A Review of the Dynamic Modelling of Pollution Flashover on High Voltage Outdoor Insulators

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Abstract. In this paper, a dynamic model that simulated and tested the flashover of polluted insulators with HV voltage is presented. Generally, developing the performance of the transmission line depends on the improvement of the insulators due to the pollutants deposited on its surface. This study focused on the classification of insulators and the factors that affect the insulators to cause flashover as well as the analysis of the insulator’s electric properties. The electric field and voltage distribution along with composite insulators used in transmission systems under different conditions were also presented. The problem of nonlinearity of the electric field and voltage distribution, especially along insulators used for HV transmission systems, was investigated and a solution for improving the electric field and voltage distribution along the insulators was suggested. Findings showed that the presence of water droplets and pollution layer distributed on weather sheds enhanced the local electric field but it did not really affect the electric field distribution inside the fibre reinforced plastic core. Moreover, for the pollution case, the effect of pollution layer conductivity was significant to the electric field. For thicker pollution layers, the maximum electric field point moved from the triple junction point. Finally, the study also found that the corona ring might be necessary for the HV insulator for both ends (HV and ground) and its behaviour was affected under polluted and wet conditions.

1. Introduction

Besides the electric stress, insulators are subjected to a lot of other stresses [1]. Outdoor environmental conditions vary widely. Temperature and moisture can greatly affect the performance of insulators. For example, moisture such as rain, dew, fog and melting ice can significantly lower the surface resistance of insulators. With the presence of pollution, the insulator surface resistance is reduced even more. The reduction of surface resistance might cause increased leakage of current to flow on the surface and dry band arching to take place. In addition, large magnitudes of leakage currents flowing on the surface for an extended period might cause degradation of the insulator surface. With these factors, flashover might be initiated, which leads to the failure of a line.

In addition, temperature can affect the insulation properties of all material. For some insulators made from organic materials, radiation from sunlight results in surface degradation. Altitude can also affect insulator performance. Since air at ambient pressure and temperature is a form of primary insulation, higher altitudes reduce air density; thus, reducing the surface insulation potency. One of the major problems for high voltage (HV) transmission lines is flashover on the surface of polluted insulators. Flashovers caused by pollution are known as temporary electrical arcs, which can change into permanent electrical arcs and cause sustained interruption. Dynamic models can predict and calculate the electrical
parameters of arcs according to the time-dependent evolution. Over the past decade, researchers and manufacturers have tried to promote mathematical models to overcome the problem of flashovers. The first model to predict flashover voltage was proposed by Obenaus [2]. Uniform polluted layers, electric field distribution along the surface of the insulator and the discharge burns in series with the polluted layer were considered under HV voltage. Then, Neumarker [3], presented the modified version of Obenaus’s model by using the uniform resistance per unit length of the pollution layer instead of a fixed resistance. Some researchers have presented the arc extinction mechanism by introducing the quantitative criteria in terms of electric stress, pollution resistance and leakage current under HV voltage. A recent study showed that source strength is a major factor in the dispersion of test results from power systems and high voltage laboratories [4]. Source parameters, including inductance, capacitance and short circuit current, were investigated systematically. Results showed that flashover in service can occur at much lower levels of contamination than predicted by international standard tests.

2. Factors Influencing Flashover Discharge.
Some of the factors that affect flashover discharge, either natural or industrial factors, are shown in figure 1.

![Flashover factors diagram](image)

**Figure 1.** Flashover factors

2.1. Natural Flashover Factors

2.1.1. Pollutions
The airborne particles that deposit on the surface of insulators will form the contamination layer. The solubility of the pollution layer has different effects on insulators depending on whether the solubility grade increases or decreases; thus, there are soluble and insoluble contamination [5]. Different components of contamination have different effects on the characteristics of flashover insulators. Wetting of pollution layers leads to leakage current on the surface of an insulator, which leads to a flashover. The extent of pollution at the surface of the insulator is usually indicated by using Equivalent Salt Deposit Density (mg/cm2) ESDD.

2.1.2. Climate Conditions
Climate variability such as rain, fog, relative humidity, and ambient temperature can cause an increase in the contamination of the insulator’s surface. Relevant experiences have shown that a flashover is very easily caused by fog, dew and drizzle, in which the biggest threat is fog. Researchers have found that weather conditions on high voltage line flashovers under heavy fog accounted for 65% of the cases and drizzling accounted for under 10%.

