



Statistical Reliability Analysis on Flashover Characteristics of Ceramic Disc Insulator and Polymeric Insulators

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Abstract

Composite or polymeric insulators have gained significant attention in recent years compared to conventional ceramic disc insulators used in power transmission. The aim of this study is to investigate the performance of ceramic disc and polymeric ceramic 11 kV outdoor products under industrial pollution using laboratory-based pollution performance tests. The insulator performance tests are conducted at various contaminants levels of cement to assess its effectiveness. Statistical analysis of the flashover voltage is investigated through survival functions, hazard functions, and withstand voltages at different failure probability levels. This is an indicator of the level of pollution in the insulator. In this study, normal and Weibull distribution-based statistical models are employed to examine the performance of insulators. The experimental results reported that the ceramic disc insulator and polymeric insulator proved to be more reliable and compatible as insulators in both normal and industrial pollution conditions based on statistical survival functions, hazard functions, and voltage withstand predictions. Based on the statistical analysis of both insulator flashover characteristics and withstand characteristics, the experimental results showed that the normal polymeric insulators and the polluted polymeric insulators have an overall functional reliability performance that is much better than ceramic disc insulators.

Keywords Flashover characteristics contamination · Survival function · Hazard function · Normal distribution · Weibull distribution

1 Introduction

The most prominent features of insulators in power transmission and distribution play a vital role in ensuring the dependability of the power system network [1]. Insulators should be able to insulate the live conductors from the current-carrying tower structure to the ground. Over the past several decades, ceramic insulators have been widely used as high voltage insulators (> 11 kV) in power transmission and distribution due to their high heat-carrying capacity, low thermal conductivity, and superior corrosion resistance [2].

Recently, polymeric insulators gained major attention among the research community in power sectors due to their higher reliability and robustness to different weather conditions [1]. Insulators should be capable of withstanding normal power frequency voltages and mechanical stresses up to a 10% level of margin. Beyond the tolerance level, the probability of flashover and puncture of the insulating material will be increased [3, 4]. Therefore, the most harmful effect is the deposition of pollution due to heat, moisture, and dirt on the ceramic insulators besides chemical deterioration, excessive voltage stress, aging effects, etc. This is one of the most common and major frightening factors which undermine the safety considerations of operating systems of the power grid, in specific if the insulators are used in chemical/cement/steel industries. Such mechanisms of flashover characteristics due to pollution can impose huge economic losses after the occurrence of lightning [5]. Hence, the main aim of this present work is to investigate the effect of flashover characteristics of different types of insulators used in industries due to different types of pollution.

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Under moist and light-rain conditions, the soluble substance in the contaminants may get dissolved and initiate the leakage current flow and thus increase the conductivity. Pollution deposition on such composite insulators is usually following a non-uniform pattern and it is mainly depending on the velocity of the wind, wind flow direction, the geometric profile of the insulator, type of composite materials, etc. [4] The deposition of non-uniform pollution will create the non-uniform current density and dissipation of power in the insulators [6]. This phenomenon leads to the formation of dry bands which have been investigated in detail [5]. The dry band formation on the insulator is influenced by many parameters like applied voltage, the thickness of pollution, wetting rate, etc. [7].

In specific, for any given application, AC flashover voltage is one of the important characteristics of insulation that to be considered for a given operational conditions. It is a measure of the ability of insulators to survive heat stress developed in real-time during normal and adverse operating conditions [8]. The flashover process is generally a random phenomenon, and it depends on various factors such as insulation design, surface condition, environmental conditions, etc. [9]. Usually, the values of flashover voltage are randomly distributed during the measurement. In the above way of estimation of flashover voltage, flashover voltage's distribution and dispersion nature must be considered in the analysis, which is important for ensuring the dependability and compatibility of outdoor insulation [10]. Hence, it is highly essential to investigate the statistical behavior of flashover voltage of outdoor solid insulators for revealing its suitability for all operating conditions. In the literature, very few studies have considered the above factors in investigating the performance of insulators in an outdoor environment. For studying the reliability and compatibility of any medium, it is important to select appropriate statistical distribution models which disclose the characteristics of flashover voltage [11]. From the statistical distribution model, the developed survival function, hazard function, and withstand voltage at various failure probability are useful for the analysis of reliable functioning of insulations in the operational area.

In literature, different statistical distribution models such as Weibull, Gumbel, exponential, log normal, frechet, generalized extreme value, etc. have been studied for different applications besides the traditional normal (Gaussian) distribution [12]. Among the models, the Weibull distribution model has high accuracy in the failure rate prediction at a lower probability range in analyzing the performance of the insulators in a variety of applications [11]. Before studying the system's performance with a statistical distribution model; a hypothesis test must be done for ensuring the data's goodness of fit with the selected distributed model. Among the different hypothesis test methodologies such as Chi-Squared (CS) test, Kolmogorov Smirnov (KS) test,

Shapiro–Wilk (SW) test, Anderson Darling (AD) Test, etc. AD hypothesis test's procedure is giving more weightage to the tails of the probability model. Hence, this test is performing well over other statistical tests in a variety of applications [12]. To study the performance of outdoor insulators under industrial pollution, this present work is proposed to conduct the test for measuring the effect of flashover voltage in polymeric insulators and further studying the statistical suitability analysis with the normal and Weibull distribution model.

The major contributions of the present work are given below:

- (a) We investigated the flashover characteristics of two types of insulators (ceramic and polymeric) under different pollution conditions.
- (b) We analysed the reliability and compatibility of the insulators based on survival functions, hazard functions, and withstand voltages at different failure probability levels using two different types of statistical models such as Weibull and normal Gaussian Distribution.

The rest of the paper is organized as follows: Sect. 2 discusses the proposed methodology for testing the characteristics of insulator, the analysis of AC flashover characteristics data is presented in Sect. 3, Sect. 3 elaborates the statistical analysis of data using different models and discussion, and the conclusion of the present study is given in Sect. 4.

2 Materials and Methods

In this work, 11 kV ceramic and polymer insulators are considered for studying their suitability under industrial pollution conditions. For creating a pollution layer on the surface of insulators, the solid layer method with the brushing technique is adopted with the required value of cement quantity and other required materials [21]. The industrial pollution of cement is prepared with various concentrations of 10 g, 20 g, and 30 g mixed with the distilled water [6]. The degree or severity of the contamination has been specified for industrial pollution with non-soluble deposit density or NSDD, which is defined as the amount of cement that would yield the same conductivity at complete dilution as the non-NaCl salt [13]. Pollution degree is determined by an equivalent salt deposit density which is measured after conducting a flashover test and removing a layer of pollution in a particular shape from the insulating surface of the insulator [14, 15].

