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Flashover Phenomena of Polluted Insulators Energized by AC Voltage

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Abstract

The study of polluted insulator flashover mechanism very important for electric power transmission reliability, efficiency and serviceability. In this paper, a new mathematical model based on Ayrton arc voltage gradient equation, which takes account of total resistance of the polluted insulator rather than the pollution resistance value has been proposed. The expression of total resistance of the insulator is also derived. The value of critical flashover voltage (CFV) obtained from the model is in good agreement with the ones obtained through experimental results.

Introduction

The problem of contamination flashover of transmission insulators and other outdoor equipment had been recognized as a source of interruption of power supply. The flashover process is dependent on different parameters such as proximity to the source of pollution, level of contamination, surrounding weather conditions and also nature of voltage waveforms.

Obenaus [1] was the first to introduce a comprehensive mathematical model for understanding the flashover mechanism of polluted insulator surface. Many researchers [2-5] have developed mathematical model to calculate the critical flashover voltage of the polluted insulator.

Rizk [6] has examined critically all the available mathematical models. But some difficulties exist like real insulators need to be converted to equivalent rectangle [2-4]. To solve the difficulties, further research about flashover phenomenon has been carried out. In this paper, the expression of pollution resistance of the insulator based on two arcs has been derived. The expression of total resistance is also derived. The value of flashover voltage of actual polluted insulator has been calculated by considering the effect of total resistance and the effect of pollution resistance.

Calculation of Pollution Layer Resistance

The geometry of the real insulator is complex. That's why, it is difficult to find out the resistance of the pollution layer of the insulator with a simple equation. For calculating pollution layer resistance one arc near cap and other arc near pin of the insulator are considered. This arc discharges are shown in Figure 1. Assumed both arcs are circular in shape. The charge of the two arcs is different but the magnitude and arc foot radius is same. The pollution layer resistance consists by two resistances, one pollution resistance associated with arc foot and other between the arcs itself. For derivation of pollution layer external resistance between the arcs, the potential at point P can be calculated according to [7]. Figure 2 shows two circular electrodes separated by a distance d and radius of equipotential surface is r.

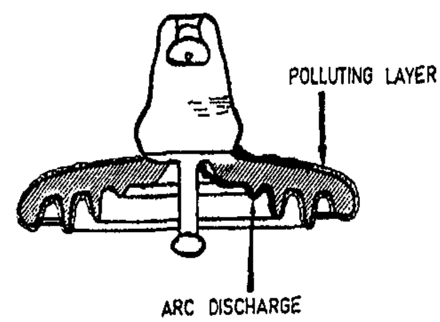

Figure 1. Cap-and-pin insulator

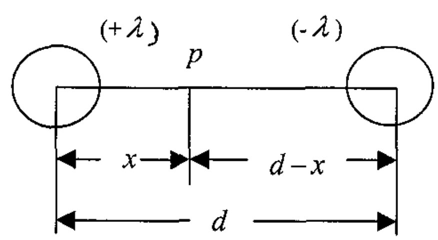

Figure 2. Two circular electrodes separated by a distance d

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The electric field intensity at point P due to linear charge density $-\lambda$ is

$$E_{-}(P) = \frac{I}{2\pi\sigma_s(d-x)} \qquad (1)$$

Similarly, the electric field intensity at point P due to same positive charge is

$$E_{+}(P) = \frac{\lambda}{2\pi\varepsilon x} = \frac{I}{2\pi\sigma_s x} \qquad (2)$$

Work done by the charge is,

$d\phi = E(P)dx$

Integrating both sides of the above equation:

$$\phi = \int_r^{d-r} d\phi = \frac{I}{2\pi\sigma_s}\left[2\ln\frac{d-r}{r}\right]$$

$$\Rightarrow \phi = \frac{I}{\pi\sigma_s}\ln\frac{d-r}{r} \qquad (3)$$

Since r is significantly small as compared to d.

$\therefore d - r \cong d$

The final expression of potential is,

$$\phi = \frac{I}{\pi\sigma_s}\ln\frac{d}{r} \qquad (4)$$

The distance between the arc foot of the insulator = $l - x = d$. Therefore, the final expression of the pollution layer external resistance between the two arcs may be obtained as,

$$R_{pe}(x) = \frac{1}{\pi\sigma_s}\ln\frac{l-x}{r} \qquad (5)$$

The internal pollution resistance due to two arcs in terms of pollution surface conductivity can be written as,

$$R_{pi} = \frac{1}{\pi\sigma_s} \qquad (6)$$

Total pollution resistance,

$$R_p(x) = \frac{1}{\pi\sigma_s} + \frac{1}{\pi\sigma_s}\ln\frac{l-x}{r} \qquad (7)$$

Calculation of Total Resistance

Here, the bulk resistance of the insulator and remaining pollution layer resistance are considered in parallel. This arrangement is shown in Figure 3. Let the total resistance of the insulator is $R_t(x)$, arc resistance $R_a(x)$ and the ratio of arc resistance to total pollution resistance is m.