2.1.3. Lightning
When impulse surges are applied, regardless of whether the surge is from lightning or air gaps, the
flashover process involves corona evolution, the figuration of channels and finally the stroke. The
formation of corona happens in a fraction of a microsecond. This is followed by a second detonation of
corona depending on the increasing rate of the applied voltage. If the voltage is high enough to evolve
a leader channel that crosses the gap, a flashover will take place. The formation of the leader channel is
the main criterion for a flashover of the gap [5].

2.2. Non-natural Flashover Factors

2.2.1. Industrialization
During the manufacturing stage of insulators, defects and damage do occur from inadequate quality
standards. For example, when setting the end fitting to the core, care must be taken to avoid damage.
Factors that could affect this are the diameter, binding stage, pre-heat temperature, moisture, and mould
temperature etc. Care should be taken to maintain these variables within acceptable limits. Any neglect
in these variables will lead to insulators facing more electric stresses then flashovers [7].

2.2.2. Handling
The insulators might be liable to tension or cantilever load, which could lead to cracking of the core
during the installation stage. Any type of physical damage to the housing material makes the insulator
rod vulnerable by exposing it directly to contamination and wetting. Cases of incisions that are ulterior
in nature during the installation process might lead to flashover during operations. Insulators might be
prone to damage caused by vandalism and a breakdown could occur due to tracking along the insulator
or brittle fractures. Regular inspections should be carried out in regions that are prone to vandalism to
prevent any disoperation due to insulators affected by gun shots or other acts of vandalism.

2.2.3. Corona
The corona phenomenon affects the electrical and mechanical performance of insulators along
transmission lines. Increasing the electric field on insulator surfaces could result in a corona, which is
caused by accelerating the free electrons around the insulator. The number of free fast-moving electrons
increases exponentially, which then leads to the air around the insulator being ionized. This causes the
corona discharge. Under dry conditions and if the electric field exceeds the threshold of 15 kV/cm,
chances to a corona discharge are very high. However, in wet conditions a corona is seen at lower electric
field magnitudes. The threshold electric field magnitude for the corona discharge not only depends on
the condition of the surface (dry or wet) but also on the type of voltage applied (AC or dc) [8].

3. Pollution Flashover Mechanism.
Generally, the contamination often leads to flashover of insulators, especially in high voltage
transmissions. The insulation property of insulators tends to decrease when the surface of the insulator
is covered by a wet pollution layer. Pollution leads to an increase in the leakage current on the insulator
surface accompanied by the widening of the dry band, which leads to an increase in the voltage and then
to a flashover. The flashover due to insulator pollution develops in the following manner:
(1) cumulative pollutants on surface of insulator.
(2) A wet pollution.
(3) Change of leakage current and voltage.
(4) Discharge of flashover arc along the polluted area.

3.1. Ac and Dc Mathematical Flashover Model of Polluted Insulators
Many mathematical models for propagation of a flashover in polluted insulators have been proposed.
Obenaus [2], proposed that the resistance of the pollution layer will be in series with the arc of flashover,
as shown in the model in figure 2.
The applied voltage is given as,

$$U = AXI^{-n} + R_p I$$  \hspace{1cm} (1)

Where,

- $U$ is applied voltage,
- $X$ is length of arc,
- $I$ is current,
- $R_p$ is resistance of the pollution layer,
- $A$ and $n$ are characteristic constants.

When the applied voltage is more than a limited value, which is called critical voltage, the $U_c$ arc will propagate until the flashover stage [9]. Most models used to predict the flashover voltage on covered-polluted insulators are derived by Obenaus but the Obenaus model is limited to explaining the AC arc propagation. The reignition of the arc condition was proposed by Claverie [10], and Porcheron, which can be described as.

$$U_m = \frac{800 \times X}{(I_m)^{1/2}}$$  \hspace{1cm} (2)

Where, $x$ is the arc length, $I_m$ is the maximum value of the leakage current, and $U_m$ is the maximum value of the applied voltage.

Based on Rizk, [11] the equation (2) could be written as:

$$U_m = \frac{2080 \times X}{I_m}$$ \hspace{1cm} (3)

Recovery of the arc condition was proposed under no significant off and rekindle, as in the following:

$$U_f = \frac{531 \times L}{I_m}$$  \hspace{1cm} (4)

The previous condition under significant off and rekindle will become:

$$U_f = \frac{1050 \times X}{I_m}$$  \hspace{1cm} (5)

Where, $x$ is length of arc, $L$ is the leakage distance of the insulator, $I_m$ is the maximum leakage current and $U_f$ is the recovery voltage.