Artificial pollution AC flashover performance test is carried out in a high voltage laboratory which is shown in Fig. 1b. The transformer rated voltage is $2 \times 0.22/100/0.22$ kV, rated current $2 \times 22.8/0.1$ A, rated output is 10kVA. The testing transformer is employed to supply AC, DC, and impulse voltage. AC Supply is given to an insulator utilizing a transformer

Fig. 1 Laboratory-based pollution test setup



(a) Control Panel used to perform flashover test analysis.



(b) Experimental Setup

through the control desk shown in Fig. 1a to regulate and provide the high voltage AC supply. The flashover voltage and leakage current are noted from the experiment using an even rising method. Here, the sequence of flashover tests was carried out 100 times for each insulator sample at a certain pollution level and the increase of voltage at a random rate is applied until the flashover is happening and then records the voltage. At the time interval of 2–3 min later, the above procedure will be repeated to record a set of data used for the analysis.

Statistical distribution models of flashover voltage of outdoor ceramic and polymeric are developed with normal distribution and Weibull distribution techniques. To predict the distribution pattern of flashover voltages based on results of hypothesis AD test with 100 measured values of test results

are considered for investigating the performance of insulators. Survival function and hazard function for distributed flashover voltage is estimated for proving the reliability of insulators under polluted conditions.

Withstand voltages for different failure probability are computed to analyze the compatibility of insulators at various risks of failure conditions. Figure 2 shows the proposed work for investigating the statistical reliability of HV insulators under cement pollution. The obtained results are compared with the standard values for flashover voltage under different conditions of insulators. The standard values of flashover voltage and withstand voltages corresponding to international standards are given in Table 1 [16, 17].



Fig. 2 Proposed Work on Investigating the Statistical Reliability on HV Insulator

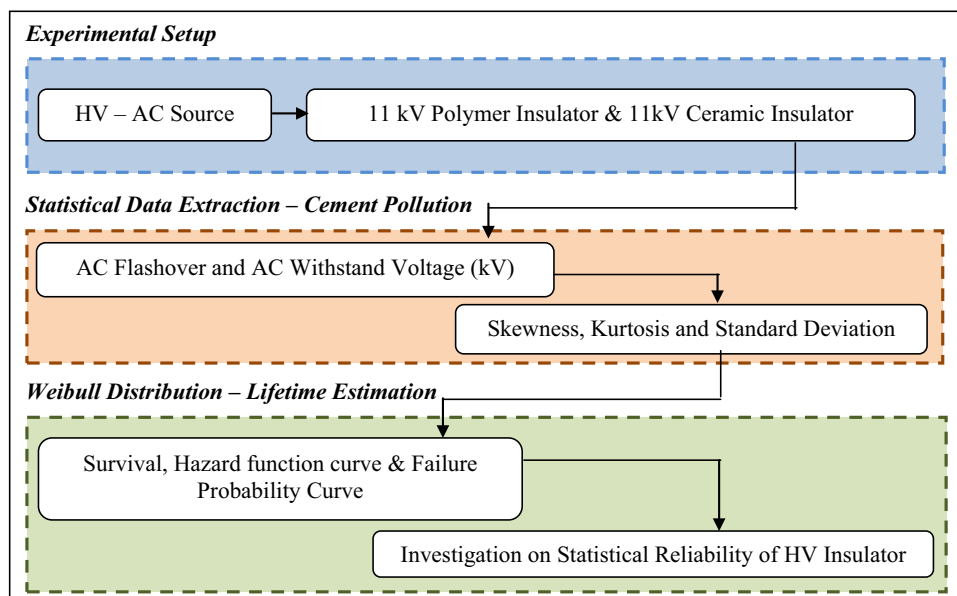


Table 1 Standards for 11 kV ceramic disc and polymeric insulators

Insulators	Standards	AC Flashover voltage (kV)		AC Withstand Voltage (kV)	
		Dry	Wet	Dry	Wet
Ceramic Disc—Ball & Socket Type 45 kN	IS731 [16]	75	45	60	35
Polymeric—Long Rod/Disc	IEC 61,109 [17]	50	40	45	35

3 Analysis of AC Flashover Voltage with Estimation of Statistical Data

Based on the procedure of testing for AC flashover voltage of insulators and methodology of the proposed study, the insulators have been subjected to test and values of flashover voltage are taken for further investigation. Along with the flashover voltage, leakage currents flowing through the insulators and NSDD are also accounted for knowing the severity of pollution. Statistical parameters of the mean (μ), standard deviations (σ), skewness (s), and kurtosis (g) of AC flashover voltages are calculated with the basic statistics formula as given in Eqs. 1, 2, 3, 4 [12].

$$\mu = \frac{1}{n} \sum_{i=1}^n x_i \quad (1)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \mu)^2} \quad (2)$$

$$s = \frac{\sqrt{n} \sum_{i=1}^n (x_i - \mu)^3}{\left(\sum_{i=1}^n (x_i - \mu)^2 \right)^{\frac{3}{2}}} \quad (3)$$

$$g = \frac{n \sum_{i=1}^n (x_i - \mu)^4}{\left(\sum_{i=1}^n (x_i - \mu)^2 \right)^2} \quad (4)$$

where, x_i refer the sample value of i^{th} sample, n refers to the maximum number of samples.

The average values of mean, standard deviation, skewness, and kurtosis of flashover voltage, leakage current, and NSDD values are listed in Tables 2 and 3, respectively for ceramic and polymeric insulators under normal and polluted conditions.

AC flashover voltage of clean insulators is higher than the standard specified value of minimum flashover voltage required for ceramic and polymeric insulators. This indicates the selected insulators can be used in real operating conditions. With polluted conditions, the flashover voltage is shown a reduction pattern as an increase in NSDD and leakage current. From the experimental results, it is inferred that flashover voltage data are distributed in a scattered manner around mean flashover voltage. Further, the unpredicted stochastic nature of AC flashover voltage under testing conditions induced the necessity for analysing the performance with statistical study to prove the reliability and compatibility of insulators.