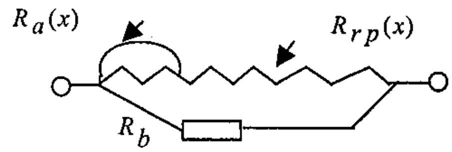


Figure 3. Arrangement for total resistance calculation

$$\therefore \quad m = \frac{R_a(x)}{R_p(x)} \qquad (8)$$

Let the remaining pollution layer resistance is $R_{rp}(x)$.

$$\therefore \quad R_{rp}(x) = R_p(x) - R_a(x) = (1-m)R_p(x)$$

$$R_t(x) = \frac{R_{rp}(x)R_b}{R_{rp}(x) + R_b} \qquad (9)$$

Putting the value of pollution resistance modifies the above expression;

$$R_t(x) = \frac{(1-m)R_b\left[1 + \ln\frac{l-x}{r}\right]}{\pi\sigma_s R_b + (1-m)\left[1 + \ln\frac{l-x}{r}\right]} \qquad (10)$$

Here R_b is the bulk resistance of the insulator before pollution and is measured 22 MΩ.

Derivation of Flashover Voltage

For calculations of critical flashover voltage of polluted insulator consider a two-dimensional flat plate model [2] is considered, when the partial arc has already developed over the dry band. The Figure 4 is the simplified electrical equivalent circuit of a two-

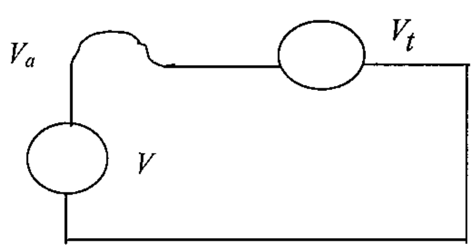


Figure 4. Electrical equivalent circuit of two-dimensional flat plate model.

The above circuit consisting of an arc of length x in series with the total resistance of the insulator. After considering the Ayrton arc voltage gradient equation, the voltage balance equation of this circuit can be written as:

$$V = Axi^{-n} + (l - x)iR_t(x) \quad (11)$$

For finding minimum values setting, $\frac{dV}{di} = 0$.

Therefore, the minimum values are respectively,

$$i_n = \left[\frac{Anx}{R_t(x)}\right]^{\frac{1}{(n+1)}} \quad (12)$$

$$V_n = (n+1)(Ax)^{1/n+1}\left[\frac{(l-x)R_t(x)}{n}\right]^{\frac{n}{n+1}} \quad (13)$$

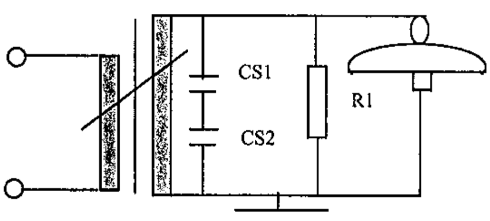
To find out critical voltage setting, $\frac{dV_n}{dx} = 0$

The critical flashover voltage can be obtained by putting the value of critical arc length in equation (13).

$$V_c = A^{1/n+1}\, l(R_t(x))^{n/n+1} \quad (14)$$

Experimental Measurement

One string of suspension insulator (glass) is chosen for the experimental work. The insulator is contaminated artificially by the NaCl solution and put it to dry in the sunlight nears about 12 hours. The dried insulator is placed in the outdoor environment for wetting naturally. Then it is placed in the high voltage laboratory for testing. During test, the temperature at dry bulb is 29 °C, wet bulb 25 °C and pressure are 990 mbar.



CS1 = 100 pf, 100 kV, CS2 = 68 nf, R1 = 140 M Ω, 140 kV

Figure 6. Experimental setup for AC systems

The pollution severity is varied between 5 and 40 μS during test. The high voltage from the testing transformer is applied to the insulator and slowly increased by control unit until the flashover occurs. The digital measuring instrument DMI 551 records the voltage, when flashover occurs on the insulator surface. Three readings are taken at same pollution severity and considered both minimum and maximum. The same procedure is repeated for other pollution surface conductivities. The experimental setup is shown in Figure 6.