The AC Dynamic Arc model was very well studied and applied in polluted ceramic insulators and ice-covered insulators by Farzaneh (2007) [12]. Mathematical and physical models were proposed to explain the dynamics and predict the pollution flashover voltage of composite insulators by Venkataraman (2006). To develop a model that can predict pre-flashover leakage current, the model must consider all dynamic arc parameters, such as voltage, arc length, surface resistance, etc. to better understand the flashover process. Zhang (1994) [13], has clearly explained arc initiation and propagation under AC voltage in the literature.

3.2. Arc Model

Until today, many arc models have been developed but only a few are used frequently by engineers. The fundamental one is undoubtedly the Ayerton’s arc model, which is based on an approximation of experimental measurements. The voltage gradient $E_{arc}$ can be approximated by the following equation:
\[ E_{arc} = \frac{v_{arc}}{x} = \frac{A l_{arc}^n}{x} = A l_{arc}^{-n} \]  \hspace{1cm} (6)

Where, \( I_{arc} \) is the current of the arc, and \( A \) and \( n \) are constants of the arc. As can be seen from the table, the constant \( A \) has a range from 30 to 310 and constant \( n \) from 0.1 to 1.38. Based on experiments by Canadian researchers CIGELE, the coefficient \( A \) and \( n \) were obtained and the equation (13) can be defined as:

\[ E_{arc} = \begin{cases} 84.6 \times I^{-0.772} & dc \\ 208.9 \times I^{-0.449} & ac \end{cases} \]  \hspace{1cm} (7)

The high variation was due to its dependency on several factors such as ambient atmospheric conditions, the medium in which the arc propagates, the voltage waveform, and the surface of an insulation layer. All these factors can influence the arc propagation and its behaviour.

4. Models of Pollutant Deposits on the Insulator Surface
Recently, the deposited pollutants on the surface of insulators under humidity condition were divided to a uniform distribution (fog) and a non-uniform (light rain) one.

4.1. Uniform Wetting Model (FOG)
In this case, the pollution that deposited over the insulator surface is assumed to have the same thicknesses along the surface of an insulator on all regions. The tiny fog droplets would move slowly in random motion under the uniform (fog) condition.

4.2. Non-uniform Wetting Model (Light Rain)
Three non-uniform diverse regions under light rain were divided namely low (L), medium (M), and high (H), as showed in figure 3. According to the wetting action, the regions that were categorized at the upper surface H represented a highly-wetted area. Region M, under the shed near the tip, was where the water could easily reach this region. The least wetted areas were in region L, which was down to the shank because it was protected by the sheds [14].

![Figure 3](image_url)

**Figure 3.** Divide of pollution layer under non-uniform conditions according to wetting level.

5. Electric Field Computation Techniques
The electric potential and field distribution along the insulating surface can be affected by the factors listed below.
1) Voltage magnitude. 2) Insulating material properties. 3) The leakage current. 4) Surface contamination. 5) Internal defects
The methods applied to compute the electric potential and field strength along the insulator surface can be divided into three classes, namely experimental, analytical, and numerical. In this chapter, all three types of methods are introduced, and each has its own advantage and disadvantage. Among the three methods, both the analytical and numerical methods were simulated on the PC platform, demonstrating similar procedures. Firstly, the theoretical models based on real insulator geometry were built, and then described by integral equations or differential equations [15]. The field details were achieved by solving these equations. In the free space, Maxwell’s equations were used to describe all the macroscopic electromagnetic phenomena.

\[
\begin{align*}
\nabla \times H &= J + \frac{\partial D}{\partial t} \\
\nabla \times E &= -\frac{\partial B}{\partial t} \\
\nabla \times B &= 0 \\
\nabla \times D &= \rho
\end{align*}
\]

To show macroscopic electromagnetic properties, three formulas are given below:

\[
\begin{align*}
D &= \varepsilon E \\
B &= \mu H \\
J &= \sigma E
\end{align*}
\]

Since the electrodes are conducting material, the principle of the charge conservation is shown below.

\[
\nabla \cdot J + \frac{\partial \rho}{\partial t} = 0
\]

Where, \(H\) is magnetic field, \(E\) is field stress, \(B\) is magnetic stress density, \(D\) is electric flux density, \(J\) is current density, \(\rho\) is electric charge density, \(\varepsilon\) is permittivity, \(\mu\) is permeability, \(\sigma\) is conductivity.