For accurate assessment of the shape of the data distribution, statistical skewness and statistical kurtosis are estimated to analyze the track of skew and sharpness with reference to the centre. With the assumption that values of zero and three



Table 2 Statistical data of AC flashover voltage of ceramic disc insulator

Quantity of Cement and Water	NSDD (g/cm ²)	Average leakage current (mA)	Mean flashover voltage (kV)	Standard deviation (kV)	Skewness	Kurtosis
Clean	0	57.33	80.84	3.1582	0.06	−0.58
10 g	0.014	59.22	70.1	1.4035	0.07	−0.45
20 g	0.055	61.44	60.51	2.0523	0.24	−0.02
30 g	0.144	63.77	60.32	2.1267	0.55	−0.05

Table 3 Statistical data of AC flashover voltage of polymeric insulator

Quantity of cement and water	NSDD (g/cm ²)	Average leakage current (mA)	Mean flashover voltage (kV)	Standard deviation (kV)	Skewness	Kurtosis
Clean	0	41.43	85.19	6.66	−0.12	−0.18
10 g	0.015	43.85	81.3	5.6595	−0.24	−0.04
20 g	0.055	46.33	78.72	5.9	−0.05	0.04
30 g	0.155	49.23	71.11	2.6458	−0.48	−0.15

are taken respectively for skewness and kurtosis in a normal distribution, statistical implications are made for exactly knowing whether the data distributions are either normal or nearly normal [11, 12]. From statistical results, it is indicated that most of the skewness values are nearly followed by the normal distribution, while kurtosis of flashover voltage data is immensely differing from the assumption. These observations are directed to study the statistical analysis with other distributions model along with normal distribution.

4 Statistical Analysis

Generally, a statistical reliability study is carried out with the calculation of survival function and hazard function of test data with an estimation of probability density function (PDF) and cumulative distribution function (CDF) for the concern distribution models [18]. Probability density function ' $f(x)$ ' of a continuous distribution model, is the probability that a functional variable ' X ' has the value equal to ' x ' in a given set of sample ' n ' with the maximum value of ' b ' and the minimum value of ' a ' as given in Eqs. 5 and 6 [12].

$$f(x) = P(X = x) \quad (5)$$

$$\int_a^b f(x)dx = P(a \leq X \leq b) \quad (6)$$

For the same model, cumulative distribution function ' $F(x)$ ' is the probability that a functional variable ' X ' has a value less than or equal to ' x ' in a given set of sample ' n '

as given in Eqs. 7, 8, 9.

$$F(x) = P(X \leq x) \quad (7)$$

$$F(x) = \int_{-\infty}^x f(x)dx \quad (8)$$

$$F_n(x) = \frac{1}{n} \cdot (\text{Number of Observations} \leq x) \quad (9)$$

The reliability of any data set has been related to the survival function of data with the statistical probability distribution model which defines survivability beyond any data of ' x ' [11, 12, 19]. The survival function is termed also as the reliability function, which is the complement function of CDF, which is the probability that a functional variable has a value higher than value ' x ' as given in Eq. 10.

$$S(x) = P(X > x) = 1 - F(x) \quad (10)$$

In reliability analysis, the instantaneous failure rate is described with an estimation of hazard function at any point in the data set. The hazard function is computed with PDF and the survival function as given in Eq. 11 [11, 12]. If the hazard function $h(x)$ is constant, it indicates the equal frequency occurrence of failure within the data set. In practice, a non-constant hazard function is obtained, and it will fluctuate for different values in the data set.

$$h(x) = \frac{f(x)}{S(x)} = \frac{f(x)}{1 - F(x)} \quad (11)$$

The normal (Gaussian) distribution is generally used in the statistical study with the estimation of statistical parameters



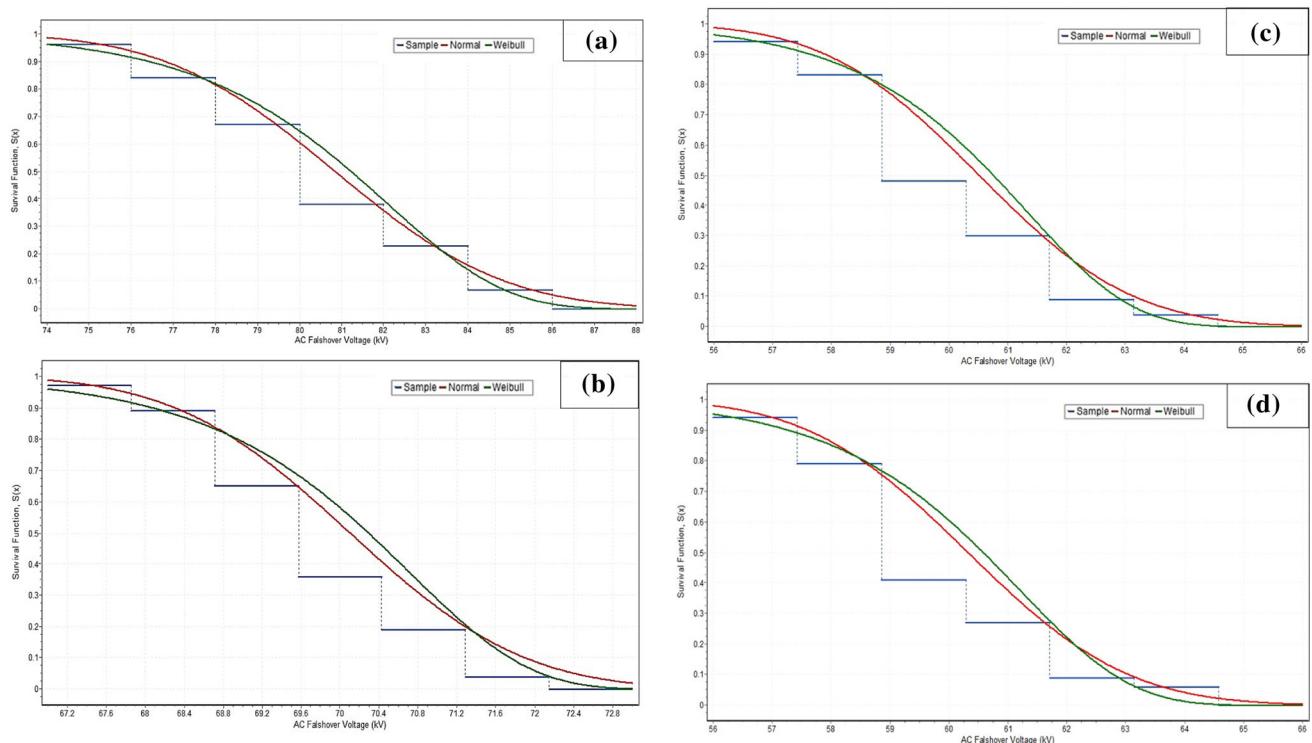


Fig. 3 Survival function curve for 11 kV ceramic disc insulator. **a** No pollution, **b** 10 g Cement pollution, **c** 20 g Cement pollution, and **d** 30 g Cement pollution

