Research on Improved Arc Model of Isolating Switch and VFTO Characteristics

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Abstract. The simulation of very Fast Transient overvoltage (VFTO) requires an accurate isolating switch arc model. Based on gas discharge theory, the trend of electron number in the gap is analyzed by particle continuity equation simulation. Based on this, the traditional time-domain arc resistance model is improved, and combined with the characteristics of time-domain arc resistance model, dynamic arc model and normal distribution, the improved arc model is established, which conforms to the physical law of arc discharge process of isolating switch. The simulation model of simulation experiment platform was established, and the simulation waveform obtained by the improved arc model, exponential resistance arc model and other arc models was compared with the experimental waveform to prove the accuracy of improved arc model.

Keywords. VFTO; improved arc model; simulation experiment; arc resistance.

1. Introduction
In fully enclosed SF6 gas insulated switchgear (GIS), arc reignition is very easy to occur repeatedly when the bus is separated or closed by isolation switch, resulting in very fast transient overvoltage (VFTO) of very high frequency. VFTO has the characteristics of steep wave front, high frequency and large amplitude. The electromagnetic interference caused by VFTO harms GIS, connected winding equipment and secondary equipment connected to the shell, and seriously affects the stability of power system and safe operation of related equipment [1-5]. Arc characteristic of isolating switch is an important factor affecting VFTO characteristic. In view of the characteristics of GIS isolating switch arc generation mechanism, influence factor, extinguishing and reburning mechanism, scholars at home and abroad have carried out relevant research by means of simulation test, mathematical modeling and simulation. At present, three traditional isolating switch arc models are generally used in VFTO simulation calculation, namely ideal switch model, constant resistance model and time-varying resistance model [1]. However, most researchers often use time-domain resistance model when establishing breakdown mathematical model. The arc time constant $\tau$ is usually 1ns or 2ns. The time of resistance drop to steady arc resistance is much longer than time of VFTO waveform rise. In this paper, the variation trend of electron number in gas discharge gap is analyzed from the microscopic point of view, the arc resistance model with approximate normal distribution is established, and the formation characteristics of arc resistance model are described in detail. The VFTO simulation waveform was generated by VFTO simulation platform, which proved the accuracy of improved model and fully described breakdown variation process more in line with the physical law of separation and closure.
2. Arc Model in Isolation Switch

In the simulation research of VFTO, there are many kinds of isolating switch arc models, including ideal switch model, constant resistance model, time-varying resistance model, segmented arc model, dynamic arc model and so on. Each arc model has its own characteristics and represents specific physical meanings.

The ideal switch model simply defines the switch state as open and off, which is easy to calculate and analyze. The fixed-value resistance model equates the arc as a fixed equivalent resistance, usually 2-5Ω. The arc model takes into account the damping effect of arc resistance on the circuit.

The time-varying resistance model considers the arc resistance change process and is widely used. The model is expressed by exponential function as

$$R(t) = r_0 + R_0 e^{-t/\tau}$$

In equation (1), $\tau = 1$ ns is time constant, $R_0 = 0.5$ Ω is the static arc resistance, $r_0 = 10^{12}$Ω is the resistance when the isolation switch is disconnected. The arc resistance variation process is considered in the arc model from insulation to breakdown.

The three-stage arc model is proposed based on time-varying resistance model, as shown in figure 1.

The model describes the arc initiation and breakdown process (AB), the stable arc burning process (BC) and arc extinguishing process (CD). Pre-breakdown process using time-varying resistance arc model. Arc burning process is represented by constant resistance. The arc quenching stage is represented by Mayr or Schwarz models.

The double exponential arc model describes the whole process of arc burning using a unified double exponential arc resistance formula, as shown below [6]:

$$R(t) = R_i \cdot e^{-t/\tau_1} + R_e e^{t/\tau_2}$$

where, $R_i$ is the resistance in the insulation state, $R_e$ is the steady-state equivalent resistance in the on-state. $\tau_1$ is the arc channel conduction time constant, $\tau_2$ is the arc channel insulation recovery time constant, the latter is much larger than the former. The approximate arc resistance curve is shown in figure 2. The dynamic arc model uses a hyperbolic arc resistance model, as shown below:

$$R_a = 2 + 2\zeta\left(\frac{t}{t_\delta} - 1\right) \quad 0 < t < t_\delta$$

![Figure 1. The curve of arc resistance variation.](image1)

Steady-state arc burning stage to choose a constant value, between 0.5-5.0Ω. The Mayr-Schwarz model is used for the arc extinguishing stage, as shown below

![Figure 2. Double exponential arc model.](image2)
\[ \frac{1}{g^{(1-\alpha)}} \frac{dg}{dt} = \frac{1}{\tau} \left( \frac{ui}{pg^\beta} - 1 \right) \]  

where, \( \tau \), \( p \), \( \alpha \) and \( \beta \) are constants.

