Mathematical Flashover Model of Polluted Insulators based on the Arc Root Voltage Gradient Criterion

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Abstract – *In this report the flashover mechanism of polluted insulators under AC voltage, a new arc propagation criterion which is based on an arc root voltage gradient is proposed. The arc channel is considered as an equivalent distributed parameter circuit model instead of using the arc voltage-gradient equation. The parameters of the arc model are obtained from the electromagnetic field distribution of the arc and the gas discharge theories. The arc root is considered as parallel paths including the polluted layer. The variation of the voltage on the arc root is related to the capability of arc propagation. This model takes the microscopic mechanism of arc root ionization into consideration, which can improve the accuracy of the flashover model.*

Key Words: *Arc root voltage gradient; Flashover mechanism; Circuit model of insulator; AC arc*

1. INTRODUCTION

Now a day, the electric power requirement has increased significantly. To full fill the requirement of power, electrical companies need to increase the transmission lines efficiency. Each individual consumer has liberty in electrical markets to choose their own supplier companies for improved and reliable service. The companies has to increase and maintain efficiency which is based on continuity of the supply to the consumers, and avoiding the faults, causes financial losses for both consumers and companies. one of the major problem to maintain the reliability is the consequence formed by contaminated insulators of transmission lines. The fundamental reason for flashover is the deposition of pollution on the insulators. When existed contaminants on surface of insulators combined with humidity of the fog or dew, rain the insulator may initiate to fail. Combination of humidity and contaminants, create a layer that turn into a conductor. This allows circulating the currents which will build up the condition of short circuit, because of a decrement in the resistance of surface of insulator. Unless there is a natural cleaning or an adequate maintenance, the electrical activity will be affected by a possible flashover in the insulator.

The flashover of polluted insulators is one of the fundamental factors undermining the protected operation of the power grid, which can prompt extraordinary monetary losses to the entire power system; hence it is of incredible incentive to concentrate the contamination flashover characteristics and mechanisms from both the engineering and academic viewpoints.

AC flashover is most complex than the pollution flashover underneath DC, due to arc reignition and arc extinction during the course of the AC flashover process, which is went with the distortion and pulses of the leakage current. Pollution flashover of dynamic and Static models were progressed and applied for insulation coordination, in view of the empirical formulae of arc reignition from the arc tests. From the current research, the criteria for arc propagation and re-ignition and arc extinction are considered as the key points of the flashover model. Prior criteria for arc propagation depends on, as power (P) varies the arc length propagation (x) also varies i.e. $dP/dx > 0$, this is not a sufficient condition but necessary condition.

2. BASIC AC MATHEMATICAL FLASHOVER MODEL OF POLLUTED INSULATORS

Most of the models used to predict the flashover voltage of contaminated insulators are concluded from the Obenaus contamination flashover model, which is appeared in Figure 1. Figure 1 represents a perfect model going for foreseeing the proliferation procedure of the curve on contaminated protectors. With this model, the basic voltage to keep up the curve can be derived from

$$U = AxI^{-n} + R_pI \qquad .....(1)$$

where U (V) is the peak value of the voltage applied , x (cm) is the arc length, I (A) is the peak value of the arc current, R_p (Ω) is the resistance of the remaining contamination layer, and A, n are the arc characteristic constants.

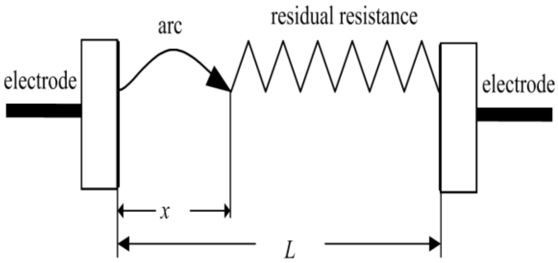

Figure 1. Circuit flashover model.

The Obenaus model is limited in explaining the AC arc extinction and reignition. Claverie and Porcheron proposed that AC pollution flashover should meet the arc reignition condition, which can be expressed as:

$$U_m = 800x/\sqrt{i_m} \quad ....(2)$$

Where x (cm) is the arc length, i_m (A) is the peak value of the leakage current, and Um (V) is the peak value of the applied voltage.

