Predicting Flashover Voltage on Polluted Porcelain Insulator

Bodise Lebrun Bolou-Sobai[1], Danfebo Franklin Ayebagbalinyo[2], Charles Godspaower Idongha[3]
[1,2,3]Department of Electrical and Electronic Engineering,
Niger Delta University,
Amassoma, Wilberforce Island, Bayelsa State
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Abstract
This paper developed a simple linear regression model to predict the flashover voltage of polluted porcelain insulators based on Equivalent Salt Deposit Density (ESDD). The developed model Y = 58.75 – 63.69(ESDD) demonstrated strong predictive capability, with a correlation coefficient (R) of 95.28%, indicating near-perfect alignment between predicted and experimental values. An R^2 value of 90.78%, confirming that ESDD explains most of the variability in flashover voltage. Statistically significant results (p-value (0.0471), F-statistic (19.70)), validating the model's reliability. It is simple yet accurate predictive model bridging the gap between laboratory experiments and field applications in pollution flashover analysis. This analysis demonstrates that ESDD is a critical predictor of flashover.

Keywords: *Regression Analysis, Porcelain Insulator, Voltage Flashover, Prediction,*

1.0 Introduction

High-voltage insulators play a critical role in electrical power systems by providing mechanical support and electrical insulation to prevent unwanted current flow. Among the different types of insulators, porcelain insulators are widely used due to their durability, high mechanical strength, and resistance to environmental degradation (Yousaf, et al., 2022). (Sanyal, *et al.*, 2020) However, when these insulators are exposed to polluted environments such as industrial areas, coastal regions, or desert climates contaminants like salt, dust, and chemical deposits accumulate on their surfaces (Hussain, *et al.*, 2017), (Zelalem, B., & Mamo, M., 2020). Under humid conditions (e.g., fog, dew, or light rain), these pollutants dissolve, forming a conductive layer that can lead to flashover, a disruptive discharge causing a short circuit (Kumar, & Maheswari, 2024). Flashover events in polluted insulators are a major concern for power utilities, as they can result in power outages, equipment damage, and significant economic losses (Salem, *et al.*, 2022), (Desta, *et al.*, 2024). The ability to predict flashover voltage accurately is essential for designing reliable insulation systems, planning maintenance schedules, and improving the safety of power networks. Traditional methods for determining flashover voltage rely on experimental tests (e.g., salt-fog tests, clean-fog tests) (Douar, et al., 2015). (Dong, et al., 2020), and empirical formulas based on pollution severity and insulator dimensions. However, these approaches may not account for the complex interactions between multiple factors, such as Pollution type and concentration (e.g., salt, cement, or industrial pollutants), environmental conditions (humidity, temperature, and wetting rate), insulator geometry (creepage distance, shed profile), and surface conductivity. To address these challenges, regression analysis has emerged as a powerful statistical tool for modelling the relationship between flashover voltages and influencing variables. By analysing historical or experimental data, regression models can provide predictive insights, helping engineers estimate flashover risks under different pollution conditions. Over the years, different researchers have developed several flashover voltage predicting strategies for polluted insulator (Ali et al., 2021), (Chandrashekhar & Pradipkumar 2016), (Gouda, et al., 2014). This paper is developing a simple but accurate regression model for predicting flashover voltage on polluted porcelain insulators which holds substantial technical, economic, and operational significance for power systems. This study focuses on developing a regression-based predictive model for flashover voltage on polluted porcelain insulators, leveraging experimental or field data to enhance accuracy and reliability. The findings could contribute to better insulation design, condition monitoring, and maintenance strategies in high-voltage power systems.

2. Flashovers of Insulator

Insulator flashovers in high-voltage AC systems happen when the voltage on the insulator's surface reaches a level where the air along the surface breaks down and becomes conductive. This can lead to localized discharges near earthed structures, sometimes escalating into continuous arcs. These flashovers are costly, causing power system downtime and equipment damage. They can be triggered by various factors, with pollution contributing significantly in certain environments. Dry bands of pollution on insulators are known to reduce flashover voltage, leading to frequent flashovers. The resulting arcs can clear pollution or cause severe damage, compromising the insulator's mechanical integrity (Chakraborty, 2017). The mechanical robustness of an insulator dictates its resistance to flashover as a higher flashover voltage can be obtained with greater insulator dimensions. To prevent insulation flashover, it's essential to ensure that the insulator does not exceed the critical disruptive discharge voltage relative to the ambient air, based on a known value of the service voltage. The limiting conditions for insulator voltage and flashover have been realized with a simple but significant experimental tool, the steep front voltage impulse and the switching impulse. The results of impulse tests can be compared to known pollution severity levels to determine the likelihood of a given insulator flashover. The mechanism of flashover on contaminated insulator surfaces has been well discussed in (Gençoğlu & Cebeci, 2008).