5.1. Experimental Methods

The rated voltage is energized onto the sample insulators in the experimental methods. To get detailed results, insulators were tested under different conditions to observe the corona and flashover phenomena. The experimental methods were the most accurate, and the results were closest to the performance of insulators in the field tests. However, the experimental methods were time-consuming and more costly than other methods. Therefore, the experimental methods were often used to verify simulations results, or to provide reference data.

5.2. Analytical Field Computation Methods

The analytical methods are used to calculate the field strength directly from the original differential formulas. The results of analytical methods are precise, whereas the scale of the model that the analytical method deals with is relatively small [16]. On the one hand, the formulas are difficult to generate due to complicated geometries in the practical cases, because the boundary conditions are often too uneven to be described with equations. On the other hand, as the model scale increases due to the voltage level, the analytical methods require copious amounts of computational resources to solve the differential equations. Therefore, the analytical methods were replaced with numerical methods. The field stress at the high voltage side was highest compared to that at the ground terminal. It was reported that the insulator with dead end facing experienced greater field stress at the high voltage terminal (as high as 30% for a 500-kV system) than the suspension insulator, as in figure 4.
5.3. Numerical Field Computation Methods

In numerical methods, the differential equations describe the electric field domain. The purpose of numerical methods is to transfer these equations into a linear matrix [17], which can be easily solved by computers. There are four steps in the process: The first step is to transfer the field functions into a set of linear independent functions with unknown variables. The second step is to cast the continuous solution domain into a discrete form, which contains several elements or fictitious charges. And the third step is to minimize the error of unknown variables from the linearization process. Finally, the solutions are taken into original equations to verify the results.

5.3.1. Finite Difference Method

The principle behind the finite difference method is to divide the field domain with regular grid, and replace the Poisson’s equations with the difference equations, whose unknown variables are the potentials at the nodes of the grid. The Poisson’s equations and the boundary conditions in the field $D$ are shown below:

$$\nabla^2 u = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = F(x, y) \quad \text{on the domain.}$$  \hspace{1cm} (11)

$$U(x, y)|_r = g(I) \quad \text{on the bound}$$  \hspace{1cm} (12)

To build the linear matrix, the potentials at the nodes are described by the Taylor series of adjacent nodes. The accuracy requirement is set as the second order. For example, the coordinate of a two-dimension node is $(x, y)$ and the adjacent node is $(x_0, y_0)$. The potential at $(x, y)$ is described by the Taylor series below:

$$\varphi(x, y) = \varphi_0 + \left[(x - x_0) \left(\frac{\partial \varphi}{\partial x}\right)_0 + (y - y_0) \left(\frac{\partial \varphi}{\partial y}\right)_0\right]$$

$$+ \frac{1}{2} \left[(x - x_0)^2 \left(\frac{\partial^2 \varphi}{\partial x^2}\right)_0 + 2(x - x_0)(y - y_0) \left(\frac{\partial^2 \varphi}{\partial x \partial y}\right)_0 + (y - y_0)^2 \left(\frac{\partial^2 \varphi}{\partial y^2}\right)_0\right]$$  \hspace{1cm} (13)

In the equation, the subscript 0 represents $(x_0, y_0)$ and the potential $\varphi_0$ can be calculated by the average potential values of four adjacent nodes. Therefore, the homogeneous functions with potential variables are built and the known potential values of the boundary nodes are set as $V_i$.

$$\begin{bmatrix} P_{11} & \cdots & P_{1j} \\ \vdots & \ddots & \vdots \\ P_{i1} & \cdots & P_{ij} \end{bmatrix} \begin{bmatrix} \varphi_1 \\ \vdots \\ \varphi_j \end{bmatrix} = \begin{bmatrix} V_1 \\ \vdots \\ V_i \end{bmatrix}$$  \hspace{1cm} (14)
The principle behind FDM is simple, and division of the field is easy to complete. The Finite difference method has great advantages in the two-dimension field, when the shapes of boundaries are relatively simple. However, FDM can get complicated when the boundary shapes are uneven. Moreover, since the infinite field domain cannot be divided, this method cannot deal with open boundary conditions.

