A New Proposed Dynamic Arc Model for Flashover Performance of a Non-Uniform Polluted Insulator String under HVAC Stress

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ABSTRACT

This paper presents a new proposed dynamic arc model of a non-uniform polluted insulator under HVAC stress taking into account the dynamic arc characteristics. The model is based on a hybrid formulation of Obenaus model and the mathematical development of arc equations by Rizk combined with the dynamic equations of the change in arc resistance by Mayr. The model adopts the criterion of Hampton for arc propagation and the model is simulated using MATLAB Simulink. The model can calculate the instantaneous changes in arc current, arc length, arc resistance, and pollution level on insulator string at which the flashover occurs at certain voltage. Practical insulator geometries have been studied to demonstrate the model with non-uniform pollution in different positions and levels of pollution. The validity of the model is verified by comparing the simulation results with the experimental results and previous works.

1. Introduction

Flashover of contaminated insulators in polluted areas has proven to be one of the most important factors influencing the operation of extra- and ultra- high voltage transmission lines and substations [1, 4]. These are power-frequency flashovers on transmission lines

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without evidence of switching or lightning overvoltages and usually take place in wet weather conditions such as dew, fog, drizzle or light rain. Near industrial, agricultural or coastal areas, airborne particles are deposited on insulators and the insulator pollution builds up gradually. These deposits do not decrease the insulation strength when the insulators are dry. However, when fog or light rain wets the polluted insulator, a conductive layer is formed on the contaminated insulator surface, which initiates leakage current. The drying effect of leakage current produces dry-bands. The line voltage flashes over the dry-band and extension of the arc causes the insulator to flashover. In an operational system, several arcing periods precede actual flashover.

The modeling of polluted insulator flashover started from a mathematical pollution flashover model put forward by Obneuas [5], which has served as the foundation for a quantified simulation of pollution-triggered-flashover. Afterwards other researchers improved and developed the pollution-initiated flashover model under various conditions, and built up both static and dynamic AC/DC models [6–11]. Dynamic models mainly consider the arc channel as an equivalent electrical circuit and simulate arc propagation step by step. The parameters of the equivalent circuit are calculated in real time at every step. The excellent feature of dynamic models is the time-dependent characteristic while the calculation of velocity is the critical point. Beroual solved this problem successfully based on an energetic balance [12] and applied in other media [12–15]. The arc channel is equivalent to a resistance series with an inductance [11]. Combining with the impedance criterion of $d|Zeq|/dx < 0$ proposed by Dhahbi-Megriche and Beroual [11], the arc circuit parameters are calculated step by step, until flashover occurs. The arc nonlinear resistance is calculated by Mayr's equation [11]. The results indicate that the arc channel inductance and capacitance are negligible compared to the arc channel resistance. That is to say, arc resistance has a critical effect on the propagation of an arc, which has been verified with the criterion given by Dhahbi-Megriche and Beroual [11].

Based on the empirical formula of arc reignition from the arc tests, static and dynamic pollution flashover models were developed and applied for insulation coordination. From the existing research, it is found that the key point of the flashover model is based on the criteria for arc propagation and arc extinction and reignition. Earlier criteria for arc propagation depended on the power (P) variation with the arc length propagation (x) that is $dP/dx > 0$, which is a necessary condition instead of a sufficient condition [7]. Another well-known criterion is the impedance criterion proposed by Beroual and Dhahbi-Megriche [16]. This criterion is based on an equivalent impedance of a whole electrical circuit and can explain why the Hampton criterion is not a sufficient condition for initiation of the arc. It is also applied to the analysis of flashover mechanism comprehensively [11,15,17].

The previous models suffer limitations as these models were based on empirical formulas for critical values of arc length, arc current, and arc voltage without taking into consideration the rapid change in arc parameters. Therefore, a new model is needed to overcome these limitations. The aim of the present work is to propose a new dynamic model of arc propagating over a non-uniform polluted insulator stressed by AC voltage taking into account the arc characteristics and insulator geometry. The proposed model allows the prediction of discharge activity leading to the flashover of polluted insulators and taking into account the instantaneous changes in the arc parameters. Also, the model is used to analyze the leakage current waveform in an attempt to predict the occurrence of flashover and the critical flashover voltage. The results of simulation were compared with experimental results obtained in the laboratory and also with others published in previous work. Considering the complicated nature of the problem the agreement between theory and experiment is found to be satisfactory.