2.1 Analysis of Flashover on Polluted Insulators

Flashover voltage is the minimum voltage required to cause electrical breakdown across an insulator, leading to a disruptive discharge (Khatoon, et al., 2022). In polluted environments, contaminants such as dust, salt, and industrial emissions accumulate on insulator surfaces. When exposed to moisture, these pollutants form a conductive layer, reducing the surface resistance of the insulator and increasing the likelihood of flashover. Understanding the impact of pollution on flashover voltage is crucial for maintaining the reliability of power transmission and distribution systems. Pollution on insulators decreases flashover voltage by creating a conductive path for leakage current. The severity of pollution is often measured using Equivalent Salt Deposit Density (ESDD), which quantifies the amount of conductive material present on the insulator surface. Figure 1 depicts the the flashover process on polluted insulator. The relationship between flashover voltage (V_f) and pollution severity is often expressed as:

$$V_f = k \cdot (ESDD)^{-m} \qquad 1$$

where: Vf = Flashover voltage, k and m are the Empirical constants based on insulator type and environmental conditions, ESDD = Equivalent Salt Deposit Density (mg/cm²)

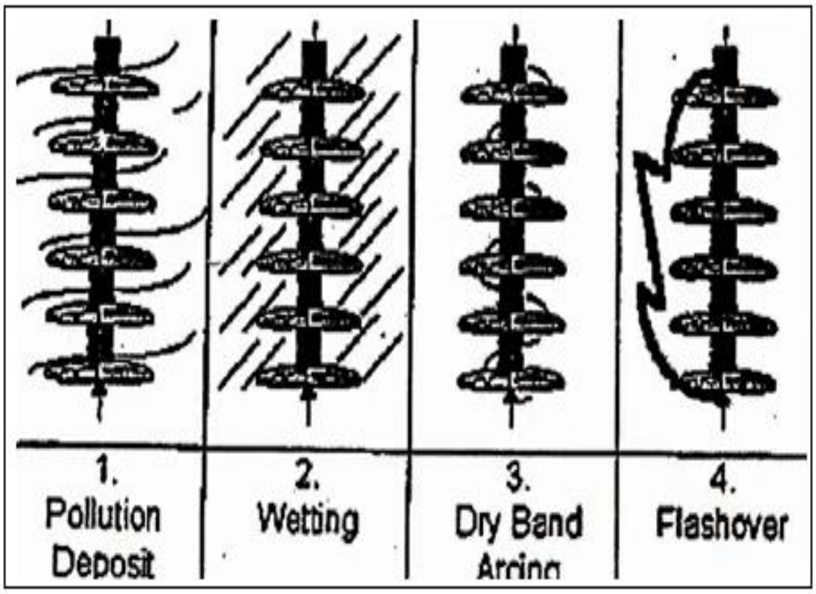

Figure 1: The effect of pollution on insulator flashover

3. Methodology

The authors in reference (Banik, *et al.*, 2015), investigate the effect of pollution on a porcelain insulator shown in Table 1to understand the flashover behaviour on the insulator, and the experimental data of the leakage current, equivalent salt deposit density (ESDD) and flashover voltage are depicted in Table 2. The parameters in Table 2 will be used with regression analysis predicting method to prediction the flashover voltages of the polluted insulator.

Table 1: The parameter of the Porcelain insulator used for the analysis

Insulator Type (Model)	Porcelain Xp -70
Diameter/Creepage (mm)	255
Length (mm)	295
Height (mm)	146
Form Factor (F)	0.736

Table 2: Experimental test result used for the study with applied voltage of 30kV (Banik, *et al.,* 2015).

ESDD (mg/cm^2	0.0790	0.1280	0.1859	0.2350	0.3540
Leakage current (I) mA	0.88	1.02	1.16	1.22	1.29
Flashover Voltage (kV)	57	52	47	41	37.5

2.1 Predicting the flashover voltage using Regression analysis

Regression analysis is a statistical method used to examine the relationship between one or more independent variables (also known as predictors or explanatory variables) and a dependent variable (also known as the response or outcome variable). The primary objective of regression analysis is to model the expected value of the dependent variable (flashover voltage) based on the values of the independent variables (ESDD), making it a vital tool for prediction, forecasting, and causal inference. In simple linear regression, the relationship is assumed to be linear, meaning that the dependent variable changes at a constant rate with changes in the independent variable.

Linear regression tries to model the relationship between variables by fitting a linear equation to the observed data. The general form of a simple linear regression equation is:

$$Y = B_o + B_1 x + \varepsilon \qquad (1)$$

Where: Experimental flashover voltage is the dependent variable (the variable we are trying to predict or explain), while the ESDD is the independent variable (the predictor or explanatory variable), β_o is the intercept of the regression line (the value of y when x=0x = 0x=0), β_1 is the slope of the regression line (the change in y for a one-unit change in x), and ε is the error term (the difference between the observed and predicted values, capturing the model's inaccuracy). Predicted (or fitted) values are the estimated values of y generated by the least-squares regression line. These are obtained by substituting the given x-values into the regression equation. Regression analysis produces statistically unbiased estimates for the slope(s) and intercept of the regression line.