Rizk advanced that arc conductivity is a portrayal of the circular segment vitality. By assuming the voltage of the curve crevice stays sinusoidal when the current is zero, the circular segment reignition condition can be reasoned as

$$U_m = 2080x/i_m \quad ......(3)$$

Where *x* (cm) is the arc length, *i*m (A) is the peak value of the leakage current, and *U*m (V) is the peak value of the applied voltage.

With the execution of the circular segment keeping up and reignition conditions, the connected voltage which can keep up the AC bend with a specific length can be computed. In this manner the circular segment spread foundation is the way to the flashover procedure. Existing criteria in light of the Obenaus model can be arranged into an angle paradigm, a power basis and an impedance standard.

The Hampton basis, which is $E_p > E_{arc}$, implying that the voltage inclination of the curve is not as much as that of the lingering contamination layer, is the slope rule. In most electrical circuit models, the Ayrton Equation, $Earc = Ai^{-n}$, is utilized to dissect the low-current nonstatic circular segments, which is entirely legitimate just for high-current static curves [5]. The power foundation, which is $dP/dx > 0$, implies that alongside the circular segment engendering, the power from the supply increments. Expecting all the power from the supply is moved into the circuit and the connected voltage is unaltered, the foundation can be streamlined to $di/dx > 0$, which implies that the spillage current increments with circular segment proliferation. Nacke considers the change of aggregate voltage for an uprooting of the release root at steady current, in particular:

$$dV = \frac{\partial V_{arc}}{\partial x_{arc}} dx_{arc} + I_{arc} \frac{\partial R}{\partial x_{res}} dx_{res} \quad ......(4)$$

At the point when $dV < 0$ happens, the release will be unsteady and flashover will happen. In any case, it is not clear why a requirement of steady current is forced, instead of the real imperative of consistent voltage. Be that as it may, amid the circular segment spread, there are various dissipative sources like light and radiation other than the curve and contamination layer. Therefore, notwithstanding when the power from the supply builds, the curve is not really proliferating.

3. Arc Root Voltage Gradient Variation during Arc Propagation

The surface arc propagation on an insulator between the high voltage and ground electrodes is a kind of air-gap surface discharge under an extremely uneven electric field. The gas molecules on the surface of insulator absorb energy from the electric field and are ionized as positive ions and electrons which blend into the arc channel causing the arc propagation owing to the high temperature and high voltage gradient in front of the discharge root. Especially, the energy variation at the arc root can determine the arc propagation, namely the mechanism of "elongation by ionization and successive root formation". With arc propagation, the newly formed arc length displaces the corresponding length of contamination layer. The applied voltage which is a constant is centralized on arc root continuously in process of arc propagation. The field at the arc root concentrates and brings about the flashover later. Therefore, during the propagation of the arc, the arc root voltage gradient variation is significant for both arc propagation and the final flashover.

3.1. Proposed mechanism of propagation

The proposed mechanism may be called 'elongation by ionisation and successive root formation', and may be explained by reference to Fig.2. The theory proposes that elongation is produced by new ionisation paths created at the tip of the discharge. The probability of ionisation immediately in front of the discharge root is high, owing to the high temperature and high voltage gradient in this region.

If sufficient ionisation exists, some current may flow through the ionised path in front of discharge tip, as shown in Fig.2b. The conductivity of the new path increases with current, while the conductivity of the electrolyte path remains constant, and so the total current will gradually divert to the new path, producing an elongation *8* of the discharge. This explanation has referred to the elongation as a discrete step *8.* In fact, it is a smooth continuous process. The effect of this mechanism on the critical current can be estimated roughly, using the simplified representation in Fig.2c. Here it is assumed that a new current path carrying a current *id* has been established immediately in front of the existing discharge tip, and this is in parallel with the resistive pollution layer, which carries a current *ip,*