2. Experimental Procedure

The artificial pollution test is performed according to IEC 60507 standards, the test insulator used in the experiment is cap and pin insulator type made of porcelain having leakage distance of 242 mm, height of 160 mm, and diameter of 280 mm. The string used in the test consists of six discs of insulators in series and suspended vertically as shown in Fig. 1. The High Voltage Laboratory in the Faculty of Electrical Engineering, Czech Technical University in Prague, Czech Republic, was used in achieving the experimental investigations of the present work.

The artificial pollution is prepared by mixing salt and Kaolin with distilled water. In the experiment, different samples of polluting mixture are prepared. In the testing setup, the clean and dry insulator string is hung to a testing support. The insulator string is polluted properly by applying the polluting mixture using a spray gun. The non-uniform pollution is obtained by changing the position and number of units which are polluted in the insulator string. The pollution is uniform for one unit of the insulator string however it is non-uniform along the whole string. Once this is done, the voltage from the high voltage transformer is applied to the insulator. Then, the high voltage is applied slowly from zero voltage until complete flashover occurs on the insulator surface. This is achieved by means of a variac connected to the input of the testing transformer. At flashover, the voltage is recorded. For each sample of polluting mixture, five shots of flashover voltages are taken to find out the maximum, minimum, and average values of flashover voltage (FOV). Similar testing procedures are repeated for other samples of polluting mixture and the corresponding FOV's are recorded.

To perform measurements, the cap of the insulator is connected to ground and the other terminal (i. e. pin stud) is connected to the source of high voltage AC. To measure the leakage current which flow on the surface of the polluted insulator, Hall Effect current sensor is used. The current sensor detects the leakage current and produces the corresponding output voltage. This analog voltage is the input of Data Acquisition card that connected to the computer to draw the leakage current waveform with rapid changes. The current sensor measures the leakage current which flow in the insulator surface and gives the output signal (voltage signal) to data acquisition connected to the computer using Universal Serial Bus (USB) cable. The software LabVIEW Signal Express is used to record the measured signals on the hard disc of the computer. The schematic diagram of the experimental setup is shown in Fig. 2. The role of resistance R_1 in the test circuit is to limit the current when the full flashover occurs. The uncertainty of voltage measurement is 0.1 % and for the current measurement 1%. The surface layer conductivity σ of the polluting mixture is measured in µS and calculated as follows.

$$\sigma = \frac{I}{V} \times FF \qquad \mu S \tag{1}$$

, where I is the measured leakage current in mA, V is the applied voltage in kV, and FF is the insulator's form factor. This form factor was calculated and equals to 0.79 for one unit and equals 4.74 for the string. The applied voltage is about 3 kV and the measured leakage current is 56 mA, so the calculated surface conductivity equals to 88.48 µS.

3. Theoretical Development and Basic Assumptions

The following basic assumptions are adopted:

(1) The surface conductivity of the pollution layer is constant.

(2) There is only one arc and one dry band.

(3) The electric field is uniform.

During the arcing period, the leakage current can be calculated using the model proposed by Obenaus [5] and mathematically developed by Rizk [6]. This model contains arcs and surface resistance connected in series. The sinusoidal supply voltage *V(t)* is given by:

$$V(t) = V_{arc}(t) + I_{arc} \cdot R_p \qquad V \tag{2}$$

, where I_{arc} is the instantaneous arc current, R_p is the pollution resistance, and $V_{arc}(t)$ is the arc voltage and this voltage is calculated by using the following equation:

$$V_{arc}(t) = r_{arc} \cdot L_{arc} \cdot I_{arc} \qquad V \tag{3}$$

, where L_{arc} is the arc length in cm and r_{arc} is the arc resistance per unit length in Ω /cm.

