Proposal of a dynamic numerical approach in predicting flashover critical voltage

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ABSTRACT
Glass insulators, due to its diverse characteristics, were used widely around the world for high voltage transmission lines. Surfaces of the insulators are exposed to high electrical, mechanical, and thermal stresses over the period of service. Accumulation of contamination distort stresses distribution along the insulators that may lead to flashover under severe condition. In this paper, Obenaus pollution model has been adopted to propose a dynamic mathematical modelling to determine flashover critical voltage with regard to parameters such as pollution conductivity, arc length, and width of layer of contamination on the surface of glass insulator. In addition, laboratory experimental works have been carried out according to IEC60305 to validate the results from numerical approach, which indicate a good agreement.

Keywords:
Arc length
Conductivity
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1. INTRODUCTION
High voltage electrical grid and outdoor power system equipments are constantly subjected to diverse types of climate, for example, snow and contaminants, that may lead to flashovers. Flashovers on insulators surface under polluted conditions are widely acknowledged. It is a highly complicated situation because of the interaction between important parameters such as electrical stress, climate and environmental aspects as well as the insulator profile/structure [1, 2]. Under the same pollution situations, the real challenge is to propose insulators design with the greatest reliability and performance. Developing accurate models to predict the flashover at the polluted layer on the insulators and understanding the extend of the discharge has been the concern of numerous studies [3-5].

Numerical approach and modelling of pollution flashover can be a good solution to minimize experimental tests on the real insulators and experimental investigation on site. Several research studies have produced comparative numerical models addressing the flashover phenomenon [3, 5]. In order to understand accurately propagation and growth of pollution flashover, dynamic aspects related to the electrical and environmental criterias shall be considered. Flashover models indicate the greatest probability of flashover occurrence on polluted insulators [6]. The model can be use to predict flashover voltage and also to determine several major parameters, such as discharge time, velocity, and leakage current (LC).

In this research work, an alternative mathematical models is proposed to accurately predict flashover voltage at critical sites. In addition, the development of electric flashovers on pollution insulator surfaces as a function with increase the polluted region on the insulator surface w, discharge distance (x) and conductivity of pollution layer, σ were also considered. Experimental results on pin-cup insulators under polluted
conditions were compared to the results obtained using the proposed mathematical model for flashover prediction have shown a good agreement.

2. POLLUTION INSULATOR FLASHOVER PHENOMENON

Various pollutants, such as dust, salt, and ice, cover the high voltage outdoor insulators, depending on wind direction, temperature, and humidity. Wet pollution is known to be the more serious type associated with a significant probability of flashover on insulator surfaces. Pollution flashover occur in stages as follow:

- the formation of pollution on the insulator surface decreases the leakage distance.
- presence of a wet layer caused by several factors, such humidity and rain on the pollution layer, causes the increase in surface conductivity.
- a formation of the dry band caused by the lc warming influences and increases the voltage, finally resulting in a flashover.

Based on laboratory tests and field experience, it was noted that flashover in insulators covered with a heavy pollution layer was not an immediate phenomenon, but results from a process involving pollution and discharges, comprised three stages, as illustrated in Figure 1 [2].

The First stage - Pollution accretion on insulators is non-uniform, as several regions on the insulators are not polluted. Such non-pollution zones are referred to as dry bands. This is due to the heating effect of the leakage current, partial arc activity, and increase in air temperature. It is generally agreed that the water film on the surface of the pollution layer is responsible for the breakdown or flashover that occurs. The increased voltage usually crosses the dry band because of conductive water on the pollution layer. The corona discharge starts mainly when there is a high electric field across the dry bands, and luminous branched filaments from the arc than appear, which develops from the root (stem), as shown in Figure 1(a).

The Second stage - The corona leads to the creation of partial arcs in the dry band regions causing a significant increase in LC. These luminous branched filaments develop to become a channel. The other properties of accumulated pollution over the insulator will modify over time due to the temperature and current leakage, as shown in Figure 1(b).

The Third stage - At this stage, the arc develops differently. One of two things occur, either the arcs die out or the arcs are propagated along the pollution layer on an insulator surface to become white arcs that occur according to a certain length from a white arc (around sixty percent of the length of the insulator). This depends on the conductivity and length of the contaminated region and finally, the flashover is complete along the insulator, as shown in Figure 1(c).

