IMPROVEMENT OF THE DYNAMIC MODEL OF POLLUTED INSULATORS UNDER AC VOLTAGE BASED ON THE ELECTRO-THERMAL CHARACTERISTICS

Sihua WANG[1], Wanli XU[2], Mingxing TIAN[3]

The flashover dynamic model of polluted insulators can simulate the dynamic change process of the development of discharge, determine the critical voltage that insulators can withstand, and provide a reference for selection of insulators and optimization for structure of insulators. In this paper, a new flashover dynamic model of polluted insulators under ac voltage based on electro-thermal characteristics of insulators is proposed. This model is suitable for the prediction of discharge development under different ambient temperatures. The critical flashover voltages obtained by this model are in good agreement with those in experiments.

Keywords: dynamic model; thermal characteristics; insulator flashover; AC arc

1. Introduction

In power systems, insulators are widely used to insulate and connect various electrical components. When the air humidity is hight, the dirt, deposited on insulator surface, will be wet, resulting in a reduction in insulators' electrical characteristics or a flashover. This reduction in electrical performance depends on many parameters, such as the properties of the insulator material and its stability, the shape of the insulator, the type and distribution (i.e. uniform or uneven distribution) of the deposits in the pollution layer and the environmental conditions (fog, dew, rain, snow or ice...), leakage current caused by locally heating and partial arcs. In addition, long distance transmission lines often need to pass through different areas with complex geography climate environments. Therefore, proper selection of insulators, depending on the environmental conditions in different regions, is of great significance in reducing the occurrence of insulator flashover accidents. Predicting the critical flashover voltage by constructing a mathematical model contributes to optimize the structure of insulators and select materials of insulators, and we can use the mathematical model in place of time consuming and repetitive tests.

[1] Prof., Dept. of Automation and Electric Engineering, Lanzhou Jiaotong University, China, e-mail: ws_h@163.com

[2] Master Student, Dept. of Automation and Electric Engineering, Lanzhou Jiaotong University, China, e-mail: 295338535@qq.com

[3] Prof., Rail Transit Electrical Automation Engineering Laboratory of Gansu Province, China

Literature [1] proposed a DC dynamic model based on taking potential gradient criterion as a development criterion. Jabbari et al. [2] established a dynamic model based on the finite element method. YANG Qing et al. [3] took the influence of surface branch beneath the arc channel into consideration and proposed an AC dynamic flashover model based on the circuit network. However, there are two inevitable problems. On the one hand, in order to simplify the calculation, the existing dynamic models ignored the thermal characteristics of the arc and the pollution layer, which have an important influence on the flashover mechanism, proved by a large number of experimental studies [4-5]. On the other hand, the majority of literatures for flashover dynamic models use arc parameters (*A* and *n*), and both *A* and *n* have been considered as invariant parameters in these documents. However, according to Slama et al. [6], the arc parameters are dynamic parameters that depend on the equivalent electrical circuit and thermal characteristics of the discharge.

Therefore, this paper will build a developed dynamic model of polluted insulators under AC voltage based on the electro-thermal characteristics, which considers the effects of arc temperature and ambient temperature. The effectiveness of the improved model was proved by comparing the computer simulation results with other researchers' experimental results and other existing model simulation results.

2. Background

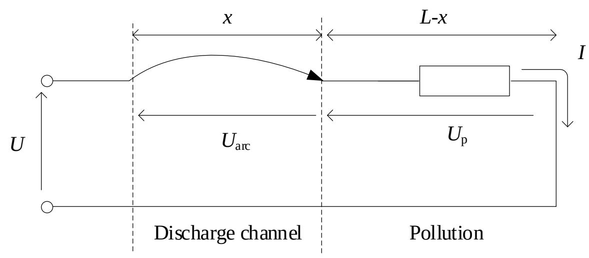

Fig. 1 A model of pollution flashover circuit [7]

Obenaus [7] first proposed quantitative analyses of arcs on contaminated surfaces, the model of the partial arc and the unabridged part of the pollution layer (see Fig.1). The electrical equation is given as follows

$$U = U_E + U_{arc} + IR_p(L - x) \tag{1}$$

where U is the applied voltage; U_E denotes voltage drop of electrode that can be ignored; I represent leakage current; $R_p(x)$ means the resistance of the the unabridged part of the pollution layer; x is the arc length and U_{arc} is the arc channel voltage. U_{arc} can be defined as follows [6]

$$E_{arc} = \frac{U_{arc}}{x} = A \times I^{-n} \tag{2}$$

where A and n are arc parameters that depend on the environmental conditions in which the discharge is burning (i.e., temperature, pressure, etc.). The values of A and n vary from one literature to another due to different environmental conditions (i.e., experimental conditions) [8-12]. Some values of A and n used in the flashover literatures are shown in Tables 1 and 2.