5.3.2. Finite Element Method
In the previous session, it was shown that FDM focuses on the nodes of the grid and derives the linear homogeneous functions directly from Poisson’s equation. Different from FDM, the FEM divides the field domain according to elements. These elements are small areas in the two-dimension model and small volumes in the three-dimension model. The related equations are then derived from the coordination of each element. In addition, FEM can solve the second-class boundary condition [18], which is the derivative of potential vectors. For a two-dimension field domain:

\[ \nabla^2 u = \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} = F(x, y) \quad \text{in the domain.} \tag{15} \]

\[ U(x, y)|_r = g(\Gamma) \quad \text{on the boundary} \tag{16} \]

\[ \frac{\partial u}{\partial n}|_r = g_2(\Gamma) \tag{17} \]

The triangle is a popular geometry of an element used in FEM. The smaller the element, the more accurate the field strength. According to the steps above, the whole field domain could be described by each point-potential of the elements. An example of a two-dimension field discretization is shown in figure 5.

![Figure 5. FEM field division and example of a triangle element ijm.](image)

Figure 5 shows that the square field domain is divided by triangle elements. The potential in each triangle has a relationship with the coordination of the triangle vertices.

\[ \phi = a_1 + a_2 x + a_3 y \tag{18} \]

The calculated coefficients \( a_1, a_2 \) and \( a_3 \)?

\[ \phi = \frac{1}{2\Delta} [(a_i + b_i x + c_i y)\phi_i + (a_j + b_j x + c_j y)\phi_j + (a_m + b_m x + c_m y)\phi_m] \tag{19} \]

Where, \( \Delta \) is the area of the triangle ijm.

The variation problem is discretized with the principle of weighted residuals. The matrix equation for the triangle elements is shown below:
In the end, the discretized linear equations are represented as, $[A][\varphi]=[V]$, and the unknown potentials at the vertices of all the triangles are calculated. Designers can divide the field domain for their own purpose with FEM. For example, small elements are set in the area where the electric field changes intensively to achieve accurate results; meanwhile relatively large elements are put in the area far from the electrode where the field strength changes slowly to reduce the requirement for calculation resources. However, the FEM calculation process is more complicated than FDM and the requirement for data storage capacity is also larger. Like FDM, the boundary for infinite distance in FEM is difficult to deal with, as the whole field domain cannot be divided.

5.3.3. Boundary Element Method
The boundary element method focuses on boundary conditions that affect the field domain. The unique characteristic of this method is the ability to decrease the dimensions of the problem. For example, a two dimension-problem can be described by the boundary line and reduced to a one-dimension problem. Three-dimension problems can be described by the boundary surface, and reduced to two-dimension problems. The procedure for the boundary element method is shown below,

- The boundary is discretized into many elements in functions with unknown potential and normal flux densities.
- The principle of weighted residuals is used to minimize the error.
- The coefficient matrix is evaluated after analysis of each element.
- The linear algebraic equations are then achieved with the proper boundary conditions to the nodes.
- In the end, the unknown potential can be calculated from the inversion of the coefficient matrix.

The major advantage of the boundary element method is to reduce the dimensions of the space, so that the orders of the homogenous function and the amount of input data are decreased. However, the coefficient matrix is an unsymmetrical full-element matrix, which consumes copious amounts of computation resources and limits the orders of the matrix. The method makes it difficult to handle the multi-media field domain, and cannot be used directly for non-linear problems.

6. Conductivity of the Pollution Layer
An enhanced electrical field combined with a high current density leads to an increase in power dissipation, which then becomes the source of energy for surface heating that initiates dry band formation [19]. The power dissipation, $PE$, for a conducting pollution layer with uniform volume conductivity, $\sigma_v$, can be represented as:

$$PE = ESJ_s = \frac{E^2}{\sigma_v}$$

(21)

The evaporation rate increases with the rising of the electric field. On the other hand, the conductance decreases when subjected to a high electric field. This process is illustrated in the curve of the electric field as a function of conductance, as illustrated in figure 6 [14].
7. Conclusion
The pollution flashover is still a major argument that influences the performance of power system operations. Studies on pollution flashover considers the prediction of flashover voltage. Overall, this is used to develop the insulator design and insulation assortment. Recent studies on acceptable methods to predict the flashover could be applied to engineering practice. The characteristics of the electric field, resistive of pollution and insulators, conductivity, leakage currents during the entire pollution flashover stage under uniform and non-uniform pollution were reviewed. The spike in the electric field profile suggests a drop-in surface conductance at the high field region, and this is attributed to evaporation and heating effects that were examined in this study. This is particularly useful to locate dry band formation on the insulator surface where discharge may occur. Further studies are needed to develop a new insulator model to investigate the above characteristics and compare the experimental results with the computed results.

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