Table 4 Goodness of fit as per hypothesis AD test

Insulator Type	Distribution	Conformity Data for $\alpha = 0.05$	Clean condition	Polluted with Industrial Condition		
				1:01	2:01	3:01
Ceramic Disc Insulator	Normal Distribution	Statistic value	0.6988	1.1631	1.2321	1.6387
		Conformity	Yes	Yes	Yes	Yes
	Weibull Distribution	Statistic value	1.731	1.9212	1.9106	1.8324
		Conformity	Yes	Yes	Yes	Yes
Polymeric Insulator	Normal Distribution	Statistic value	1.3451	0.41727	0.27211	0.5153
		Conformity	Yes	Yes	Yes	Yes
	Weibull Distribution	Statistic value	1.944	0.6078	1.0423	1.1539
		Conformity	Yes	Yes	Yes	Yes

PDF ($f(x)$) and CDF ($F(x)$) as given in Eqs. 12 and 13, respectively.

$$f(x) = \frac{e^{\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)}}{\sigma\sqrt{2\pi}} \quad (12)$$

$$F(x) = \varnothing\left(\frac{x-\mu}{\sigma}\right) \quad (13)$$

where, $\varnothing(x)$, is the Laplace Integral operator of CDF of Standard Normal Distribution and given in Eq. 14.

$$\varnothing(x) = \frac{1}{\sqrt{2\pi}} \int_0^x e^{-\frac{t^2}{2}} dt \quad (14)$$

Weibull distribution is utilized in many research studies in the literature due to the superior fitting of data at a lower probability range than other distribution analyses. PDF and CDF of data with Weibull distribution are estimated as per

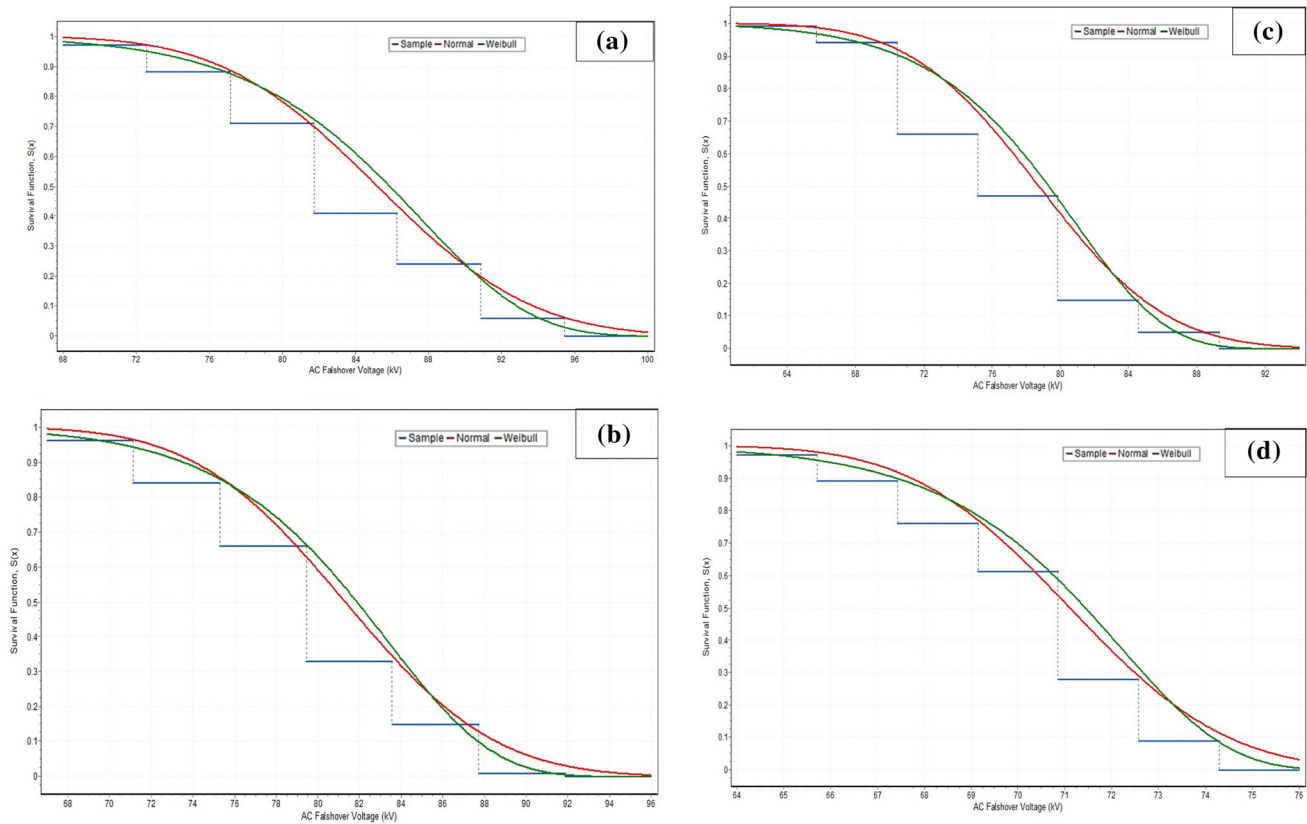


Fig. 4 Survival function curve for 11 kV polymeric insulator. **a** No pollution, **b** 10 g Cement pollution, **c** 20 g Cement pollution, and **d** 30 g Cement pollution

Eqs. 15 and 16, respectively.

$$f(x) = \frac{\alpha}{\beta} \left(\frac{x}{\beta}\right)^{\alpha-1} e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \quad (15)$$

$$F(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \quad (16)$$

Inaccurate probability as normal distribution leads to the imprecision of statistical analysis with Weibull distribution. Values of shape parameter (α) and scale parameters (β) are estimated with the maximum likelihood function as per Eqs. 17–19.

