

AC voltage in the range of 4-10 kV was used depending on the dimensions of the test samples. The high voltage was applied across the insulator terminals. Aluminum tape electrodes were used for this purpose. The applied voltage was high enough to obtain a reading but not high enough to initiate discharge across the sample. A variable resistance box (100 **Ω**, 470 **Ω**, 1000 **Ω**) was connected in series with the insulator sample. The leakage current was measured across the resistance box using an oscilloscope. Using basic circuit analysis techniques the surface resistance of the insulator sample was calculated. It takes about 40-60 minutes to obtain a satisfactory value of surface resistance.

6.1 Surface resistance measurement

Four samples were used for surface resistance measurement study. One sample was porcelain and the remaining three were RTV Silicone Rubber coated samples.

Each insulator was tested for surface resistances at three ESDD levels from medium to heavy pollution i.e. 0.1 - 0.5 mg/cm^2.

Surface resistance measurement was done as soon as the contamination applied on the insulator dried up. Silicone Rubber coated insulators exhibit a behavior known as hydrophobicity recovery. The RTV insulators were allowed to recover their hydrophobicity after the surface resistance test. The rest time for the RTV insulators was 3 days and then the recovery surface resistance was measured.

Table 4: Surface Resistance values for Porcelain sample at different ESDD levels

Porcelain Sample	
ESDD (mg/cm^2)	**Surface Resistance (kΩ/cm)**
0.1	73
0.3	59
0.5	48

Table 5: Surface Resistance for RTV Silicone Rubber coated insulators

Surface resistance Measurement for RTV Silicone Rubber coated insulators (kΩ/cm)						
Sample	**ESDD Level (mg/cm^2)**					
	0.1		**0.3**		**0.5**	
	Without Recovery	**With Recovery**	**Without Recovery**	**With Recovery**	**Without Recovery**	**With Recovery**
N1	98	164	83	98	76	94
N2	181	213	90	148	82	110
N3	101	196	76	96	62	83

Table 6: Surface Resistance values for EPDM samples
(values obtained from previous research work at ASU [7])

Sample	**ESDD Level (mg/cm^2)**	**Surface Resistance(kΩ/cm)**
Sample 3	0.55	103
Sample 5	0.41	130
Sample 6	0.48	104

6.2 Flashover test results

Flashover experiments were carried out for each of the samples at various ESDD Levels. The results are as shown in Table 7. Note that the flashover experiments were carried out immediately as the samples dried up after contamination process.

Table 7: Flashover voltages for RTV silicone rubber coated and porcelain samples

Flashover Voltage Measurements		
Sample	**ESDD (mg/cm^2)**	**Flashover voltage (kV)**
Porcelain	0.1	48
	0.3	40
	0.5	30
N1	0.1	> 66
	0.3	60
	0.5	50
N2	0.1	>66
	0.3	60
	0.5	58
N3	0.1	> 66
	0.3	66
	0.5	46

7. Statistical Modeling

The statistical analysis was done using Minitab 16. The regressors used for model are the ESDD levels, permittivity (Perm) of the surface of the insulator, rating (Rating) and leakage distance (LD) of the insulator sample. The response is Flashover Voltage (FOV).

From Figure 9, it is inferred that the measured surface resistance values are normally distributed. The model is therefore robust to normality assumption for analysis of variance.