Table 1

Values of flashover characteristic constants *A* and *n* according to different authors

Authors	Ref	A	n
Wilkins	[10]	63	0.760
Hampton	[9]	530	0.240
Farzaneh	[11]	208.9	0.449
Ghosh	[12]	360	0.590
Topalis	[8]	131.5	0.374

Table 2

Values of flashover characteristic constants *A* and *n* [12]

Electrolyte	A	n
NaCl	360	0.59
CaCl2	461	0.42
FeCl2	270	0.66
CuSO4	450	0.49

3. Improvement of the Dynamic Model of Polluted Insulators under AC Voltage

3.1. Improved Dynamic Model for AC Insulators Flashover Based on Electro-thermal Characteristics

3.1.1. Equivalent electrical circuit and calculation of circuit parameters

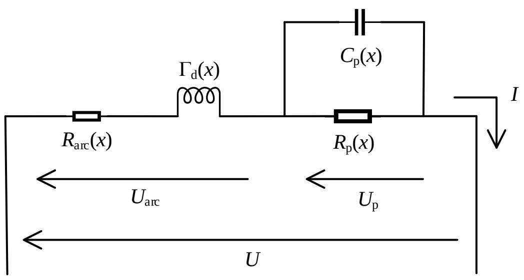

Fig. 2 Equivalent electrical circuit [6]

The equivalent electrical circuit, shown in Fig. 2, simulates a contaminated insulator that has produced a localized arc of length x and a residual layer of length (L-x). The electrical equation of this model is given by

$$U = R_{\mathrm{arc}}(x)I + \mathrm{j}\omega\Gamma_{arc}(x)I + \frac{R_{\mathrm{p}}(x)I}{1 + \mathrm{j}\omega R_{\mathrm{p}}(x)C_{\mathrm{p}}(x)} \qquad (3)$$

with

$$R_{\mathrm{arc}}(x) = r_{\mathrm{arc}} \times x = x \times \frac{\rho_{\mathrm{arc}}}{s_{\mathrm{arc}}}\,;\ \Gamma_{arc}(x) = l_{arc} \times x\,;\ R_{\mathrm{p}}(x) = r_{\mathrm{p}} \times (L-x) = \frac{\rho_{\mathrm{p}}}{s_{\mathrm{p}}} \times (L-x)$$

$$C_{\mathrm{p}}(x) = \frac{c_{\mathrm{p}}}{L-x} = \varepsilon_{\mathrm{p}} \times \frac{s_{\mathrm{p}}}{L-x}$$

in which R_{arc} and Γ_{arc} are the resistance and inductance of the arc; R_{p} and C_{p} mean the resistance and capacitance of the pollution layer respectively; $\omega=2\pi f$, f is the frequency; ε_{p} denotes the relative dielectric Constants; r_{arc}、 ρ_{arc} and s_{arc} are the linear resistance of the arc channel, resistivity and cross-sectional area respectively. L denotes the insulator leakage distance. Because the linear inductance l_{ac} is considered to have very low value [13], therefore, the electrical equation can be re-expressed by eq. (4).

$$U = R_{\mathrm{arc}}(x)I + \frac{R_{\mathrm{p}}(x)I}{1 + \mathrm{j}\omega R_{\mathrm{p}}(x)C_{\mathrm{p}}(x)} \tag{4}$$

According to Wilkins[14], the resistance of the unabridged part of the pollution layer $R\mathrm{p}(x)$ is given by eq.(5).

$$R_{\mathrm{P}}(x) = r_{\mathrm{p}} \times \left[(L-x) + \frac{b}{2\pi} \ln \frac{b^2}{4 \times \pi^2 \times a_{\mathrm{arc}}^2} \right] \tag{5}$$

where r_{p} is the linear resistance of the unabridged part of the pollution layer; b and a_{arc} represent width of the pollution layer and arc radius, respectively.