$$\ln \ln L(\theta/t) = \sum_{i \in F} \left[\ln \ln(\alpha) + (\alpha - 1) \ln \ln x_i - \alpha \ln \ln \beta - \left(\frac{x_i}{\beta}\right)^{\alpha} \right] + \sum_{i \in C} \left[-\left(\frac{x_i}{\beta}\right)^{\alpha} \right] \quad (17)$$

$$\frac{\partial \ln \ln L(\theta/t)}{\partial \alpha} = \sum_{i \in F} \left[+ \ln \ln \beta - \left(\frac{x_i}{\beta}\right)^{\alpha} \ln \ln \left(\frac{x_i}{\beta}\right) \right] + \sum_{i \in C} \left[-\left(\frac{x_i}{\beta}\right)^{\alpha} \ln \ln \left(\frac{x_i}{\beta}\right) \right] = 0 \quad (18)$$

$$\frac{\partial \ln \ln L(\theta/t)}{\partial \beta} = \sum_{i \in F} \left[-\frac{(\alpha)}{\beta} + \frac{(\alpha)}{\beta} \left(\frac{x_i}{\beta}\right)^{\alpha} \right] + \sum_{i \in C} \left[(\alpha - \beta) \left(\frac{x_i}{\beta}\right)^{\alpha} \right] = 0 \quad (19)$$

4.1 Hypothesis Test

In this work, the Hypothesis AD test is proposed to validate the data's goodness of fit with the selected distribution model. Statistic value is estimated with Anderson Darling Statistic (A^2) as given in Eq. 20 [11, 12].

$$A^2 = -n - \frac{1}{n} \sum_{i=1}^n (2i - 1) \cdot [\ln \ln F(x_i) + \ln \ln (1 - F(x_{n-i+1}))] \quad (20)$$

As per Stephen's table for different statistical significance values, the critical value is 2.5018 for the significance value of 0.05 in the hypothesis AD test [18]. By estimating the statistical values for a significance level, the data's goodness of fit is verified, if the statistic value is less than the critical value for a specific significance level [11, 12]. In this work, the hypothesis AD test is adopted to verify the data's goodness of fit with normal and Weibull distribution. Statistical



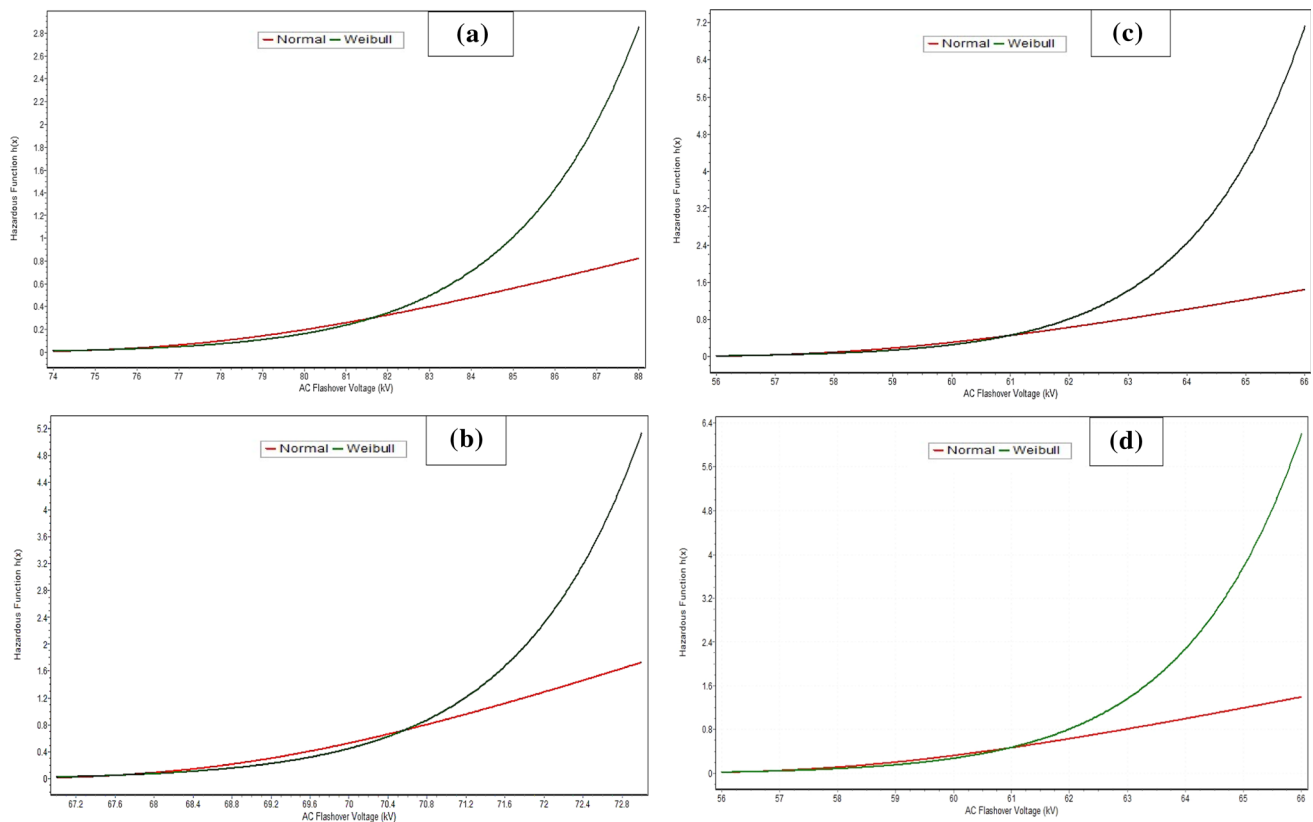


Fig. 5 Hazard function curve for 11 kV ceramic disc insulator. **a** No pollution, **b** 10 g Cement pollution, **c** 20 g Cement pollution, and **d** 30 g Cement pollution

value and conformity for normal and Weibull distribution for two insulators are given in Table 4 for both clean and polluted conditions.

From the hypothesis AD test, the flashover voltage of all investigated insulators confirmed their goodness of fit with normal, and Weibull distributions. For a significance level of 0.05 or lesser causes reduction in predicting the status of HV insulator pollution characteristics.

4.2 Survival Function

With the measured values of AC flashover voltage for the investigating samples of insulators, survival functions for each case are estimated by developing cumulative distribution function (CDF) with normal and Weibull distribution models of statistical study.

In statistical survival investigation, the Kaplan–Meier method is utilized to find the sample estimate and the probability of statistical survival at all intervals with the data set. Kaplan–Meier method is the nonparametric estimate/modelling of the survival function in probability analysis. Kaplan–Meier estimator is a statistical method and can be computed using an Eq. 21. Survival estimator is calculated with the probability of survival of each instant at the

time it occurs [11]. The denominator of the estimator is the population at risk at the time of each instant's occurrence.

$$Var(s(t)^2) = s(t)^2 \sum_{i=1}^t \frac{d_i}{[n_i - d_i]} \quad (21)$$

where $s(t)$ is the estimated survival function, d_i is the number of possible survival cases, n_i is the total number of observations.