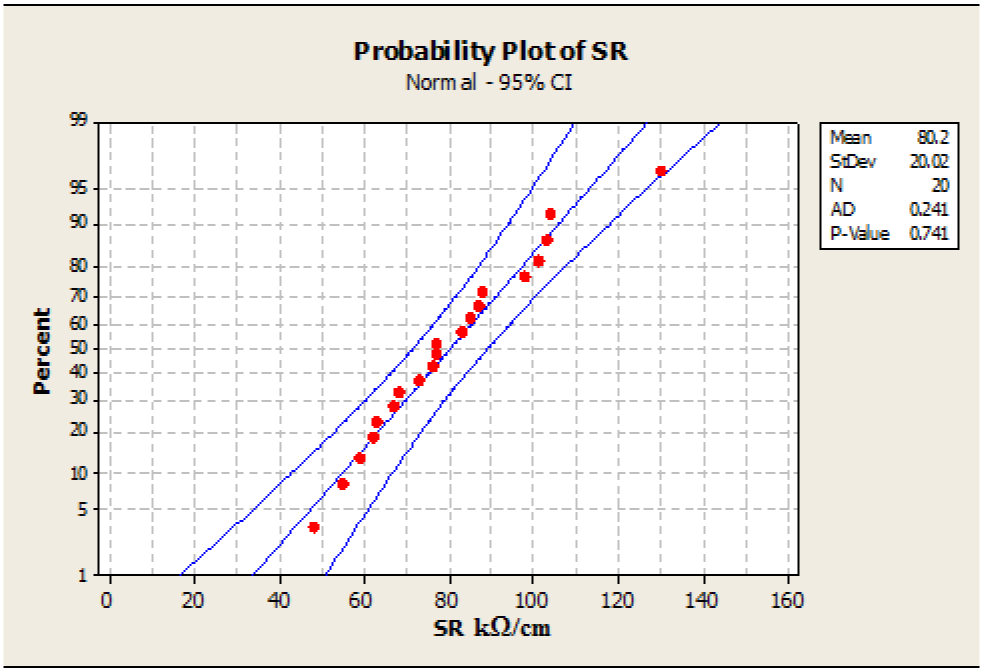

Figure 9: Normal distribution plot for surface resistance values

7.1 Regression Analysis: FOV versus ESDD, Perm, LD, Rating

The regression equation obtained from Minitab is as shown below

FOV = 47.7 - 55.0 *ESDD - 9.28 *Perm + 0.160 *LD + 0.771 *Rating

Predictor	Coef	SE Coef	T	P
Constant	47.69	10.32	4.62	0.000
ESDD	-55.025	6.397	-8.60	0.000
Perm	-9.2773	0.870	-10.65	0.000
LD	0.1599	0.125	1.28	0.221
Rating	0.7714	0.866	0.89	0.387

S = 3.90624 R-Sq = 96.6% R-Sq(adj) = 95.6%

The high adjusted R-squared value shows high reproducibility i.e. the model developed is capable of explaining the variability over a wide range.

The high P values for LD and Rating indicate that leakage distance (LD) and rating of the insulator are not major contributors in the model. This limitation can be eliminated by including more data points in the regression model.

7.2 Analysis of variance

```
Source          DF     SS      MS       F       P
Regression       4   6409.3  1602.3  105.01  0.000
Residual Error  15    228.9    15.3
Total           19   6638.2
```

```
Source   DF   Seq SS
ESDD      1   2954.6
Perm      1    313.6
LD        1   3129.1
Rating    1     12.1
```

```
Unusual Observations
Obs   ESDD     FOV     Fit SE    Fit   Residual  St Resid
  5   0.100  80.000   72.589  1.787    7.411     2.13R
 14   0.500  58.000   50.579  1.627    7.421     2.09R
 20   0.500  25.000   25.000  3.906   -0.000       * X
```

R denotes an observation with a large standardized residual.

X denotes an observation whose X value gives it large leverage

SE Coef – Standard error coefficient
T - Standard “T” Statistic
P - Probability of testing the significance of null hypothesis
F- Standard “F” Statistic
S - Standard deviation
R-Sq – Residual sum of squares
R-Sq(adj) – Adjusted Residual Sum of Squares
DF – Degrees of Freedom
SS – Sum of Squares
MS - Mean sum of squares.