![Figure 1. Process of flashover on polluted insulator](image)

3. CONCEPT OF THE MODEL

One of the first models of flashover on polluted insulator surfaces was introduced by Obenaus [7]. Thus far, the most analytic models proposed by researchers since then have depended on the known design, in which a contaminated insulator was modelled by an electrical equivalent circuit consisting of an electrical resistance with an arc in series.

Where the dry band resistor was in series with the wet region resistor of an insulator, a contaminated surface was assumed. In this model, the arc channel was equivalented as a cylinder with a radius \( r \) and length \( l \). It was also transferred to an RLC electrical circle, as shown in Figure 2.

The salient features of this model are briefly represented here. Figure 3 illustrates a flowchart of the mechanism model comprising the geometry of the insulator, characteristics of the contaminated layer, applied voltage, and some values of the initial reading used as the input data. The flashover discharge time was divided into steps \( dt \) (below the time constant for an arc) from \( t \) equals zero. From this, an estimated voltage of the arc was made, which must be high enough to obtain an arc that exceeds the first length for an
arc. When the prevalent criterion is met based on Hesketh’s \(\frac{dP}{dx} > 0\), where \(P_a\) is the arc power supply from the source of the power), the arc will start to develop. It is agreed that the propagation of the arc will be at that voltage. The internal variables (radius, velocity, etc.), as well as the remaining pollution layer’s resistance, are then determined[8]. The determination of electrical parameters demands the immediate unbridged contaminated layer resistance, which is determined from the insulator geometry; thus, illustrating the effect of the flashover process. The voltage \(U_s(t)\), in the AC voltage form, was calculated at each time based on the same hypothesis as for the static modelling, which determined the voltage for the flashover, i.e. at the maximum value of voltage \(U_s\) during a very short time, a flashover will occur. At each time \(dt\), the critical situation for continued growth of the flashover were tested and, if it was favorable, the flashover would continue forward to the final leap step.

![Diagram](image)

Figure 2. Modelling propagating flashover on a contaminated surface and Electrical equivalent RLC circuit

Otherwise, the arc will die-out, and a discharge would not occur. Then, a new step is repeated by increasing the applied voltage. The computing is re-run again by initializing the input parameters. When the arc length is equal to more than half the insulator length \(L_f\), the discharge would occur. Under alternating voltage, this occurs at the top value of the last quarter of the period cycle \(T/4\) and consequently, velocity is modified to obtain all discharges at the same time. Thus, if the critical value is more than the surface conductivity, it is considered that the arc length is similar and any variation in the current is a result of the variation in the conductivity at the wet layer surface, as well as the resistance of the arc [9]. Then, using the determined value of FOV, the data in the last phase would be determined by repeating the simulation. At each \(\Delta t\), the length of the arc and its resistance was initialized. If the criterion is not matched, the flashover would not occur. In this case, a new step increased the voltage \(U_s\). The computation was re-run by setting the input data as shown in flow chart in Figure 3.

4. THE TESTS AND PROCEDURE

Before the start of the descriptive experiment, the essential parameters that influenced the flashover voltage (FOV) were explained as follows:

The geometry of the insulator (i.e. diameter and length of arcing). The shorter the arcing distance, the smaller the flashover voltage; also, with a shorter diameter, the flashover voltage is at a maximum [10];
- A wet layer conductivity and pre-pollution;
- Properties of applied voltage (form and polarity);
- Environmental, temperature, atmosphere, stress and moisture;
- Type and nature of contaminants deposited (hard or soft rime, and water), with a lower density of pollution leading to higher flashover voltage;
- A uniform and non-uniform contamination layer surface
- Presence of dry bands: pollution deposits with lesser dry bands have lower flashover voltage [11];

Wet-pollution, which is the most dangerous type of pollution that creates flashovers, was used in the experiments carried out in this study. To achieve pollution, cold powder and salty water were used. To ensure prepared water for each experiment, the conductivity of water was measured by mixing sodium chloride \(\text{NaCl}\) (salt) and water [10].