From the developed survival model, survival function curves are drawn for visualizing the reliability nature of insulators under normal and polluted conditions. Survival plots are shown in Figs. 3 and 4, respectively for ceramic disc insulators and polymeric insulators under various levels of industrial cement pollution.

In the analysis of survival function, it is observed that the survival functions of AC flashover voltage under both distribution models are slightly following the Kaplan Meier sample estimate which indicates the accurate estimation of the survival function. As the voltage values increase significantly, the survival rate is monotonically decreased to near 0 from the maximum survival rate of 1. From the survival plot, it is further inferred that the polymeric insulators have a higher survival rate for the same operating voltage under



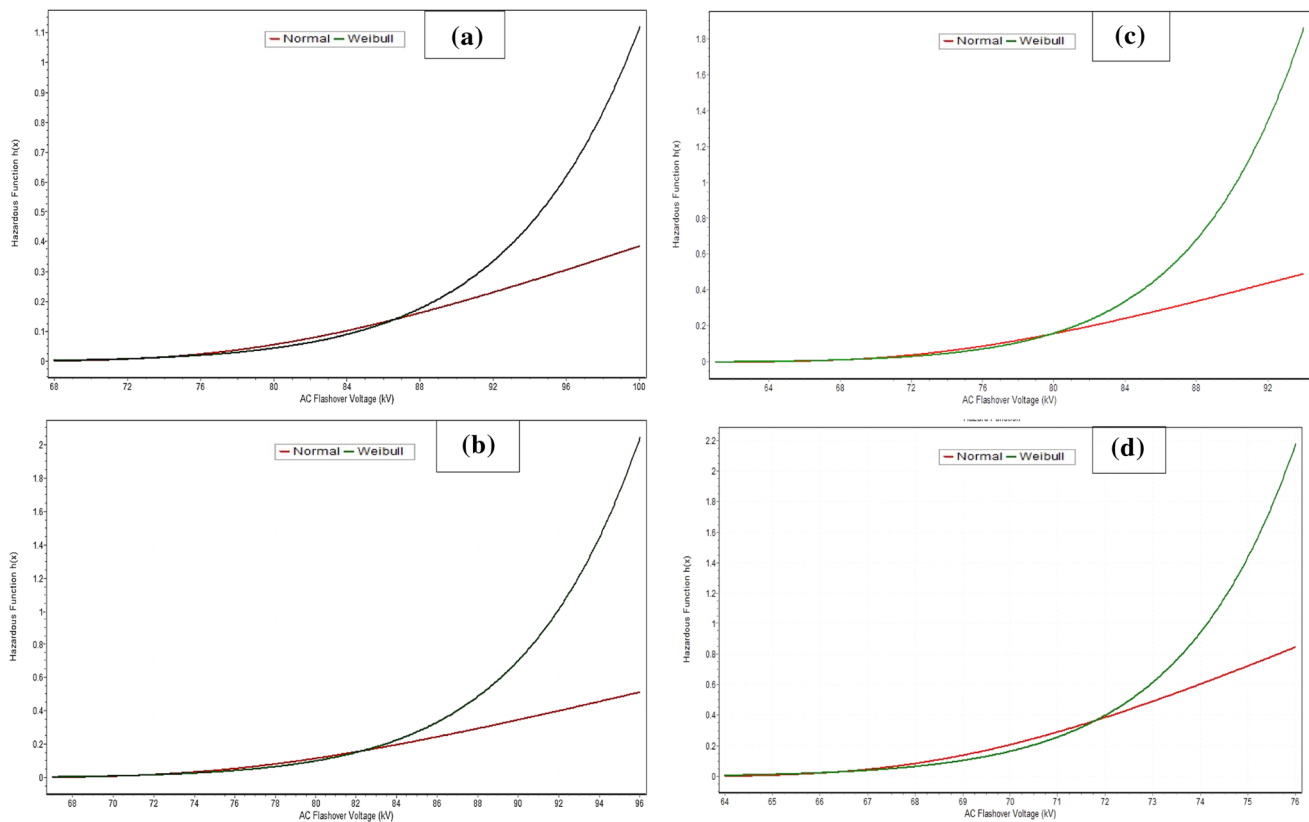


Fig. 6 Hazard function curve for 11 kV polymeric insulator. **a** No pollution, **b** 10 g Cement pollution, **c** 20 g Cement pollution, and **d** 30 g Cement pollution

normal and polluted conditions than that of ceramic disc insulators. The survival rate is low only at highly stressed operating voltage conditions. These observations are useful to know the reliable operating ranges for the insulators under real-time conditions.

4.3 Hazard Function

With a normal and Weibull distribution model, the possible range of failure is predicted with the development of hazard functions for the normal and polluted conditions of the ceramic disc and polymeric insulators. The hazard function is derived with the probability density function (PDF) and survival function for the measured values of AC flashover voltages with different samples of insulators. Hazard functions will be helpful in the prediction of the range of failure and types of possible failure that can happen with help of the bathtub model curve during the service life of the insulators.

Hazard function for the two types of insulators revealed the information about the possible failure of insulators or flashover only at wear-out range during their prolonged service life. The hazard rate of the insulators is extremely low at the lower operating ranges, and it increases slowly as an increase in the operating voltages. Both normal and

Weibull distributions predicted a roughly equal values for hazard rates at lower operating ranges. Normal distribution predicted a lower value of hazard rate, while Weibull distribution predicted a higher value of hazard rate for the same operating voltage. According to the literature, the Weibull model reports higher accuracy in statistical evaluation than the normal distribution model since the Weibull distribution considered the shape parameter and scale parameter of the studied data [18]. With this consideration, prediction of hazard rate with Weibull distribution may be considered as a higher accuracy model than the normal distribution.

The hazard function plots are shown in Figs. 5 and 6, respectively for ceramic insulator and polymeric insulator under various levels of industrial cement pollution.