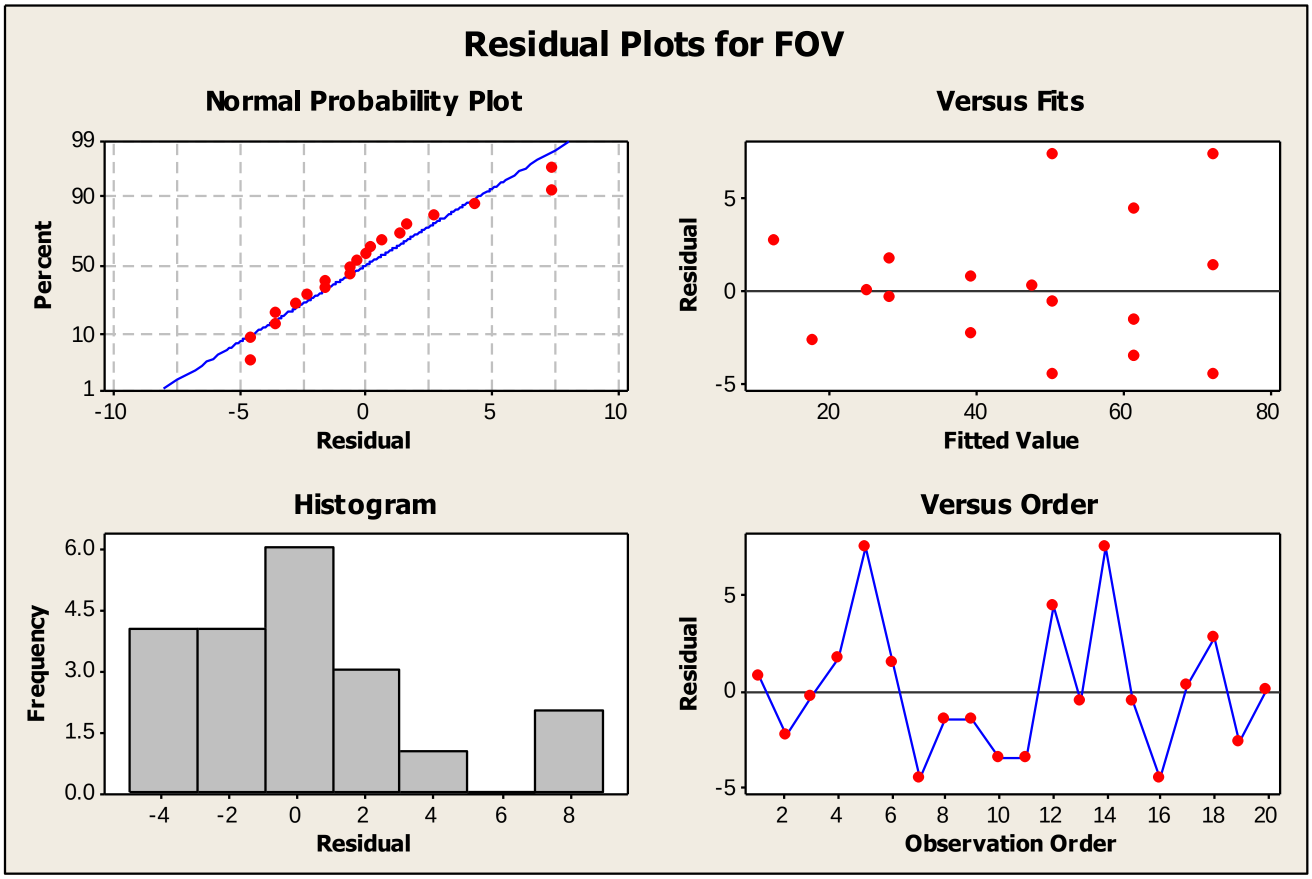

Figure 10: Residual plots for flashover voltage

The developed regression model is valid only when certain assumptions are true.

The assumptions that were checked are listed below.

- The errors are normally distributed.
  From Figure 10, the normal probability plot, it is seen that there are no outliers and the residuals lie approximately in a straight line. There is no considerable deviation from normality.
- The errors have zero mean and constant variance.
  The plot residual v/s fitted values from Figure 10 it is infers that there is no pattern or shape indicated. Therefore the constant variance assumption for errors stands true.
- The errors are uncorrelated.
  The plot residual v/s observations order from Figure 10 shows no discernible trend which implies that the errors were uncorrelated.

All the assumptions were checked and found satisfied, therefore, the model developed is valid [8].

The regression model was used to obtain plots for RTV Silicone Rubber Coated and bare porcelain insulators.

Figure 11 shows flashover performance for the insulators at different service voltages.