3.1.2. Calculation of *A* and *n*

Slama et al.[6] analyzed the physical significance of the arc parameters A and n, and redefined the A and n under AC, based on the equivalent electrical circuit and the thermal characteristics of the discharge, as follows

$$A = r_{\mathrm{p}} \frac{k}{\alpha} \left(\frac{\pi \times \lambda(T_{\mathrm{arc}}) \times T_{\mathrm{arc}}}{r_{\mathrm{p}}} \times \frac{\alpha}{k} \right)^{(n+1)/2} \tag{6}$$

$$n = \frac{k(k-1)}{k - 1 + (r_{\mathrm{p}} c_{\mathrm{p}} \omega)^2} \tag{7}$$

with

$$k = \frac{\alpha \cdot r_{\mathrm{arc}}}{r_{\mathrm{p}}}\,;\ \alpha = 1 + (\omega \cdot \sigma_{\mathrm{p}} \cdot \varepsilon_{\mathrm{p}})^2\,;\ \omega = 2 \cdot \pi \cdot f\,;\ c_{\mathrm{p}} = \varepsilon_{\mathrm{p}} \cdot s_{\mathrm{p}}\,;\ r_{\mathrm{p}} = \frac{R_{\mathrm{p}}(x)}{L-x}$$

in which f denotes the frequency; c_{p}, ε_{p} and s_{p} are the linear capacitance, dielectric constant and cross-sectional area of the pollution layer, respectively. s_{p} can be simplified to the cross-sectional area of the partial arc s_{arc}. The thermal conductivity $\lambda(T_{arc})$ depends on the arc temperature T_{arc} and species constituting the arc column [6].

Based on the heat equation and the Mayr arc model, Hadjrioua expressed the instantaneous variation of the arc temperature as follow [15]

$$\frac{\mathrm{d}T_{arc}}{\mathrm{d}t} = \frac{1}{m \times C_v} \times \left[\sigma_{arc} \times E_{arc}^2 - r_{arc} \times \left(\frac{\pi \times \lambda(T_{arc}) \times T_{arc}}{r_{arc}} \right)^{(n+1)/2} \right] \tag{8}$$

where T_{arc} is the arc temperature; m denotes the mass of the added air plasma; C_v, σ_{arc} and r_{arc} are, the specific heat, the arc conductivity and the arc linear resistance, respectively [15].

By calculating the instantaneous variation of the arc temperature at every time-interval of the dynamic model, the instantaneous value of the arc temperature during the development of the partial arc can be obtained.

3.1.3. The Effect of Ambient Temperature on Contamination Conductivity

The pollution on the surface of the insulator ionizes in solution, by being exposed to moisture, will cause a higher conductivity than purified water, it has a strong temperature dependence, the fundamental cause of which is actually the change in the viscosity of the solution, not the change of the ions itself in the solution[18]. The correction formula for the conductivity of the pollution layer at different ambient temperatures is given as follows [16]

$$\sigma_\theta = \sigma_{25} \left(\frac{\eta_\theta}{\eta_{25}} \right)^{-\mathrm{d}} \tag{9}$$

where σ_θ (S/m) and σ_{25} (S/m) denotes the conductivity of the solution when the temperature is θ(°C)and 25°C, respectively; η_θ (N·s/m^2)represents the viscosity of the solution when the temperature is θ(°C); η_{25} (N·s/m^2) means the viscosity of the solution at a temperature of 25℃, which is equal to 0.0000083 N·s/m2; d is a dimensionless constant, which is about 0.806 ~0.933, and its average is 0.877. When the temperature is θ(°C), the viscosity of the solution is described as follows[16]

$$\log \frac{\eta_\theta}{\eta_{25}} = \frac{\mathrm{B}(25-\theta) - \mathrm{C}(25-\theta)}{\theta + \mathrm{D}} \tag{10}$$

where B, C and D are constants, with the value of 1.1278, 0.001895°C^{-1} and 88.93°C, respectively. Therefore, according to both (9) and (10), we obtain the functions of solution conductivity as follows

$$\sigma_\theta = \sigma_{25} \times 10^{-\mathrm{d}\left[\frac{\mathrm{B}(25-\theta) - \mathrm{C}(25-\theta)}{\theta + \mathrm{D}} \right]} \tag{11}$$

On the other hand, when the ambient temperature is 20°C, the surface conductivity of the dirty layer is presented as follows

$$\sigma_{20} = (369.05\rho_{ESDD} + 0.42) \times 10^{-6} \quad (12)$$

where ρ_{ESDD} is equivalent salt density.

