Research of uneven arc burning of parallel necks of DC fuse

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Abstract. When breaking low current, DC fuse is prone to voltage drop. It is caused by uneven arc burning between parallel necks. The problem of uneven arc burning in parallel slows down the breaking speed of the fuse, and in severe cases causes the fuse to overheat and arc spray. To solve this problem, this paper establishes a mathematical model of fuse arc, a commutation model between parallel necks and a pre-arc time model of necks. Based on Matlab, the current of each branch is calculated as well as temperature of necks. Then this paper explains the cause of uneven parallel arcing and analyzes the influence of the machining error and current on the phenomenon. Finally this paper calculates the minimum current density that fuse can arc evenly in parallel under different machining errors, and the conclusion can be used to guide the design of DC fuse.

1. Introduction
In recent years, due to the application in new fields such as electric vehicles, photovoltaic power generation and rail transit, DC fuses have developed rapidly and have broad application prospects.

At present, the research on DC fuses mostly focuses on the pre-arc phenomenon and the ultimate breaking capacity. There are few studies on the breaking under low overload current. Xie Yunxiang and others conducted theoretical analysis and experimental verification for the problem that the arcing time of the high-voltage current-limiting fuse is too long under low overload current and the arcing phenomenon occurs at the tail of the fuse. Li Feng et al. conducted simulation and experimental analysis on the failure of breaking due to overheating and arc spraying when the DC fuse is breaking low overload current. Mao Qidong established a model for the uneven arcing phenomenon in series under low overload current, and calculated the uneven arcing phenomenon in series; the article proposed an improved idea of setting a stepped neck, which effectively eliminated the phenomenon of arc ablation to the end cover, and the safe breaking of the current is ensured.

However, the current research of fuses under low overload current is only the problem of uneven arcing between the series necks. There is no literature on the problem of uneven arcing between the parallel necks. The uneven arcing between the parallel melts will cause a sudden drop in arc voltage. In severe cases, the melt will ignite to the fuse end cover where the current density is large, resulting in overheating, arcing and other consequences.

This paper takes a certain 4000V/2000A DC fuse as an example and establishes a semi-empirical mathematical model of fuse arc and a commutation model between parallel necks, and uses Matlab to calculate the model and analyzes the influence of the machining error and current on the phenomenon.
2. Analysis of the uneven arcing of parallel necks

2.1. Uneven arcing phenomenon of parallel necks
Take a certain 4000V/2000A fuse as an example. The fuse is designed as two pieces of melts in parallel, each melt has 5 rows of fractures, and the distance between the two fractures is the pitch. According to the requirements, the fuse is verified by the breaking test of 20kA and 2500A. The arc voltage current waveform of the low overload current 2500A breaking test is shown in Figure 1. After the test, the fuse is disassembled and ablated. The fulgurites of fuse is shown in Figure 2.

![Fig. 1 Experimental waveform under 2.5kA](image)

![Fig. 2 Fulgurites of fuse after fault current interruption](image)

It can be seen from the figure 2 that the arc length between the two parallel melts is seriously uneven, and the ablation length of melt 1 is longer than the pitch, and the arc has been extended to two safe area that is reserved on the side. The arc length of the melt 2 is much shorter than that of the melt 1. It can be seen from the breaking waveform that the arc voltage is stepped down due to the uneven arc between the parallel necks, and the breaking time is greatly increased, which seriously affects the low-overload breaking capacity of the fuse.

2.2. Principle of the uneven arcing of parallel necks
At present, laser cutting is mostly used for fuse cutting, and machining errors are inevitable during cutting. According to multiple measurements, the process error is mostly ±0.02mm.

Due to the inevitable machining error, there are differences in the cross-sectional area of the necks on the same row of fuse. The smallest necks will be the first to fuse and generate an arc. With the instantaneous increase of arc voltage, the current will quickly commutate to other necks in the same row. If the larger neck is fused and arced before the current is completely commutated to other necks, the current will be commutated to the smallest neck again, and finally parallel current sharing and arcing will be realized; otherwise, the first one will extinguish because the current drops to zero, and then only the melt that starts arcing continues to arc to complete the breaking. When the arc voltage reaches the breakdown voltage of the fracture, the extinguished neck will be severely broken down. The neck that caused the extinguishment to start arcing again. The arc voltage step and sudden drop in the breaking characteristic waveform is caused by the heavy breakdown of the fracture. Since the arcing time of the neck of the rear arc is longer, the arc may be ablated to the fuse cover, causing overheating and arcing.
3. Mathematical model of parallel arcing

The uneven parallel arcing between melts greatly limits the low overload breaking capacity of the fuse. Therefore, it is necessary to establish a mathematical model of the melt parallel arcing.