A Simple Regression Model can be written as

$$\widehat{y} = \widehat{\beta}_o + \widehat{\beta}_1 x \qquad (2)$$

Residuals are the deviations of observed and predicted values

$$\varepsilon = y - \widehat{y} \qquad (3)$$

If equation 2 be the prediction of Y based on the i^th^ value of X, then $\varepsilon = y - \widehat{y} = \widehat{y} = \widehat{\beta}_o + \widehat{\beta}_1 x$ is the i^th^ residual.

The residual sum of squares is given as

$$RSS = e_1^2 + e_2^2 + + + e_n^2 \qquad (4)$$

Least Sum of Squares method chooses β'_o and β'_1 to minimize the value of $\beta_I = \frac{\sum(X_I - \widehat{Y})(X_I - \widehat{X})}{\sum(X_I - \widehat{X})^2}$ to be calculated as;

$$\widehat{\beta}_o = \bar{y} + \widehat{\beta}_1 \bar{x} \qquad (5)$$

For the regression model to be meaningful we assume that$x_1 - \bar{x} \neq 0$in other words, there must be some variation in the independent variable *xx* to help explain variation in the dependent variable *y*. Once we have an estimate of the slope (β_1), we can use the regression line equation at the mean values: $y = \beta_o + \beta_1 \bar{x}$. Solving for β_o, we obtain the estimated intercept: $\widehat{\beta}_o = \bar{y} + \widehat{\beta}_1 \bar{x}$. This calculation implicitly assumes that each observation is equally weighted, which holds true if the error variance is approximately constant across observations. In other words, the squared residuals $(y - \widehat{y})^2$ should be similar for all data points.

3. Result and Discussion

The simple regression analysis was used in the thesis to predict the polluted insulator flashover and the result is compared with the experimental test result in Table 3 (Banik, *et al.*, 2015). The experimental flashover test result is used as the dependent variable while the ESDD was used as the independent variable.

The regression analysis method develops a predictive model that is used to predict the pollution flashover of the insulator. The regression statistic gave a 95.28% correlation between the experimental test and the predicted flashover voltage showing that the prediction is very good. The analysis also gave a percentage variation of about 90.78% which indicates that 90.78% of the variance in flashover voltage is explained by ESDD, confirming a strong relationship and surpasses the typical threshold (>70%) for reliable predictive models. The ANOVA in Table 4 shows the significance F as 0.0471and is less than 0.05, and shows that it is statistically significant, rejecting the null hypothesis that ESDD has no effect on flashover voltage. Also, F-statistic is 19.70 which far exceeds the critical F-value (e.g., ~4.26 for df = 1,2 at α = 0.05), confirming model reliability. Regression analysis-based prediction with the experimental test (Banik, et al., 2015) are shown in Table 5

Table 3: ANOVA

	df	SS	MS	F	Significance F
Regression	1	112.2884	112.2884	19.70122	0.047194006
Residual	2	11.39913	5.699566		
Total	3	123.6875			

Table 4: Statistical data

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%	Lower 95.0%	Upper 95.0%
Intercept	58.75271386	3.452184	17.019	0.003435	43.89916334	73.60626	43.89916	73.60626
0.079	-63.69570875	14.35039	-4.43861	0.047194	-125.440448	-1.95097	-125.44	-1.95097

The prediction model from the regression analysis can be given as;

Y = 58.75 – 63.69 (ESDD)

Table 5: Regression analysis prediction

Experimental Test (Banik, et al., 2015)	Regression Predicted	Error
57	53.72075287	3.279247134
52	50.59966314	1.400336863
47	46.9116816	0.088318399
41	43.7842223	-2.784222301
37.5	36.20443296	1.29556704

4. Conclusion

The reliability and efficiency of electrical power transmission networks largely depend on the performance of outdoor insulators. These insulators serve as critical components in transmission lines, ensuring electrical isolation between conductors and supporting structures. However, their performance is significantly affected by environmental pollution, which can lead to flashover, a phenomenon that compromises the integrity of the power system and leads to outages, equipment damage, and financial losses. Predicting the flashover effect using different predicting strategies emphasizing the need for effective mitigation strategies is crucial. This research provides a foundational regression-based approach for flashover voltage prediction, offering utilities and engineers a practical tool to enhance power system resilience in polluted environments. Future refinements could transform this model into a comprehensive decision-support system for high-voltage insulation management. The model Y = 58.75 – 63.69(ESDD) is statistically valid and practically useful for predicting flashover voltage in polluted porcelain insulators, with >90% accuracy. While simple linear regression suffices for moderate pollution levels, extending the model to non-linear or multivariate cases could enhance its robustness for extreme conditions.

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