The arc current is given by:

$$I_{arc}(t) = \frac{V(t)}{r_{arc} \cdot L_{arc} + R_p} \qquad \text{A} \tag{4}$$

The pollution resistance R_p is calculated from the form factor, as in reference [10,6,18]:

$$R_p = \frac{FF}{\sigma} \qquad \Omega \tag{5}$$

, where σ is the surface conductivity of pollution layer in Siemens, S and FF is the form factor and this factor is calculated as in references [18, 19]:

$$FF = \int_0^L \frac{d\,l}{2\,\pi\,r(l)} \tag{6}$$

, where l is the distance from the upper electrode (cap) on the insulator surface, $r(l)$ is the radius of the insulator at a distance l from the upper electrode, and L is the leakage distance in cm.

The pollution resistance per unit leakage path can be calculated as follows:

$$r_p = \frac{R_p}{L - L_{arc}} \qquad \Omega\,/\text{cm} \tag{7}$$

The arc re-ignition (V_{ig}) voltage can be calculated by an empirical formula. The same formula is used as the extinction voltage even though this may not be the case for real arcs. After the supply voltage passes through the natural current zeros, the arc reignites when the supply voltage exceeds this value of V_{ig} which is given in references [6, 18]. It is noted that the values of the constants 23 and 0.4 used in Eq. (8) were obtained graphically as these values of constants have been calculated using the plot of dynamic voltage-current characteristic for the arc taken during laboratory tests.

$$V_{ig} = 23L \cdot r_p^{0.4} \quad \text{V} \tag{8}$$

The arc will only propagate (arc length increases) if the electrical field is lower in the arc than in the pollution layer ($E_{arc} < E_p$). This is known as Hampton's criterion for propagation [2].

$$E_{arc} = N \cdot I^{-n} \quad \text{V/cm} \tag{9}$$

and

$$E_p = N^{\frac{1}{n+1}} \cdot r_P^{\frac{n}{n+1}} \quad \text{V/cm} \tag{10}$$

, where E_{arc} is the electric field in arc in V/cm, E_p is the electric field in pollution layer in V/cm, N is the static arc constant which equals to 60 VA^n/cm [20], and n is the exponent of static arc characteristics which equals to 0.5 [20]. The values of the coefficients N and n change due to the environment conditions where the arc is ignited.

The arc resistance per unit length r_{arc} is obtained dynamically from Mayr's equation [18, 20] as shown in Eqs. (11 and 12).

$$\frac{d\ r_{arc}}{d\ t} = \frac{r_{arc}}{\tau} - \frac{r_{arc}^2 \cdot I_{arc}^{n+1}}{\tau \cdot N} \tag{11}$$

$$(r_{arc})_{new} = (r_{arc})_{new} + d\ r_{arc} \quad \Omega\text{/cm} \tag{12}$$

, where τ is the arc time constant and equals to 100 µs [20]. The arc is characterized by a time constant, which depends on the electrical inertia of the arc, because of energy storage in the arc associated with its conductance and finite rates of energy flow. The value of arc time constant of 100 µs is valid for low current AC arcs with arc testing in open air.

The flow chart of the dynamic arc model is shown in Fig. 3. The present work uses the MATLAB Simulink to construct a Simulink model to study the flashover process and analyze the leakage current waveform, arc length, arc resistance and arc voltage by solving the above equations for a specific insulator data and certain pollution level.

4. Results and Discussion

In the laboratory, an insulator string with six cap-and-pin porcelain discs is tested with AC energization. Egyptian Electricity Transmission Company frequently uses this type of porcelain insulators on its transmission and distribution lines. The results of the proposed model under AC voltage application have been compared with the experimental results**.** The same data of the insulator and the pollution level used in experiment are entered to the MATLAB Simulink model.

The results are given for two different pollution levels with different positions for each pollution level. These two pollution levels are presented in the following two subsections. The first subsection deals with a pollution mixture of 15g salt and 40g kaolin with a liter of distilled water. The other subsection presents a pollution mixture of 60g salt and 160g kaolin with a liter of distilled water.

In each case of pollution level, the measured and simulated flashover voltages are given in tables whereas representative waveforms for the voltage and current, from start of the test till flashover occurrence, are presented in figures. Hereafter, a waveform is given for representative cases with A: Experimental Voltage, B: Simulated Voltage, C: Experimental Current, and D: Simulated Current.