Therefore, by arranging eqs.(11) and (12), we get the function of solution conductivity σ_θ depends on θ and ρ_{ESDD}

$$\sigma_\theta = (415.0633\rho_{ESDD} + 0.4736) \times 10^{-d\left[\frac{B(25-\theta)-C(25-\theta)}{\theta+D}\right]-6} \quad (13)$$

From eq.(13), the relation curves that the conductivity σ_θ varying with temperature θ are obtained, when ρ_{ESDD} takes different values. As presented in Fig. 3, the influence of temperature on the conductivity is the greater.

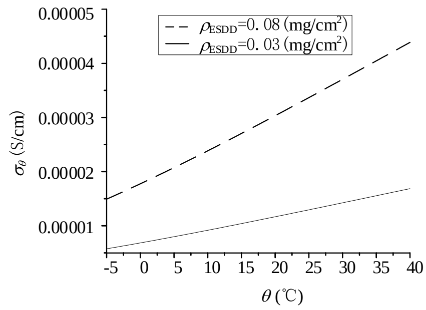

Fig.3. Predictive value of temperature influence on conductivity

3.1.4. Influence of Ambient Temperature on Reignition Condition of AC Arc

The fundamental difference between AC and DC insulator flashovers is the reignition process of AC arcs. In order to maintain the burning of the arc, the applied peak voltage U_m must be greater than the arc reignition voltage peak U_{cx}, which is formulated as follows

$$U_{cx} = U_d x \quad (14)$$

where U_d is the minimum breakdown voltage of the residual arc.

The mathematical model of the arc reignition is formulated as follows [17]

$$U_d = U_{da}\left\{1 + \frac{S_0/S_b - 1}{1 + \frac{4a*(S_0 - S_b)t_d}{r_b^2}}\right\}^{-1/\beta} \quad (15)$$

where U_{da} is the voltage gradient of air breakdown; S_0 denotes the function of heat flux at the initial arc temperature,with the value of 350.8J/(m · s) at 3000K; S_b represents the function of heat flux at ambient temperature; a* means the fitting constant, with the value of 3.78×10^{-6}m^3/J; β is the fitting constant, with the value of 1.778; r_b denotes the arc boundary radius; t_d is the time to reach the maximum value of AC. The ambient temperature will affect the heat flux S_b, and it can be expressed as follows[18]

$$S_b = 0.0002 \cdot T^{\beta} \tag{16}$$

where T is the temperature in K; the unit of S_b is J/(m·s). By substituting corresponding S_0, S_b and U_{da} (depended on temperature) in eq.(16), we can obtain the reignition voltage gradient for different values of ambient temperature. Take, for example, the temperatures are 0°C, 20°C and 40°C, the U_{da} values corresponding to be 5620V/cm, 5233 V/cm and 4900 V/cm, respectively. Therefore, one can obtain the voltage gradient predictions of reignition. As shown in Fig.4, when increasing the peak value of the arc current at the preceding half cycle of the AC, the minimum breakdown voltage of the residual arc decreases.

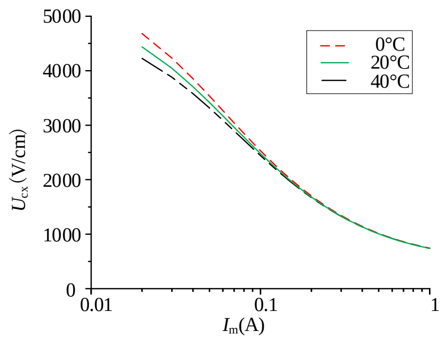

Fig. 4 Predictive value of temperature influence on reignition voltage gradient

3.2. Simulation of Dynamic Model for AC Pollution Flashover of Insulators

If the impedance Z_{eq} of the equivalent circuit decreases with the increase of the discharge length x, the arc develops, which is described as follows[19]

$$\frac{\mathrm{d}\left|Z_{eq}\right|^2}{\mathrm{d}x} \le 0 \tag{17}$$

According to Slama et al. [6], eq.(18) can be reformulated as follows

$$0 < k < 1 \tag{18}$$

If the condition of eq.(15) is satisfied, the arc will move forward at velocity V_d, and $V_d(t)$ is expressed as[13]

$$V_d(t) = \frac{I}{q} \tag{19}$$

where q is the average charge per unit length, which can be considered as a constant [13].