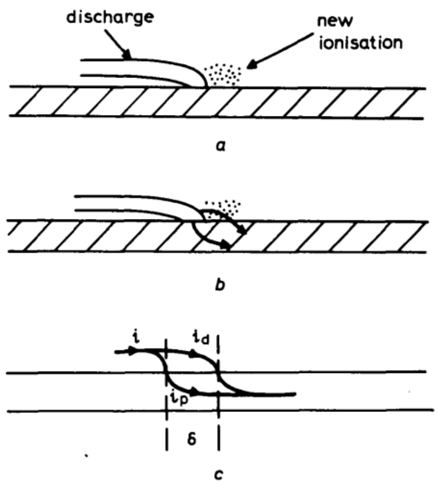

Figure2** Proposed mechanism of elongation **a) Ionisation in front of discharge tip ***b)*** Possible current paths **c)**Simplified model for analysis

3.2. The Arc Root Voltage Gradient Criterion

The arc propagation is characterized by new ionization at the arc root which forms the plasma channel, as shown in Figure 2. The voltage gradient of arc root has a decisive effect on the formation of new ionization. Jolly considered that pollution flashover is essentially an electrical breakdown process caused by the field concentration at the discharge tip, so the arc root voltage gradient criterion is proposed as follows:

$$\frac{dE_{ion}}{dx} > 0 \quad ......(5)$$

where E_{ion} is the voltage gradient of the arc root and x (cm) is the arc length

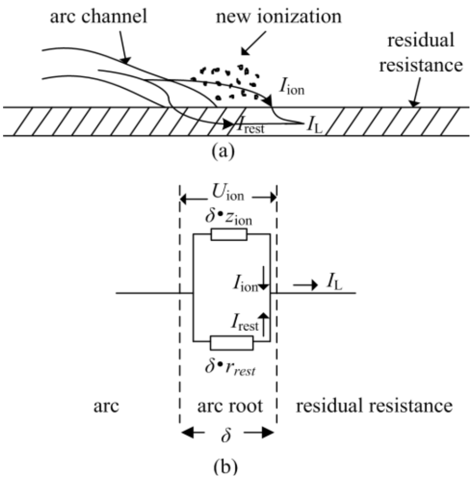

Figure 3. Arc root equivalent electrical circuit model. (**a**) Arc root physical analysis;(**b**) Arc root equivalent electrical circuit.

According to the relationship between voltage drop and voltage gradient, due to the fact the size of arc root remains almost unchanged, the following equation is deduced.

$$\frac{dU_{ion}}{dx} = \delta \frac{dE_{ion}}{dx} \quad ......(6)$$

Where U_{ion} (V) is the arc root voltage drop and δ is the length of arc root which can be treated as a constant. When $dE_{ion}/dx > 0$, $dU_{ion}/dx > 0$ is obtained. This means the voltage drop at the arc root increases with arc propagation. In Figure 3, z_{ion}(Ω/cm) is the per unit length impedance of the new ionization area of arc root; I_{ion} is the current which flows into the new ionization branch. U_{ion}(V) is the arc root voltage drop and δ is the length of arc root which can be treated as a constant. r_{rest} (Ω/cm) is the per unit length resistance of the remaining contamination layer; I_{rest} is the corresponding current of remaining contamination layer branch. I_L(A) is the surface leakage current. From Figure 3, the voltage drop of the arc root can be expressed as

$$U_{ion} = z_{equ} \delta I_L \quad ....(7)$$

Where I_L(A) is the surface leakage current and z_{equ} (Ω/cm) is the equivalent impedance per unit length at the arc root and can be deduced as:

$$z_{equ} = \frac{r_{rest} z_{ion}}{r_{rest} + z_{ion}} \quad ....(8)$$

Where r_{rest}(Ω/cm) is the per unit length resistance of the remaining contamination layer and z_{ion} (Ω/cm) is the per unit length impedance of the new ionization area of arc root.

When the arc propagates an iota of length dx, differentiating Equation (7) and combining with Equation (8), the derivative of U_{ion} is:

$$\frac{dU_{ion}}{dx} = z_{equ}\delta \frac{dI_L}{dx} + \delta I_L \frac{dz_{equ}}{dI_L}\frac{dI_L}{dx} = (z_{equ}\delta + \delta I_L \frac{dz_{equ}}{dI_L})\frac{dI_L}{dx} \quad ....(9)$$

The steepness of the arc front at the arc root increases with the leakage current, which is equal to the total impedance of the new ionization increasing, namely $dz_{equ}/dI_L > 0$. Thus from Equation(9), when $dU_{ion}/dx = 0$, $dI_L/dx = 0$ is obtained.