4.1 Case I (pollution mixture of 15g salt and 40g kaolin with a liter of distilled water)

Table 1 gives the readings of flashover voltage for five shots and the average value of these readings. The readings are taken for a pollution mixture of 15g salt and 40g kaolin with a liter of distilled water and with non-uniform pollution encountered by polluting different number of discs in the insulator string for different positions. The experimental average reading is compared to the simulated value of flashover voltage. The simulated value is lower than the experimental average one by a percentage from 3% to 6%. This difference between experimental and simulated value is attributed to inherent limitations in the simulated dynamic model. These limitations include non-uniformity of conductivity and also pollution layer thickness as the initial conductivity (assumed constant in the simulated dynamic model) varies continuously and irreversibly during the progress of a flashover test. Also, the arc may not necessarily follow the surface of the insulator and also physical processes in the arc may create propagation speeds much higher than that used in the simulated dynamic model. Table 1 also reveal that as the position of polluted discs be near the energized electrode, the magnitude of flashover voltage be higher than the polluted discs far from the energized electrode. The explanation of this effect could be that the surface pollution creates a semiconducting layer. This layer influences charge distribution along the insulator and makes the voltage gradient smaller (voltage distribution is then more linear at the beginning of insulator string). This led to the increase of flashover voltage.

Figure 4 shows the output waveforms of voltage and current for the case of insulator string with clean discs during the test of flashover. Both experimental and simulated waveforms for voltage and current indicate random fluctuations in magnitude and shape. The leakage current for the withstand (non-flashover) has intermittently large peaks whereas the flashover case exhibits a continuous train of large peaks.

Figures 5 to 7 show representative waveforms of voltage and current for the case of insulator string with a pollution mixture of 15g salt and 40g kaolin with a liter of distilled water. Figure 5 represents the case of polluting two discs (first and second), Fig. 6 represents the case of polluting four discs (first, second, third, fourth), and Fig. 7 represents the case of polluting all of the six discs.

Figure 5 shows the oscillograms of the measured and simulated voltage and leakage current for the case of polluting two discs. With the introduction of the polluting mixture, soluble contaminants are dissolved, a thin conductive layer is formed and the leakage current path becomes resistive and base current magnitude increases. Heating effect of leakage current leads to dry-band formation and partial discharges across the dry-bands. The effect of these discharges is to create current surges and to modify the current waveshape; narrowing the width of the current wave. With increasing the voltage, the leakage current increases. The increased current leads to further drying, which again produces localized surface arcing. Extinction and re-ignition of the local arcs also change the current shape; short duration impulses superimposed on the fundamental current. The arc length gradually increases, which ultimately leads to flashover. As compared with Fig. 4 (the clean discs), the magnitude of flashover voltage is decreased whereas the magnitude of leakage current is increased.

Figure 6 shows the oscillograms of the measured and simulated voltage and leakage current for the case of polluting four discs. As compared with Fig. 4 (the clean discs) and Fig. 5 (two polluted discs), the magnitude of flashover voltage is decreased whereas the magnitude of leakage current is increased.

Figure 7 shows the oscillograms of the measured and simulated voltage and leakage current for the case of polluting all of the six discs. As compared with Fig. 4 (the clean discs), Fig. 5 (two polluted discs), and Fig. 6 (four polluted discs), the magnitude of flashover voltage is decreased whereas the magnitude of leakage current is increased.

The figures 5 to 7 reveal that as the number of polluted discs increases, the magnitude of flashover voltage considerably decreases. Also, the oscillograms of the measured and simulated leakage current of polluted insulators exhibit erratic changes in magnitude and shape. The oscillograms also reveal that the leakage current has shown a strong fundamental component with little or no harmonics under normal conditions whereas under arcing conditions the harmonic content increases. Numerous publications [21–24] attribute this behavior to a flashover process that is non-linear and predominantly random in nature; the surface discharges are nonlinear arcs, the pollution levels, wetting rate and also leakage current density are all non-uniform.