The thickness of the pollution layer on the insulator was then determined. Wet-pollution was deposited on the insulator with a normal temperature of 25 °C. Figure 4 shows the experimental insulator used that consisted of an IEC standard 146 mm by 255 mm cap and pin glass insulator discs, one clean and one polluted.
Proposal of a dynamic numerical approach in predicting flashover critical voltage (Ali. A. Salem)
Experiments have validated on 4 IEC standard insulator units, the dimensions of insulator used is illustrated in Table 1.

| Table 1. Geometrics of insulators used |
|--------------------------------------|
| Shed diameter mm | Shed spacing mm | Arcing Distance for 4 units mm |
| 255 | 146 | 320 | 584 |

A test setup comprising of a high voltage single transformer of 220 kV, capacitive divider for measure apply voltage, control panel, and data collect systems is shown in Figure 5. The transformer empowers the insulators with voltage. Parameters measuring system, which provides the factors effect on the Leakage Current such as the time changes, peak value, and mean value, includes an advanced oscilloscope and a 10 kΩ resistor divider for measuring LC under pollution and clean insulator. Leakage current measurements were carried out by applying voltage of \((20 / (3)^{0.5}) = 11\) kV RMS approximately.

![HVAC circuit testing](image1)

![Experimental test setup and arrangement](image2)

Figure 5. (a) HVAC circuit testing on outdoor insulator (b) Experimental test setup and arrangement and data acquisition system

5. RESULTS AND ANALYSIS

5.1. Influence of insulator diameter

This study is suitable for very heavy pollution cases on insulators, which are usually affected by dust or snow [12], [13]. The width \((d)\) was commensurate to the insulator diameter. However, it is practically impossible to obtain such insulators. The contamination layers often accumulate on the windward regions of the insulators. Therefore, the simulation had used an experimental model as shown in Figure 6[11].
The contamination layer was estimated as a half cylinder with a width \( d \) over the insulator given as:

\[
d = \frac{\pi(D+2w)}{2}
\]  

(1)

where \( D \) is the diameter of the insulator and \( w \) is the contamination layer thickness.

While the equivalent diameter of insulator \( D' \) is given by:

\[
D' = \frac{2d}{\pi} - 2w
\]

(2)

the insulator diameter influence was computed with different widths of the pollution layer covering the insulator surface. A pollution layer thickness \( w \) of 1.5 mm and widths \( d \) of 4 cm, 9.4 cm, 14 cm, and 28 cm respectively was selected for testing.

The results shown in figure 8 indicate that any increase in the width of the pollution layer \( d \) on the insulator would see a decrease in critical voltage \( V_c \). In addition, there was a good agreement between simulation and experiment results, as shown in Figure 7.

5.2. Length of arc effect

Critical voltage \( V_c \) is proportional to the length of arc \( L \) and number of insulator units increasing and decreasing. Figure 8 shows the critical voltage as a function with arc length for different leakage distance of insulator. Comparisons of the experimental results using one to four IEC60305 standard glass insulator units uniformly covered with wet contamination layer with critical flashover voltage simulated by the model are shown in Figure 8. The thickness of the pollution deposited on the insulator was about 1 mm for all the tests.
5.3. Conductivity of wet-pollution layer effect

Based on field investigations and laboratory experiments, it was found that wet-contamination layer conductivity has a considerable influence on the flashover voltage of insulators. Critical voltage was found to decrease as the contamination layer conductivity increased. The model outputs were also compared to laboratory results, acquired from a string of 4 units of IEC60305 standard glass insulators, where various water conductivities were tested as show in Figure 9. These results show that there is a good degree of agreement between the critical voltage calculated from the computation and the laboratory test results. The FOV had reduced with increasing conductivity of the pollution layer with minor errors.

![Figure 9](image)

Figure 9. Critical voltage (Vc) as a function of pollution layer conductivity for w = 1.5 cm.

Based on the results, it was observed that there was good convention between the calculated results for the flashover voltage and those found experimentally. Arcing events are so difficult that many facilitating assumptions must be produced to obtain numerical modelling in an easier way.

6. CONCLUSION

In this study, a dynamic model was applied to investigate the effects of some parameters on the flashover voltage of polluted insulators. The suggested numerical model affected the sequential spread of the arc. The model inputs were the geometry of the insulator, pollution layer properties (a), applied voltage and some essential values. The outcome of the mathematical model was validated against the experimental model using pollution covered IEC60305 standard glass insulators, taking to account different lengths of the arc and diameters as well as different wet pollution layer conductivity. The experimental results closely resembled the results from the model and could forecast the flashover voltage (FOV) under AC voltage with agreeable accuracy.
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