Based on the experimental data, the breakdown process is studied to improve the widely used time-varying resistance model. In figure 3, a is the curve corresponding to the arc time constant of 0.5ns, 1ns, 1.5ns and 2ns respectively, which is simulated by using time-varying resistance model through MATLAB self-programming. The ordinate was logarithmically processed to obtain an obvious time inflection point, as shown in figure 3b. It can be seen from the obtained time point that the resistance drops to the stable arc burning stage for about 14ns at 0.5ns. When 1ns is used, the steep drop time is 26ns. When 1.5ns is used, the drop time is 40ns. When the value is 2ns, the steep drop time is about 54ns.

![Figure 3. Exponential time domain resistance arc model.](image)

It can be seen from figure 3 that the arc time constant does not represent the inflection point time when the arc resistance decays to the stable arc resistance.

3. Improved Arc Model of Isolation Switch

According to the streamer theory of uniform electric field self-sustaining discharge under high pressure, with the development of electron collapse, the number of electrons in electron collapse increases exponentially according to \( n = e^{ax} \), \( a \) represents the ionization coefficient, \( x \) represents the advance distance of electron collapse. Thus, the number of electrons in the avalanche head advancing towards the anode can be obtained, as shown in table 1 [7].

| \( x/cm \) |  0.4 |  0.5 |  0.6 |  0.7 |  0.8 |  0.9 |  1.0    |
|---|------|------|------|------|------|------|--------|
| \( n \) |  81  | 245  | 735  | 2208 | 6634 | 19930 | 59874  |

Divided into ten parts with a distance of 1cm, the number of electrons generated by the last distance accounted for 60% of the total number, and the number was \( N_1 = 39944 \). In the time domain, the number of electrons increases slowly and then quickly. Since the ionization coefficient \( a \) is constant, the number of electrons in electron collapse head is related to the distance \( x \), \( x_i = W/Eq = Ui/E \) can be obtained from the collision ionization condition \( qEx_i \geq W_i \), so the number of electron collapse reaching the anode is related to the electric field intensity. It can be considered that the electron collapse head melts into the positive plate after reaching the anode to form plasma and regenerates positive ion charge. The charge number and the electric field formed by the cathode should be equivalent to the voltage formed by the positive plate and the cathode plate. Therefore, when the streamer column is formed, the electron number...
of the whole streamer is considered to be 10 times of 39944. In addition, according to the streamer theory, positive and negative streamer will generate photons after electron avalanche develops to a certain extent, as shown in figure 4.

Since the speed of photon is $3 \times 10^8$ m/s, which is the limit speed of matter, the photoionization electron collapse formed by photoionization generated by photon leads to the faster speed of subsequent electron collapse until the streamer is formed and more electrons are generated. Reference 4 mentioned that the development speed of electronic collapse is $1.25 \times 10^7$ cm/s, and the development speed from the collapse head reaching the anode plate to the completion of streamer is $1 \times 10^8 - 2 \times 10^8$ cm/s [7], with a ratio of 1:8-1:16. Therefore, the time of electronic collapse is about 7/8 or 15/16 times of the process time from the gap breakdown to the formation of the streamer. The streamer takes only a fraction of the time to form. In reference 5, the cloud chamber photographic results of discharge process are mentioned. The same characteristic of discharge is that the velocity of discharge development increases very rapidly, which is about $10^8$ s. In an experiment with a discharge gap of 20cm, it was observed that the first 3cm streamer went 3us, and the last 17cm streamer only went 0.9us, that is, the final velocity of the streamer has increased to $10^5$ m/s. Based on the above analysis, it is considered that the breakdown process of the arc resistance model should be a decreasing trend of resistance first slow and then fast.

The SF6 gas discharge simulation model was established. The electrode of rod and plate was discharged with a gap of 0.5cm and a pressure of 0.1 mpa. The electron density distribution was obtained by simulation calculation, and the relationship of the number of electrons in the gap with time was obtained, as shown in figure 5. It can be seen that the increasing trend of electron number changes from slow to fast.

Based on this theoretical basis, this paper believes that the variation trend of gap breakdown arc model can be described as shown in figure 5, and its mathematical formula can be obtained according to the traditional arc mathematical model and the formula of normal distribution law. In probability and statistics theory, normal distribution is often used to describe many phenomena that occur in nature, industry and research fields. For example, the distribution of the velocity of gas molecules. The density function of normal distribution is [8-10]

$$f(x) = \frac{1}{\sqrt{2 \pi \sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad -\infty < x < \infty$$  \hspace{1cm} (5)

where, $\mu$ is the mean value and $\sigma^2$ is variance.