4.2 Case II (pollution mixture of 60g salt and 160g kaolin with a liter of distilled water)

Table 2 gives the readings of flashover voltage for five shots and the average value of these readings. The readings are taken for a pollution mixture of 60g salt and 160g kaolin with a liter of distilled water and with non-uniform pollution encountered by polluting different number of discs in the insulator string for different positions. The experimental average reading is compared to the simulated value of flashover voltage. The simulated value is lower than the experimental average one by a percentage from 4% to 5%.

Figures 8 to 10 show representative waveforms of voltage and current for the case of insulator string with a pollution mixture of 60g salt and 160g kaolin with a liter of distilled water. Figure 8 represents the case of polluting two discs (first and second), Fig. 9 represents the case of polluting four discs (first, second, third, fourth), and Fig. 10 represents the case of polluting all of the six discs. The figures reveal that as the pollution severity increases, the magnitude of flashover voltage considerably decreases whereas the magnitude of leakage current increases.

4.3 Comparison of the proposed model with the previous work

The results of the proposed model under AC voltage application have been compared with the dynamic arc model of Rizk [20]. Rizk used simplified equivalent circuit including the source and the test insulator. The source is represented by its shortcircuit impedance elements resistance and inductance and by the equivalent shunt capacitance. The insulators are represented by two resistances the first is the variable resistance of the wet unbridged layer in series with the dynamic arcs and the second is the resistance shunting the arc represents any residual conductance of the insulator part bridged by the arc. The equation used to describe the dynamic change in arc resistance per unit length is the same for Rizk model and the proposed model and other equations are different. The analytical results for arc current and arc length are compared for the polluted insulator with leakage distance of 134 cm and form factor of 5.69

and the surface conductivity of 23.6 μS and the peak value of the supply voltage is 59 kV (powerful source). The leakage current of the simulated results of Rizk was 0.61 A at ωt = 240. It is noted that the measured value of leakage current by Rizk was 0.84 A.

The same data used by Rizk are entered to the proposed simulink model and the leakage current was 0.58 A at ωt = 240. The percentage of reduction in the leakage current as compared with Rizk model was about 4.9 %. Also, the arc length of Rizk model was 96.5 cm and compared with the arc length of the simulink of the proposed model which was 92 cm and so, the percentage of reduction was 4.7 %.

The principal application of this model would be to help simulate as much as possible the practical conditions under which insulators perform. More wide application of the present model can be achieved with incorporating numerical calculation of electric field and taking into account non-uniformity of electric field and effect of arcing horns and fittings on electric field distribution across the insulator string.

5. Conclusions

The present paper introduces a new proposed dynamic arc model in order to investigate the flashover performance of a non-uniform polluted insulator string under HVAC stress. The non-uniform pollution is obtained by changing the position and number of units which are polluted in the insulator string. The pollution is uniform for one unit of the insulator string however it is non-uniform along the whole string. The proposed model accounts the dynamic arc characteristics and is simulated using MATLAB Simulink. The validity of the model is verified by comparing the simulation results with the experimental results and previous works. The main conclusions of the present study are as follows.

(1) For the two representative cases investigated, the predicted flashover voltage of the insulator string is lower up to 6% than the measured value.

(2) The model and experimental work reveal that as the position of polluted discs be near the energized electrode, the magnitude of flashover voltage be higher than the polluted discs far from the energized electrode.

(3) The measured and simulated leakage current for the withstand (non-flashover) has intermittently large peaks whereas the flashover case exhibits a continuous train of large peaks.

(4) The measured and simulated leakage current has shown a strong fundamental component with little or no harmonics under normal conditions whereas under arcing conditions the harmonic content increases.

(5) The model and experimental work reveal that as the pollution severity increases, the magnitude of flashover voltage considerably decreases whereas the magnitude of leakage current increases.

(6) The results of the proposed MATLAB Simulink model are in good agreement with the measured results from the experimental work.

(7) The arc current and arc length of the proposed model are compared with Rizk model and the comparison results are satisfactory.

References

[1] Lloydand KJ, Schneider HM. Insulation for Power Frequency Voltage. Transmission Line Reference Book (345 kV and above); Electric Power Research Institute, Palo Alto, California, USA, 1982.