Hazard rates for the unpolluted insulators are much lower for the minimum flashover voltage of 75 kV and 50 kV, respectively for ceramic and polymeric insulators concerning standards for 11 kV dry normal insulators [16, 17]. As the pollution level increases, the flashover voltage reduces as proportional to pollution. This is indicated in the hazard function curves. Under wet conditions, the expected minimum flashover voltages are 45 kV and 40 kV, respectively for ceramic and polymeric insulators [16, 17]. For analysis with assuming the wet condition of samples as an adverse one,



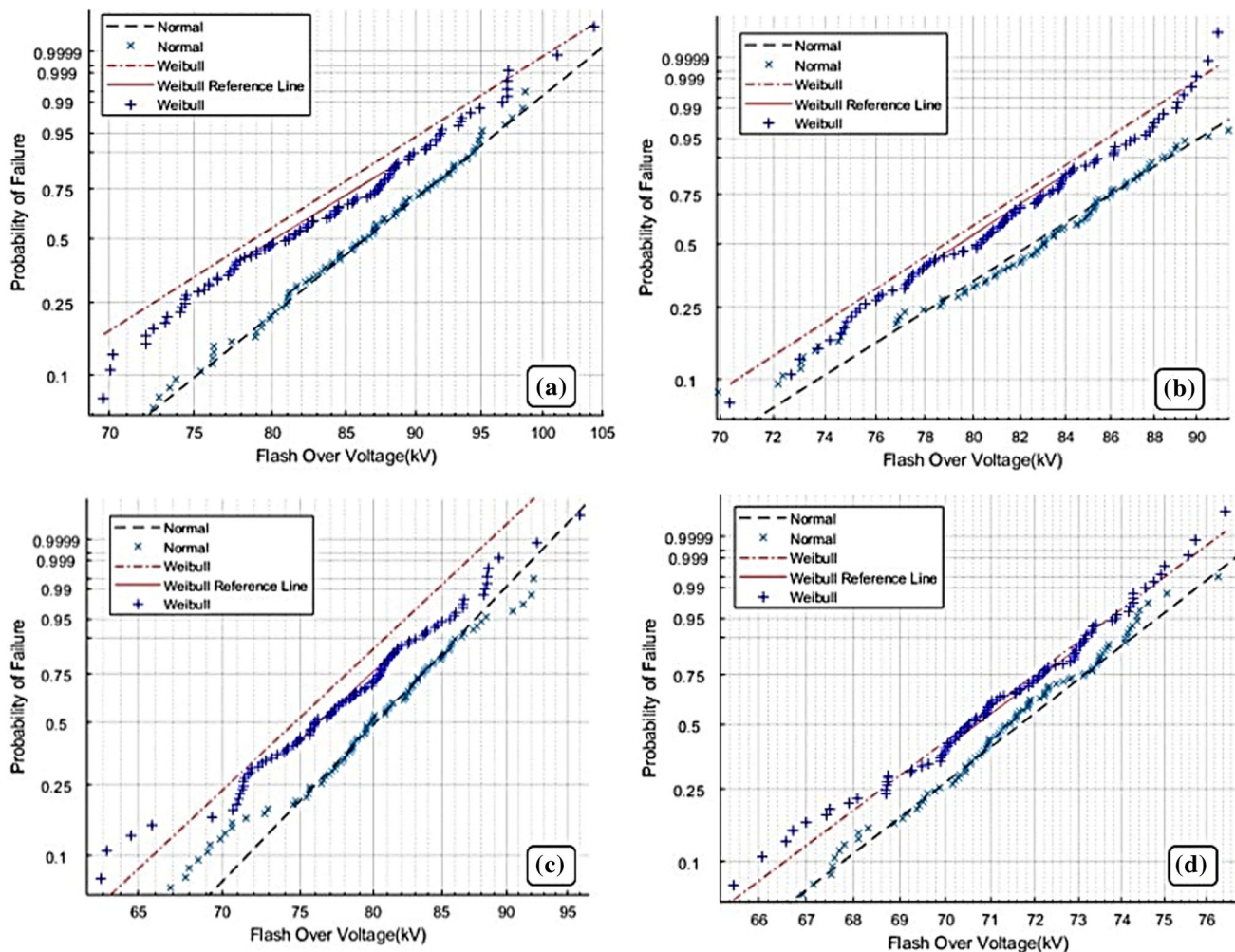


Fig. 7 Failure probability curve for 11 kV ceramic disc insulator. **a** No Pollution, **b** 10 g Cement Pollution, **c** 20 g Cement Pollution, and **d** 30 g Cement Pollution

the hazard rate for a polluted sample is compared with the standard value of flashover voltage at wet conditions. Hazard rates for polluted samples are much lower for the flashover voltages prescribed for wet insulators. Regarding observations, it is further justified that the investigated insulator samples under normal and under industrial cement pollution conditions can offer reliable functioning as insulators. The insulators considered in this work have an extremely low possibility of failure at earlier and intermediate stages. Even though pollution layers formed on the surface, there may be a possible failure only at wear out or later stages of their service life due to aging-related phenomenon.

4.4 Failure Probability Curve

Failure probability curve or CDF will be helpful to estimate the compatibility of insulators at different failure rates. The cumulative distribution function is used to compute withstand voltage at different failure probability rates. This

voltage prediction measures the range of low risk of failure rather than inferring the voltage at which the insulators failed [20]. Further, the estimation of withstand voltage will assist in design or modification in insulators with assigning the proper safety margin [11, 12]. Failure probability curves for ceramic disc and polymeric insulators are given in Figs. 7 and 8, respectively.

In failure probability curves, prediction at tail ends of probability has lesser accuracy in most cases. The predicted model fitted accurately with the flashover voltages data in the middle region of the failure probability curve. This may be eliminated by taking more numbers of samples for testing. The Middle region of the plot plays a crucial role in the determination of withstand voltages, even though both distribution models have lesser accuracy at the tail ends. By comparing the distribution model in prediction analysis based on the hypothesis AD test, Weibull prediction is considered more accurate than the normal distribution.