3.1. Mathematical model of fuse arcing

This article first establishes the mathematical model of the arc combustion process of the melt containing quartz sand. The mathematical model of the melt arc process is divided into 4 parts, the melt ablation model, the quartz sand ablation model, the arc voltage model and the circuit model. The ablation model solves the expansion of the arc in the length direction by calculating the heat conduction inside the melt, and its control equation is shown in equations (1)-(2).

\[
\frac{\partial}{\partial t} \left( \rho \cdot H \right) = \nabla (\lambda \nabla T) + \frac{\partial \delta^3}{\partial t} \tag{1}
\]

\[
\frac{I^2}{S^3} \cdot \rho \cdot \Delta H_{\text{cool}} \cdot \rho \cdot \Delta H_{\text{cool}} \tag{2}
\]

In the circuit calculation, first use the arc shape obtained above to calculate the arc resistance, and obtain the total arc resistance by integrating the length of the entire arc. The arc resistance and loop current are used to obtain the arc voltage, and the total arc voltage is used calculate the circuit current change, and its control equation is shown in equations (3)-(4).

\[
U_{\text{arc}} = n \cdot (U_e + \int_0^1 \frac{1}{\gamma} \cdot S_L \cdot dL) \tag{3}
\]

\[
U_e = I \cdot R + I \frac{dI}{dt} + U_{\text{arc}} \tag{4}
\]

3.2. Mathematical model of current commutation of parallel necks

In order to study the commutation process between parallel necks, the equivalent circuit diagram in the breaking process is drawn as shown in the figure below:

![Fig. 3 The equivalent electric circuit diagrams of the switching processes](image)

When the current flows through the fuse, because the neck 1 is small, the neck 1 will arc first. Then the neck will generate a large step arc voltage at the moment, the current changes rapidly under the action of the arc voltage. When flowing to the neck 2, the speed of the commutation current changes depends on the equivalent inductance of the neck. The current in the neck 2 continues to increase, and the temperature of the neck 2 continues to rise. If the arc voltage and total current of the neck I have been calculated, the branch currents I_1 and I_2 can be solved:

\[
\begin{align*}
U_{\text{arc1}} &= I_1 R_1 + L_2 \frac{dI_2}{dt} \\
I &= I_1 + I_2
\end{align*} \tag{5}
\]

Since the commutation process is very fast, the current will rise rapidly in a short time, so the heat conduction between the melt and the quartz sand and the heat conduction on the melt are not considered in the calculation, the temperature of the neck can be obtained from I_2 of the neck 2. The calculation formula is as follows:
ItcT \rho \Delta \mathbf{\gamma} = \mathbf{I}^2 \Delta t / S^2 \cdot \gamma \quad (6)

4. Influencing factors of uneven arcing in parallel

The uneven parallel connection of DC fuses under low overload conditions will cause excessive current density at the uneven current, and the arc ablation length far exceeds expectations, and it is easy to cause ablation to the end cover to cause overheating and arc spraying. Therefore, it is of great significance to explore the factors that affect the uneven arcing in parallel.

4.1. The influence of machining error on uneven arcing

Using the above mathematical model to complete the Matlab self-programming simulation calculation of parallel arcing, the currents of the two branches and the temperature of the large and narrow neck during the commutation process are calculated, so as to judge whether the unevenness of parallel arcing will occur.

Different machining errors between necks are very important to the occurrence of uneven arcing. The effect of commutation process of different machining error is simulated and compared.

(a) The simulation result when the machining error is 0.005mm and 0.01mm

(b) The simulation result when the machining error is 0.02mm

Fig. 4 Simulation results of different mechanical errors

When the machining error between necks is 0.005mm, temperature of the large neck is 1078°C when the small neck starts arcing. Then arc voltage of the small neck rises to 340V, and the current quickly commutates to large narrow neck. After 30us, the big neck melts and starts arcing. The large neck can successfully fuse and start the arc before the current of the small narrow neck crosses zero. At this time, the current can be shared between the parallel necks, and subsequent arc extinguishment and breakdown will not occur. Similarly, when the machining error is 0.01, uneven parallel arcing will not occur.
When the machining error between necks is 0.02mm, the current of the small necks drops to zero after 200us commutation, while the temperature of the large necks is only 990°C. After that, there is only a large neck burning arc. When the arc voltage is greater than or equal to the breakdown voltage of the fracture, the small neck will break down.

4.2. The influence of current on uneven arcing
Uneven arcing in parallel is a problem that only occurs during low-overload breaking. When the low overload current is interrupted, the heat accumulation time is longer than the commutation time, so it is easy to appear that the small neck current will be zero when the large neck has not started arcing.

The simulation calculates the minimum current that can be connected in parallel for uniform arcing under different machining errors, and the results are shown in the following figure:

(a) The simulation result at 4000A and 3000A
(b) The simulation results at 2000A

Under a short-circuit current of 4000A, necks with a machining error of 0.1mm can be arced in parallel after a 100us commutation process, but the current of branch 2 has dropped below 10A, reaching a critical state. Therefore, when the current is 4000A, in order to ensure that the melts will arc at the same time in parallel, the maximum allowable machining error is 0.1mm.

Similarly, the simulation results show that at current of 3000A, the maximum allowable machining error is 0.04mm to ensure that the parallel necks are arcing at the same time. When the current is less than 2000A, the maximum allowable machining error is 0.02mm. The relationship between the machining error and the minimum current density is shown in Table 1.
Table 1. The relationship between relative machining error and minimum current density

| Relative machining error | Current density |
|-------------------------|-----------------|
| 7.14%                   | 3571A/mm²      |
| 2.85%                   | 2678A/mm²      |
| 1.42%                   | 1785A/mm²      |

5. Conclusions

This paper establishes the commutation model and fuse arcing model, and realizes the simulation calculation of the commutation process of the parallel necks through Matlab.

For a certain DC fuse rated at 4000V, this paper use the model to analyse the minimum current that the fuse can safely break under different machining errors. With a relative machining error of 7.14%, the minimum current for uniform arc is 4000A. Under the relative machining error of 2.85%, the minimum current is 3000A, and under the relative machining error of 1.42%, the minimum current is 2000A.

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