[2] Hampton B. Flashover mechanism of polluted insulation. Proc. IEE 1964; 111:985-990.

[3] Obenaus F. Kriechweguberschlag von Isolatoren mit Fremdschichten. Elektrizitatsirtschaft 1960; 24:878-882.

[4] Looms TJ. Insulators for High Voltage. Peter Peregrinus Ltd.; London, United Kingdom, 1988.

[5] Obenaus F. Contamination flashover and creepage path length. Dtsch. Elektrotechnik 1958; 12:135-136.

[6] Rizk FAM. Mathematical models for pollution flashover. Electra 1981; 78:71-103.

[7] Wilkins R. Flashover voltage of high voltage insulators with uniform surface pollution films. Proc. IEE 1969; 116:457-465.

[8] Alston LL, Zoledziowski S. Growth of discharges on polluted insulators. Proc. IEE 1963; 110:1260-1266.

[9] Gopal S, Rao YN. Flashover phenomena of polluted insulators. IEE Proc. 1984; 131:140-143.

[10] Sundararajan R, Gorur RS. Dynamic arc modeling of pollution flashover of insulators under dc voltage. IEEE Trans. Electr. Insul. 1993; 26:209-218.

[11] Dhahbi-Megriche N, Beroual A. Flashover dynamic model of polluted insulators under ac voltage. IEEE Trans. Dielectrics Electr. Insul. 2000; 7:283-289.

[12] Beroual A. Electronic and gaseous processes in the prebreakdown phenomena of dielectric liquids. J. Appl. Phys. 1993; 73:4528-4533.

[13] Beroual A, Fofana I. Modelling of the leader and the return stroke currents with an equivalent electrical network. 9th International Symposium on High Voltage Engineering, Graz, Austria, No. 2141, 28 August - 1 September 1995.

[14] Beroual A. Universal dynamic model of discharge propagating in air, liquids, solid/liquid interfaces and polluted. 13th International Symposium on High Voltage Engineering, Delft, The Netherlands, 25 - 29 August 2003.

[15] Beroual A, Dhahbi-Megriche N. Dynamic model of discharge propagation on polluted surfaces under impulse voltages. IEE Proc. Gener. Transm. Distrib. 2000; 147:279-284.

[16] Beroual A, Dhahbi-Megriche N. A new proposal model for flashover of polluted insulators. J. Phys. D 1997; 30:889-894.

[17] Slama ME, Beroual A, Hadi H. computation of discharge characteristic constants and critical parameters of flashover of polluted insulators. IEEE Trans. Dielectr. Electr. Insul. 2010; 17:1764-1771.

[18] Karady G, Amrah F. Dynamic modeling of AC insulator flashover characteristics. IEE Symposium on High Voltage Engineering, No. 467, August 1999, pp. 107-110.

[19] Ghosh PS, Chatterjee N. Polluted insulator flashover model for ac voltage. Proc. IEEE Trans. Dielectrics Electr. Insul. 1995; 2:128-135.

[20] Rizk FAM, Nguyen DH. AC source-insulator interaction on HV pollution tests. Proc. IEEE Transaction on Power Apparatus and Systems 1984; PAS-103(4):723-732.

[21] Boudissa R, Djafri S, Haddad A, Belaicha R, Bearsch R. Effect of insulator shape on surface discharges and flashover under polluted conditions. IEEE Trans. Dielectrics Electr. Insul. 2005; 12:429-437.

[22] Gencoglu MT, Cebeci M. Computation of AC flashover voltage of polluted HV insulators using a dynamic arc model. Euro. Trans. Electr. Power 2008; 10:249-262.

[23] El-Refai EMM, El-Noaman MT, Mohamed MK. Dynamic arc modeling of pollution flashover process on HV insulators under AC voltage. 13th Middle East Power Systems Conference, MEPCON'2009, Assiut University, Egypt, 2009; pp:662-667.

[24] Yang Q, Wang R, Sima W, Jiang C, Lan X, Zahn M. Electrical circuit flashover model of polluted insulators under ac voltage based on the arc root voltage gradient criterion. Energies 2012; 5:752-769.

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