4. Pollution Flashover Model based on Arc Root Voltage Gradient Criterion

The electrical circuit model of the arc proliferation along the encasing is spoken to by electrical circuit arrange parts, which is a proficient technique for demonstrating the flashover procedure. In the Obenaus display, the bend voltage-inclination condition is embraced to delineate the connection between the circular segment voltage and curve current. Since the contamination flashover is a sort of gas breakdown, the proportional electrical circuit organize display in the long air crevice release can be utilized for demonstrating of the contamination surface flashover. That is to state, the bend channel of contamination flashover can likewise be demonstrated as a conveyed parameter circuit, whose parameters are chosen by the electromagnetic field dissemination of the circular segment and the gas release speculations. Besides, as indicated by previous analysts, the electric field dissemination close to the curve root is unified, however rapidly weakens. The high electric potential angle close to the circular segment root is in charge of the curve proliferation and last flashover. The ionization and recombination of the gas atoms chiefly happen close to the bend root. Wilkins suggested that the circular segment spread is a consequence of the prolongation by ionization and progressive bend root development. The curve root can be dealt with as a parallel circuit with the ionized gas and dirtied layer, as appeared in Figure 3(a).

In view of the above investigation, another electrical dispersed parameter circuit model of contamination flashover is introduced in this paper, which is appeared in Figure 4. Because of the circular segment spread along the surface of a cover, some piece of the streams will likewise exchange from the bend channel to the surface contamination layer on underneath the curve channel. In this way, the circular segment channel and the surface contamination branch underneath the bend ought to have some association focuses. That is to state, a disseminated parameter circuit of the bend channel can portray this wonder superior to anything a fixation parameter circuit of the circular segment voltage-slope condition. In the circulated parameter demonstrate, the circular segment channel is spoken to by the impedance lattice, and the surface contamination branch underneath the bend is spoken to by the induction framework. Since the bend inductance and the circular segment capacitance are both far littler than the curve resistance, the inductance and the capacitance in the impedance and permission frameworks are overlooked.

Therefore, the per unit length impedance of the curve channel and the per unit length induction of the circular segment channel are controlled by the resistance of the bend channel and the surface contamination layer resistance individually. The circular segment root is partitioned into two sections, as appeared in Figure 2(b). The upper channel is the place the new ionization happens. The lower channel is through the defilement layer, speaking to the lingering contamination resistance in parallel with t he circular segment root. δ is the length of the bend root, which can be dealt with as a steady, and satisfies the condition that δ << x, δ<<L−x

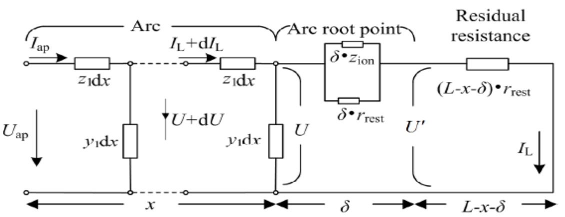

Figure 4 .Advanced electrical circuit flashover model.

The admittance between the arc channel and the earth is determined by the surface pollution resistance. Then the average admittance per unit length between the arc channel and the earth can be calculated by the following equation as:

$$y_1 = \frac{y_{surface}}{L} = \lambda\frac{\frac{1}{r_{rest}L}}{L} = \lambda\frac{1}{r_{rest}L^2} \quad .....(10)$$

Where $y_{surface}$ is the admittance of polluted insulator surface, L is the leakage distance, ë is the correction factor which is determined by the pollution resistance. Due to the admittance of surface pollution branch beneath the arc very small, the surface resistance can reach about one hundred million ohms. According to literature, the value of ë is about 20 when the surface resistance is one hundred million ohms under the polluted severities encountered in practice.