Fig. 5 shows the flow chart of the AC pollution flash dynamic model. When it comes to the arc development part, the arc will extend to (x_i=x_i-1+dx), with a speed V_d. Then judging whether the arc reignition conditions of this ambient temperature condition are satisfied. If not, it is considered that when the leakage current crosses zero, the arc will not extinguish but become weaker and shorter. Otherwise, the arc flashover judgment will be performed directly. And if the flashover condition is not satisfied, the program returns to the part of calculation model parameters, and the cycle is repeated until the arc length equals the creepage distance, i.e. the flashover occurs.

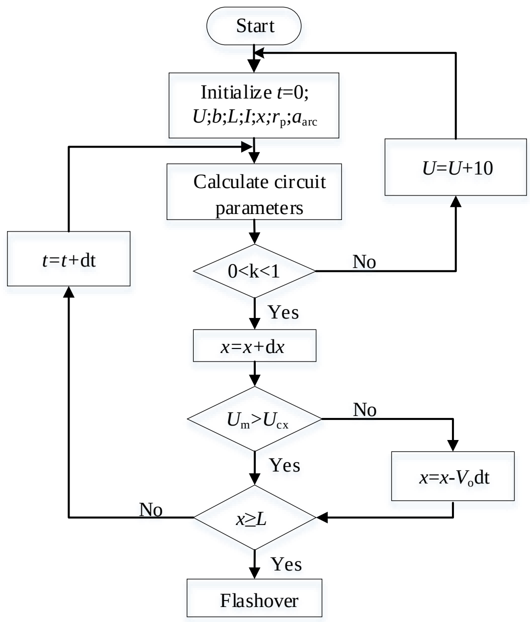

Fig. 5 Simulation flowchart of polluted flashover

4. Simulation results and comparative analysis

4.1. Analysis of simulation results of Dynamic Model for AC Pollution Flashover of Insulators

According to Fig.5, we performed the dynamic simulation experiment for a plate insulator model with length L = 10cm and width b = 4cm, and adopted the conditions consistent with the experiment in literature[20] as parameters for simulation calculations. The ambient temperature is set to 20°C, r_p=5 kΩ/cm. The initial arc length is 1/100 of the leakage distance (i.e. the starting arc length x_0 = 1/100L).

It takes the time t=0 as the starting point of arc development to calculate the initial value of each circuit parameter in Fig.2. The starting voltage U_0 = 100 V and the time step is set to 0.1 ms. At this point, the initial value of the circuit parameters is solved. Then it is judged according to the arc development criterion-eq.(18) whether the arc develops or not. Raising the applied voltage until the criterion is met. The applied voltage rises by 10 V each time, as shown in Fig.5. After the arc development criterion is satisfied, the arc advances at the speed calculated from eq.(19), resulting in an increase in arc length of the local arc. Equations (14) - (16) is used to calculate the reignition peak of the arc at this ambient temperature. According to the arc re-ignition criterion, it can be judged whether the arc can reignite after the current zero crosses, or not. If the criterion is met, the arc length remains the original length. Otherwise the arc will be shortened. Finally, whether the arc is flashover depends on whether the arc length reaches the leakage distance.