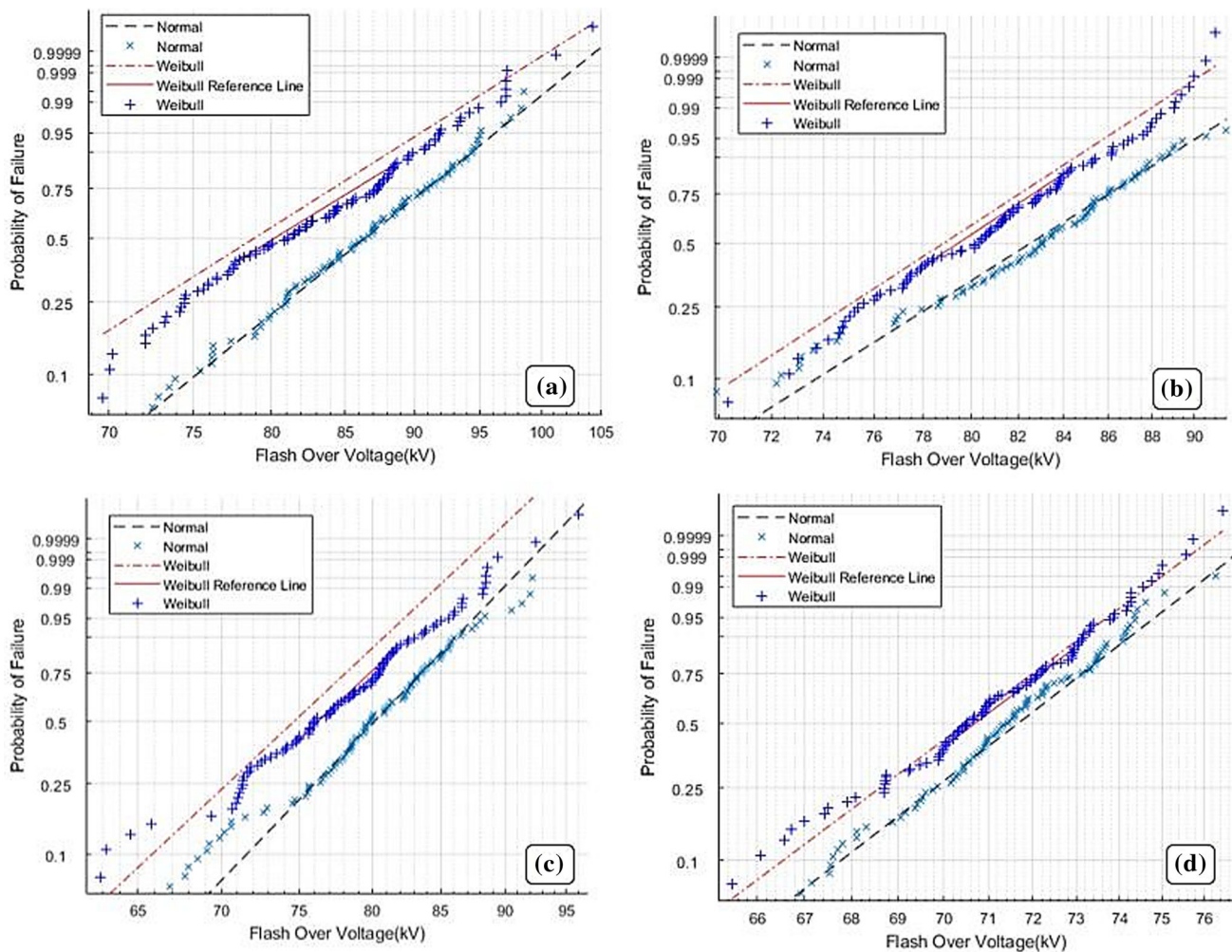


Fig. 8 Failure probability curve for 11 kV polymeric insulator. **a** No pollution, **b** 10 g Cement pollution, **c** 20 g Cement pollution, and **d** 30 g Cement pollution

From the failure probability curves, withstand voltage can be found for different failure rates such that failure probability varies from 0 to 1. In most cases related to withstand voltage, the failure probability of 50% is studied as one of the indicators of the performance of equipment. Failure probability of 50% (0.5) gives the information about the voltage at which there is a 50% occurrence of failure. As per standard required, the withstand voltage for 11 kV ceramic disc insulator and 11 kV polymeric insulators are 60 kV and 45 kV under normal dry conditions [16, 17]. From the failure probability curves, it is evident that the withstand voltage for 50% of failure probability is much more than the standard withstand voltage. It indicates the compatible functioning of the studied insulator under normal conditions. For checking its compatibility under polluted conditions, adverse case wet conditions are considered as a comparison factor. 35 kV is the required minimum AC withstand voltage for both 11 kV ceramic disc and polymeric insulators under wet conditions

[16, 17]. Under polluted conditions, both investigated insulators have a higher value of withstand voltage at 50% of failure probability. The withstand voltages under normal and polluted conditions have shown the compatible nature of studies in insulators for any working conditions. Among the ceramic disc and polymeric insulators, polymeric insulators have much better withstand characteristics than ceramic disc insulators based on the withstand voltage for the different probability of failures.

In [22], the researchers have investigated the flashover characteristics of Silicone Rubber (SiR) insulators using HVDC transmission under heavy pollution conditions. Some of the major types of pollution such as fog, salt, and other types are considered for investigating the insulator flashover characteristics. In another work, a group of researchers has developed a diagnostic tool based on multiresolution analysis using Discrete Wavelet Transform (DWT) to investigate the



effects of pollutants (sodium chloride) in two types of outdoor insulators (ceramic and SiR) [23]. They have analyzed the leakage current signals and the phase angle between the supply voltage to leakage current for developing the diagnostic tool. In [24], the researchers have used artificial neural network (ANN), fuzzy logic (FL) in addition to the DWT method to identify the effects of pollutants (fog) in porcelain insulators using leakage current (LC) signal.

Although the present study performed an in-depth analysis of two different types of insulators using statistical methods, it has some limitations and provides an opportunity for future research:

- (a) We have only examined the performance of insulators based upon one type of industry pollution (cement). As part of our future research, we wish to investigate the effects of pollution caused by other types of industrial activities on the insulators such as sodium chloride, fog, salt, etc.
- (b) The present investigation has been designed to investigate the effects of insulators on voltages of 11 kV. Our plans to investigate other voltages that can be applied to the insulators in the future will allow us to evaluate their performance.
- (c) Only two types of statistical distribution models are used to evaluate the flashover characteristics of two different types of insulators. Future research will examine the behavior of insulators with other statistical distribution models to develop a more generalized model.

5 Conclusion

In this experimental investigation, the performance of HV insulators was evaluated in the presence of a pollution layer and flashover voltage relative to the materials. It has been observed that the flashover voltage of artificially polluted insulators decreases with the level of pollution. This study investigates the reliability and compatibility of 11 kV outdoor ceramic disc and polymeric insulators for assessment under normal and industrially polluted conditions by performing statistical analysis of the AC flashover voltages, involving a ceramic disc and a polymeric insulator. Based on statistical comparisons of the ceramic disc and polymeric insulator with the standard values of flashover voltage and withstand voltage, it is concluded that both 11 kV ceramic disc and polymeric insulator have reliable nature and compatible flashover characteristics for real operating conditions. Ceramic and polymeric insulators can retain the required standard values and only fail in wear-out areas. In conclusion, polymeric insulators offer superior performance when operating at the

same voltage level as ceramic insulators. Clearly, this is a factor that will encourage a replacement of ceramic insulators with polymeric insulators in lower operating voltage ranges.

Availability of data and materials The authors confirm that the data supporting the findings of this study are available within the article.

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