According to the curve characteristics of normal distribution, the GIS isolating switch arc model is modified as shown in the equation below:

$$Ra = 2 + Ri e^{-\frac{(l-w)}{\delta}} \ast (1-e^{-\sqrt{\frac{w}{\delta}}})$$  \hspace{1cm} (6)
where, $R_a$ is the time domain resistance. Steady-state arc burning resistance is $2\Omega$. $R_i$ is the resistance before clearance breakdown, which is $10^{12}\Omega$. $t$ is time. $\mu, \delta, n, k$ are adjusting waveform parameters. When $u = 0$, that is, the arc resistance decreases from $t = 0$. Parameters $\delta, n$ are judged and selected by self-programming threshold to obtain the desired waveform. $t_\delta$ arc delay time. That is, the intersection of the breakdown formation process and the steady-state arc. The waveform curve of the arc resistance model is adjusted using a regulatory factor $1 - e^{-0.5(t-t_\delta)}$. The regulatory factor is obtained by modifying the principle of hyperbolic arc resistance model, which determines the inflection point position of the breakdown process and steady-state arc burning. In the formula, constant $K$ is the value of the program after debugging of multiple waveform groups, and 10 is better, which can be used to make the improved arc resistance model meet the expected curve.

According to the obtained parameters, the improved arc resistance model curve is shown in figure 6. The inflection time of the resistance model from the insulated body to the steady-state arc burning stage is 1ns and 2ns respectively. Figure 7 shows the logarithmic change of the improved arc resistance model, and the inflection point time can be clearly seen.

4. Influence Analysis of Improved Arc Model on VFTO

In figure 8, the acquisition of VFTO simulation waveform is achieved by superimposing oscillation waveform on the basis of lightning wave. The resistive and capacitive voltage divider model is composed of R1, C1, R2 and C2, and the ratio of high pressure arm to low pressure arm is 1000:1. R3, C3, R4 and C4 constitute the weakly damped capacitive voltage divider simulation model.

Figure 8. The simulation circuit model of VFTO.

Figure 9 shows the equivalent results of different arc resistance models in the simulation experiment. With the ideal switch model as the reference, other arc models replace the ideal switch model in turn. Among them, the waveform of P4 point uses the ideal switching equivalent arc model. The P4-1 point waveform was obtained using the traditional time-domain resistance model. The P4-2 point waveform was obtained using an improved arc resistance model. The P4-3 point waveform uses a constant
resistance equivalent arc resistance model. As can be seen from figure 9, according to the simulation model built by the VFTO simulation experimental circuit and the characteristics of each arc model, the time from the insulation state to the conduction state of the arc resistance model determines the vibration amplitude generated by the steepening gap breakdown. The improved arc resistance model directly sets the time point to steady-state resistance, and its effect is similar to that of the ideal switch model. The time constant of the traditional time-domain resistance model is 2ns, and it is about 50ns when the steady-state arc resistance is reached. Its effect is similar to that of the resistance equivalent arc resistance model. In order to further prove the effectiveness of the simulation model, the VFTO diagram was obtained from the arc model modified by GIS under a certain working condition. Figure 10 shows the local comparison of VFTO curves of the arc model. Figure 11 shows the VFTO curves of improved arc model. Figure 12 shows the VFTO curves of traditional time domain resistance arc model.

![Figure 9](file22070310.pl4;x-var t)  v:1-2
![Figure 10](file22070310.pl4;x-var t)  v:1-2

**Figure 9.** Comparison of the arc model results.

**Figure 10.** Local comparison of VFTO curve of arc model.

![Figure 11](file22070310.pl4;x-var t)  v:1-2
![Figure 12](file22070310.pl4;x-var t)  v:1-2

**Figure 11.** The VFTO curves of improved arc model.

**Figure 12.** The VFTO curves of traditional time domain resistance arc model.

The VFTO of the improved arc resistance model is similar to that of the traditional arc resistance model. Since the model describes the arc breakdown formation process according to the breakdown theory, it is considered that the improved arc resistance model has a certain practical value [11-12], and can be further improved in academic research according to the ideas in this paper.

5. Conclusion
An improved arc model of isolating switch is proposed in this paper. The pre-breakdown process of exponential decay changes into the decay trend of first slow and then fast. Combined with the simulation model of VFTO simulation experiment platform, several arc models are simulated and analyzed, and the correctness of improved arc model is verified. The simulation results show that the VFTO waveform of improved arc resistance model is similar to that of other arc models. In this paper, according to the
stream theory, combined with the characteristics of traditional time-domain resistance arc model, dynamic arc resistance model and normal distribution, through the micro simulation analysis, VFTO simulation test and simulation, it can be found that improved arc model can better describe the breakdown process and physical law in switch operation.

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