5. The Calculation of Critical Flashover Voltage

According to the research on the air-gap arc discharge in, the arc channel resistance per unit length can be deduced as:

$$r_1 = \frac{1}{\sigma\pi a^2} \quad .....(11)$$

Where σ (S/cm) and a (cm) are respectively the conductivity per unit length and the radius of the arc channel and can be expressed as:

$$\sigma = f(I) = \frac{I_L^{1.006}}{24.34} \quad .....(12)$$

$$a = \sqrt{\frac{I_L}{1.45\pi}} \quad ......(13)$$

Where I_L is the leakage current.

Combining Equations (11), (12) and (13), the following equation is obtained:

$$r_1 = \frac{35.3}{I_L^{2.006}} \quad ......(14)$$

Unit length impedance Z_1 of arc channel which can be considered as a resistance, thus

$$Z_1 = r_1 = \frac{35.3}{I_L^{\ 2.006}} \quad ......(15)$$

Meanwhile, the new ionization is considered as a shunting of arc, who's per unit length impedance can be calculated as follows:

$$Z_{ion} = \frac{35.3}{I_{ion}^{\ 2.006}} \quad ....(16)$$

In Figure 3, the following equations set can be obtained as:

$$\begin{cases} Z_{ion} I_{ion} \delta = r_{rest} I_{rest} \\ I_L = I_{ion} + I_{rest} \end{cases} \quad ...(17)$$

the leakage current can be expressed as:

$$I_L = I_{ion} + \frac{35.3}{r_{rest} I_{ion}^{\ 1.006}} \quad ......(18)$$

Differentiating Equation (18) with respect to I_{ion} and setting it equal to zero:

$$\frac{dI_L}{dI_{ion}} = 1 + \frac{35.3 \times (-1.006)}{r_{rest} I_{ion}^{2.006}} = 0 \quad ......(19)$$

Due to the fact $dI_L/dI_{ion} = dI_L/dx/dI_{ion}/dx$ the critical current which satisfies the condition of $dU_{ion}/dx = 0$, namely $dI_L/dx = 0$, also satisfies the Equations (18) and (19). So the critical current can be expressed as follows:

$$I_c = 2 \times \left(\frac{35.3}{r_{rest}}\right)^{\frac{1}{2.006}} \quad ......(20)$$

Under critical condition, $dI_c/dx = 0$ is satisfied, so combining with Equation (15), the per unit length resistance of arc channel can be calculated:

$$Z_1 = \frac{35.3}{I_c^{\ 2.006}} \quad ......(21)$$

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$$U_c = \frac{2I_c}{\gamma} \sqrt{r_{rest}(r_{rest} + Z_1)} \quad ...(22)$$

By combining this equations we have

$$U_c = \frac{2I_c}{\sqrt{\frac{35.3}{I_c^{\ 2.006}} y_1}} \sqrt{r_{rest}\left(r_{rest} + \frac{35.3}{I_c^{\ 2.006}}\right)} \quad ....(23)$$

The calculation formulas of critical voltage and critical arc length can be obtained as

$$U_c = 11.83\ L\ r_{rest}^{\ 0.5015} \quad .....(24)$$

$$x_c = 0.43\ L \quad ....(25)$$

The critical arc length in the critical zone is between 0.4 L ~ 0.63 L, which agrees well with our model calculation results in Equation (25).

6. Discussion of results

6.1 The Comparison of the Flashover Voltage:

In this paper the mathematical analysis has been done under AC based on Arc root voltage gradient. Based on this criterion, a new distributed parameter electrical circuit flashover model of polluted insulators is proposed. The arc channel is considered as an equivalent distributed parameter circuit model instead of using the arc voltage-gradient equation. This numerical replica is performed utilizing MATLAB- programming.

The design represents 70KN disc insulator which is having working Voltage of 11KV with minimum creepage distance of 330mm & Diameter of the Disc insulator is of 255mm respectively & the form factor is 0.79, when the surface conductivity changes between 15 ~ 40 μS, the corresponding pollution layer resistance is about 1.98 × 10^4~5.27 × 10^4 Ω. According to Equation (37), the calculation formula of critical flashover voltage is obtained as follows:

$$U_c = 390.39\ r_{rest}^{\ 0.5015} \quad ...(26)$$

Equation(26) satisfies Claverie's reignition condition.