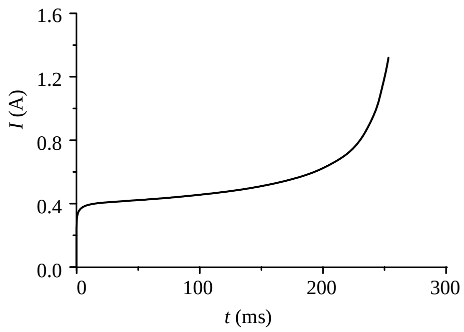

Fig. 6 Simulation result of AC dynamic flashover model

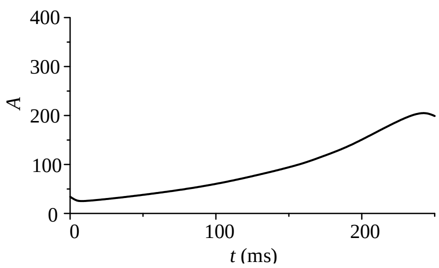

Fig. 7 Simulation result of Analytic parameters A

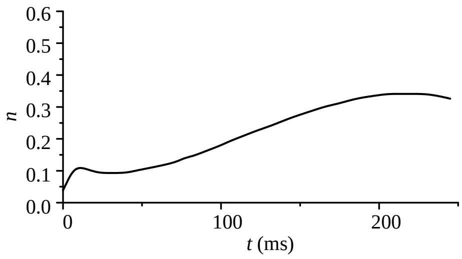

Fig. 8 Simulation result of Analytic parameters *n*

Fig. 6-8 show the results of a typical simulation experiment. Fig.6 presents the change of leakage current over time, which can be divided into three phases. The first phase is the beginning of discharge, and the current rapidly rises; The second phase is the arc elongation phase, in which the current slowly increases, and lasts longer; The third phase is the flashover phase, when the arc extends to the critical arc length, the leakage current starts to increase sharply from the critical value. Then flashover occurs when the arc length exceeds the creepage distance. The above process is in line with the actual arc development process.

Fig.7 and Fig.8 show the variation of the values of arc parameters *A* and *n* with time, respectively, indicating that *A* and *n* are not a fixed value in the arc development process, but are dynamic parameters affected by the leakage current and the environmental conditions.

4.2. Comparison of simulation results

4.2.1. Comparative Analysis of Static Parameters Model and Dynamic Parameter Model

In order to verify the effectiveness of this dynamic model, we compared the results of actual test[20] with the results of model calculation, and the predictor curves that treats the arc parameter as a constant. The value of the static arc parameters adopts the values in the literature [8, 11, 12], respectively.

It can be seen from Fig.9 that the critical flashover voltage rises as the linear resistance of the pollution layer increase. The dynamic model prediction values provided in this paper are closer to the experimental values, which confirm that this model is effective.

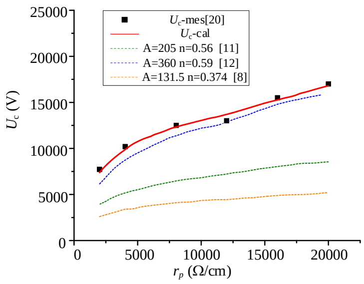

Fig. 9 Relationship between critical voltage and linear resistance of pollution layer

4.2.2. Comparison of Simulation Results and Experimental Values under Different Ambient Temperatures

In order to verify that this model can be used for flashover voltage prediction at different ambient temperatures, we adopted the conditions consistent with the experiment in literature [21] as parameters for simulation calculations, and compared the results of actual test [21] with the results of model calculation with temperatures between 0°C and 40°C. As is shown in Fig.10, the critical flashover voltage gradually decreases as the ambient temperature increases. The curve of predicted value is linked to the experimental data, confirming that the model can reflect the influence of ambient temperature on the AC flashover voltage, to a certain extent.

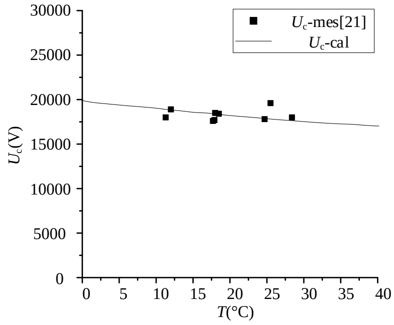

Fig. 10 Relationship between critical voltage and temperature

5. Conclusions

(1) Ambient temperature affects the conductivity of the unabridged part of the pollution layer and the reignition voltage of AC arc, and thus affects the flashover voltage. Therefore, it should be considered when building the flashover dynamic model of polluted insulators.

(2) Based on the dynamic value of arc temperature, it is effective to use arc dynamic parameters (A and n) in the flashover dynamic model under ac voltage.

(3) In this paper, a dynamic model of polluted insulator under ac voltage is proposed, in which the influence of the dynamic change of arc parameters, arc temperature and ambient temperature on the insulator flashover are consided. It provides a new idea for prediction of the critical voltage.

(4) The simulation results of this model still have some difference from the results of actual experiments, for the fact that the arc shape is considered as cylindrical plasma, and some other deficiencies of our proposed model, it still should be studied to further validate, refine, and improve the model in the future.

Acknowledgments

This work was financially supported by the National Natural Science Foundation of China (51567014), (51767014), the Scientific and Technological Research and Development Program of China Railways (2017J010-C).