Results and Discussion

The flashover voltages are calculated from the equation (14) by considering the arc distances 9.33 cm, 14 cm and 18.67 cm. During this calculation the values of m are 0.005, 0.01 and 0.05. The calculated results at different arc distances are plotted together with the experimental results for comparison. It is shown in Figure 6 to 9. From these it is shown that the calculated flashover voltage from the proposed mathematical model at 9.33 cm arc distance is closer than the 14cm and 18.67 cm arc distance.

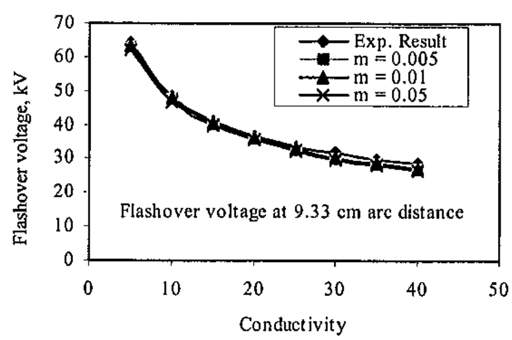


Figure 5. Characteristics of flashover voltage

The deviation between the calculated results and experimental results are very negligible, when arc distance 9.33 cm. The flashover voltages obtained from the experiment are plotted in Figure 10. The same obtained from the model considering and without considering of total resistance of polluted insulator are also shown in Figure 8 for comparison. From this Figure it is shown that the percentage of error between the experimental results and model results with considering total resistance are 1.2 %

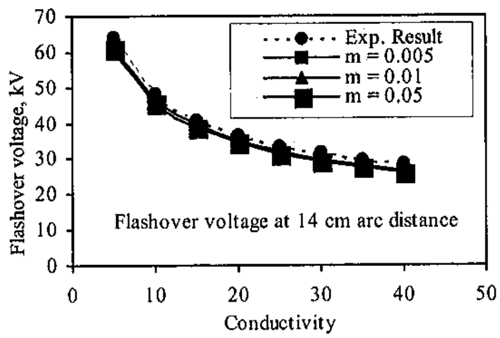


Figure 6. Characteristics of flashover voltage

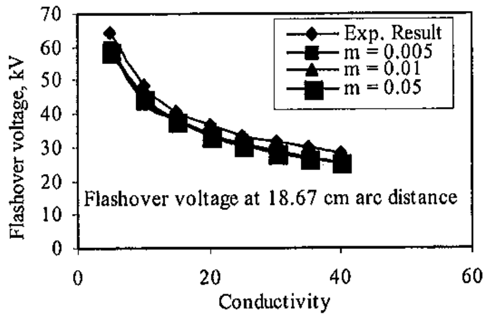


Figure 7. Characteristics of flashover voltage

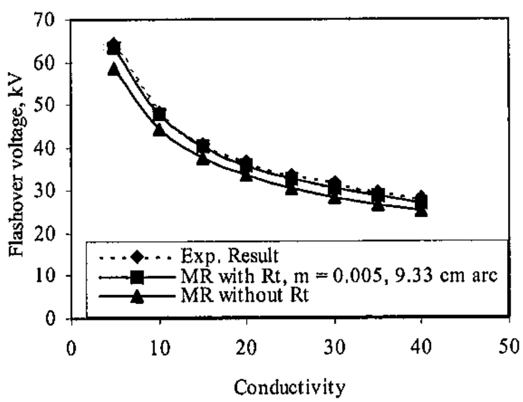


Figure 8. Variation of flashover voltage with conductivity with and without considering total resistance

This percentage increases to 8.9 % when the total resistance is not being considered. This proves that the proposed model considering the total resistance value represents the actual contamination in the field condition closely. It can be recommended for designing the insulator for 500 kV transmission line with better accuracy.

Conclusions

For understanding of flashover mechanism of polluted insulator, the expression of total resistance of the insulator based on two arcs separated on a distance has been derived in terms of leakage distance, arc distance, bulk resistance and also pollution surface conductivity. The measured value of bulk resistance of the clean insulator is 22 MΩ. New mathematical model is developed by including the effect of total resistance of the insulator. Analytical results predicted by the model matches closely with the experimental results, which could be used for the design of 500 kV transmission line insulator. Therefore, the new model presented in this paper represents the actual flashover voltage of contaminated insulator more closely. In this research, it has been recommended that the value of total resistance should be considered during the calculation of flashover voltage on the real contaminated insulator surface.

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