The comparison between the proposed model and former models is illustrated in Figure 5.

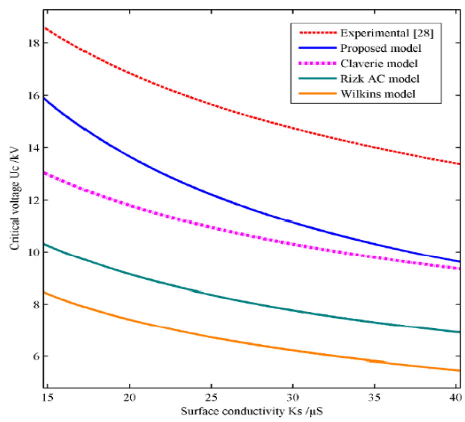

Figure 5. The relationship between surface conductivity and critical flashover voltage for various models.

It can be judged from Figure 5 that the basic flashover voltage is diminishing with the expansion of the surface conductivity. From base to best the bends speak to the Wilkins show, Rizk AC demonstrate, Claverie display, the proposed model and investigation comes about in this paper, separately. The proposed display in this paper is nearest to the Claverie show, and with the expansion of the surface conductivity, the distinction between the two models is diminishing. As the Claverie model depends on an exact equation from fake contamination tests, it has the benefit of mirroring a genuine circumstance. It can be found that the proposed display situates between the Claverie show and the explore comes about because of writing, which shows the proposed model is in great concurrence with the down to earth results to a specific degree. The distinction between the proposed demonstrates and the Claverie display and the investigation results may come about because of the estimations of the resistance of bend channel and the surface resistance of contamination encasing.

6.2 The Comparison of the Flashover Current

The relating basic flashover current examination between the proposed demonstrates and other numerical models is outlined in Figure 6. It can be seen from Figure 6 that the basic flashover current is expanding with the expansion of the surface conductivity. The bends of the Al-Baghdadi display, explore comes about and the proposed model are neighboring. Al-Baghdadi display and the proposed show consider parallel current ways set up through the contamination layer other than the current through the circular segment, which represents the somewhat better correspondence seen between the computed and measured qualities.

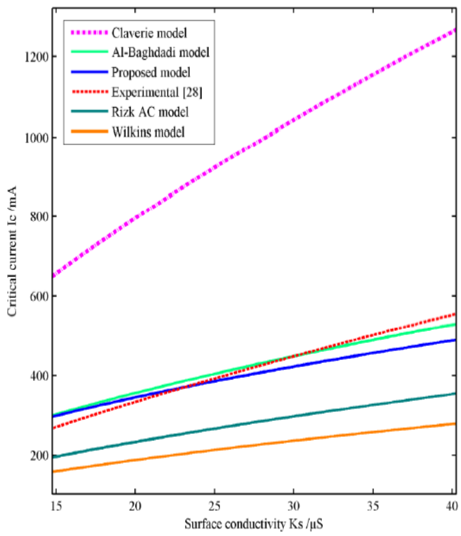

Figure 6. The relationship between surface conductivity and critical flashover current for various models.

7. CONCLUSIONS

From the electrical field variation near the arc root, the voltage gradient criterion $dE_{ion}/dx > 0$ is proposed by connecting the arc propagation with the concentration of field at the arc root. Based on the proposed criterion, a new electrical circuit model of polluted insulators under AC voltage is presented by considering the arc channel as an equivalent distributed parameter circuit model. The calculation results are in good agreement with existing models and artificial, which verifies the electrical field concentration at the arc root in the process of arc propagation. In other words, the voltage gradient near the arc root increases.

Most of the mathematical model are limited to the static state under DC voltage and then extended to the AC case, with no consideration of the re-ignition process. Therefore, they cannot be considering as a complete model that can predict the entire temporal evolution of the flashover process. But $U_c = 390.39 r_{rest}$ this equation satisfies Claverie's re-ignition condition. It means the proposed model can be considered as a complete model that can predict exact evolution for flashover process.

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