R E F E R E N C E S

[1]. *Sundararajan R，Gorur R S*．Dynamic arc modeling of pollution flashover of insulators under dc voltage．IEEE Transactions on Electrical Insulation，1993，28(2) 209-218.

[2]. *Jabbari M, Volat C, Fofana I*. Application of a new dynamic numerical model to predict polluted insulator flashover voltage// IEEE Electrical Insulation Conference. IEEE, 2014:102-106.

[3]. *Yang Qing, Wang Rui, Sima Wenxia*, et al. Study on the Dynamic Model of Polluted Insulators Under AC Voltage Based on the Circuit Network. Proceedings of the CSEE, 2013(25):204-212.

[4]. *Cherney E A, Beausejour Y, Cheng T C, et al*. The AC clean-fog test for contaminated insulators. IEEE Power Engineering Review, 1983, PER-3(3):29-30.

[5]. *Mizuno Y, Kusada H, Naito K*. Effect of climatic conditions on contamination flashover voltage of insulators. IEEE Transactions on Dielectrics & Electrical Insulation, 2002, 4(3):286-289.

[6]. *Slama, M., Beroual, A., Hadi, H.*: ‘Analytical computation of discharge characteristic constants and critical parameters of flashover of polluted insulators’, IEEE Trans. Dielectr. Electr. Insul., 2010, 17, (6), pp. 1764–1771

[7]. *Obenaus, F.*:'Die Ubersclagspannung Verschmutzter Isolatoren'，ETZ，1935,56，pp. 369-370.

[8]. *Topalis F V, Gonos I F, Stathopulos I A*. Dielectric behaviour of polluted porcelain insulators. IEE Proceedings - Generation, Transmission and Distribution, 2002, 148(4):269-274 [06] GUAN

[9]. *Hampton B. F.*, “Flashover Mechanism of Polluted Insulation”, Proc. of IEE, Vol. 11, No. 5, pp. 985-990, 1964.

[10]. *Wilkins R.*, Flashover voltage of high-voltage insulators with uniform surface-pollution films. Proceedings of the Institution of Electrical Engineers, 2010, 116(3):457-465.

[11]. *Zhang J, Farzaneh M.* Propagation of AC and DC arcs on ice surfaces. IEEE Transactions on Dielectrics & Electrical Insulation, 2000, 7(2):269-276.

[12]. *Ghosh P S, Chatterjee N.,* Polluted insulator flashover model for ac voltage. IEEE Transactions on Dielectrics & Electrical Insulation, 1995, 2(1):128-136.

[13]. *Tavakoli C, Farzaneh M, Fofana I, et al,* Dynamics and modeling of AC arc on surface of ice. IEEE Transactions on Dielectrics & Electrical Insulation, 2007, 13(6):1278-1285.

[14]. *Wilkins R.,* Flashover voltage of high-voltage insulators with uniform surface-pollution films. Proceedings of the Institution of Electrical Engineers, 2010, 116(3):457-465.

[15]. *Hadjrioua F, Mahi D, Slama E A.*, Electro-thermal dynamic model using the analytical arc parameters for the prediction of the critical flashover condition on the HVDC polluted insulator. Iet Generation Transmission & Distribution, 2017, 11(2):427-436.

[16]. *Masaki Hayashi*, Temperature-Electrical Conductivity Relation of Water for Environmental Monitoring and Geophysical Data Inversion. Environmental monitoring and assessment, 2004, 96(1-3):119.

[17]. *Rizk F. A. M., Rezazada A. Q.*, Modeling of altitude effects on AC flashover of polluted high voltage insulators. IEEE Transactions on Power Delivery, 1997, 12(2):810-822.

[18]. *Masoud Farzaneh, William A. Chisholm*, Insulators for Icing and Polluted Environments. Beijing：China Machine Press.2014.

[19]. *Dhahbimegriche N., Krahenbuhl L., Beroual A.*, A new proposal model for flashover of polluted insulators. Journal of Physics D Applied Physics, 1997, 30(5):889-894.

[20]. *Zmajkovič P.,* Modélisation du contournement électrique et validation expérimentale du mécanisme proposé pour l'extension de la décharge. Toulouse, 1996.

[21]. *Mizuno Y., Kusada H., Naito K.*, Effect of climatic conditions on contamination flashover voltage of insulators. IEEE Transactions on Dielectrics & Electrical Insulation, 2002, 4(3):286-289.