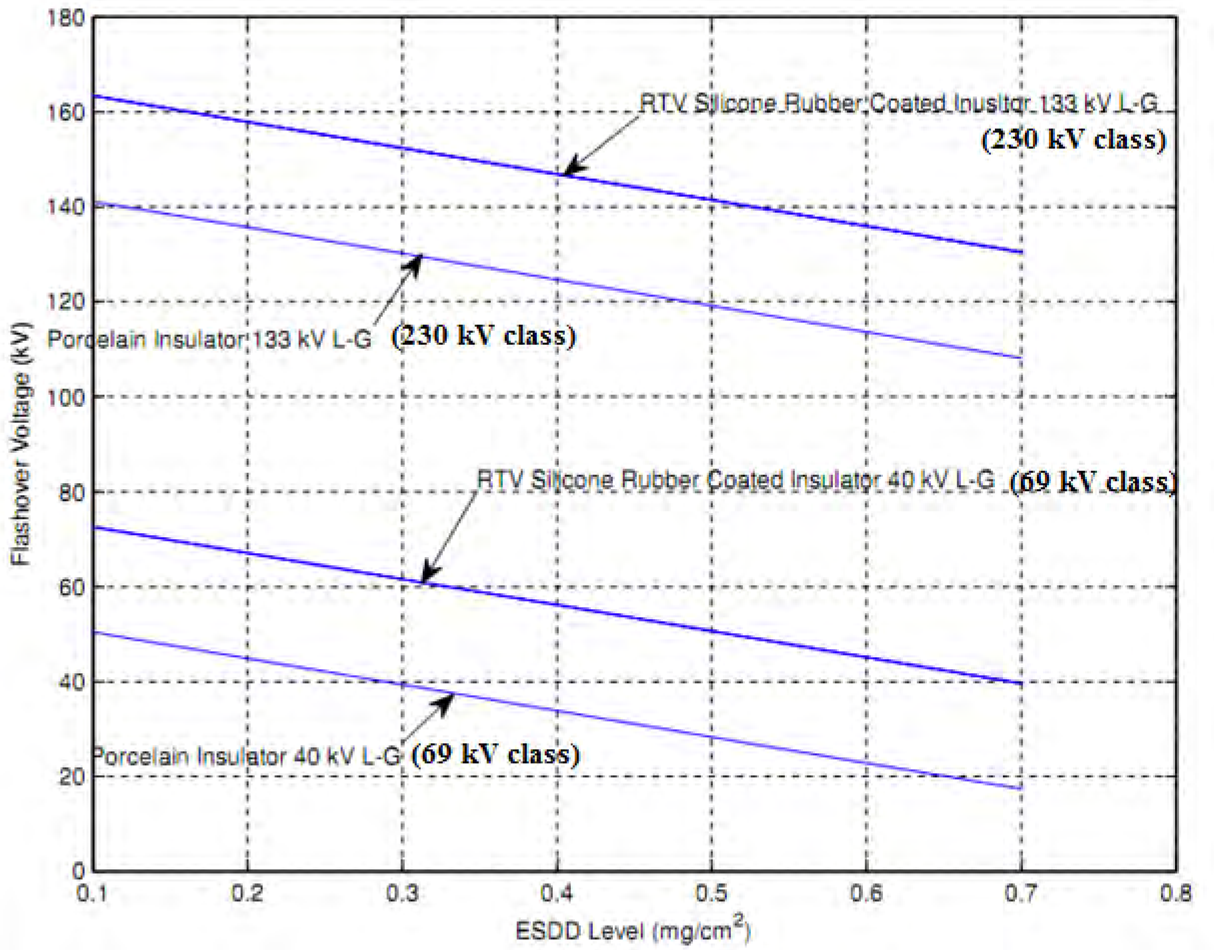

Figure 11: Plot for flashover performance of RTV silicone rubber and porcelain insulators at different operating voltages

8. Conclusions

1. The adhesion of the RTV coatings to the porcelain was excellent. This was even after many tests where there was significant discharge activity during the tests. The coating was sprayed on to the insulators by a trained employee of the coating supplier.
2. RTV coated insulators withstood much higher levels of contamination when compared with porcelain. This was the case when the coating had completely lost its hydrophobicity. The hydrophobicity loss was created by spraying isopropyl alcohol on the coated insulators.
3. RTV coated porcelain posts can for a reduced height give same or better performance than taller posts or posts with extended leakage distance.

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