Simulation Analysis of Main and Arcing Contact Current Commutation Process in SF6 Circuit Breaker

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Abstract. In order to study the current variation characteristic and its influencing factors of the main and arcing contact during switching and opening process of high voltage circuit breaker, it is necessary to calculate the current commutation process. Firstly, the current formula in the commutation process was obtained based on the circuit model of current commutation. Secondly, based on the theoretical model of switching arc, the MODELS module and language were used to simulate the resistance variation characteristics of piecewise time-varying arc model. Finally, a simplified model of the SF6 circuit breaker arc quenching chamber was established in ATP-EMTP, and each calculation parameter was selected. The current commutation process was calculated by comparing the effect of main contact resistance and arcing contact resistance on current commutation time. It was found that the effect of the contact resistance on the current commutation time was consistent with the contact variation trend. But the effect of main contact resistance on current commutation time was small, while that of arcing contact was large.

1. Introduction

High voltage circuit breaker is the most important control and protection device in the power system [1-2], whose operating state is inseparable from the reliable operation of power system. The electric life of high voltage circuit breaker is one of the main factors affecting its service life. Once it is used beyond the life range, the failure of switching off current and restriking is likely to occur frequently. The research on the dynamic characteristics of the current transfer process between the main contact and arcing contact during the switching and opening process of circuit breaker contacts is helpful to determine the influencing factors and influencing mechanism of electrical life, which has important engineering guiding significance for the operation and maintenance of power system. Some scholars have conducted some related research on the current commutation process of the circuit breaker contacts. Walter Widmann pointed out that the electrode shape would have a significant impact on the commutation process. In order to ensure that the ablation of the contact by the arc root is as small as possible, the current commutation time should be as small as possible[3]. Prodriguez et.al have used experiments to prove that there is a great relationship between arcing commutation ability and the contact material loss. The interaction between the arc and the electrode would cause pollution through the arc to erode the surface of the contact, and the ability of the contact current conversion ability would be affected, thereby adversely affecting the performance of circuit breaker[4]. Kaveh Niayesh proposed that the current commutation process would increase the channel resistance through theoretical calculation and experimental comparison[5]. All the above studies are related to the current commutation process of the contact and have certain reference value, but none directly study the current commutation process between the parallel structure of the main contact and arcing contact of the high voltage circuit breaker.
In this paper, based on the characteristics of interrupting AC arc and current commutation process in the circuit breaker, an appropriate arcing calculation model was established. The simplified equivalent model of the SF6 circuit breaker arc quenching chamber was established in the ATP-EMTP simulation software to realize the calculation of the current commutation process of the 126kV circuit breaker. And the complete effect of contact resistance on current commutation time during the degradation of electrical life was analyzed.

2. Theoretical calculation model

2.1. Circuit model of contact current commutation

The current commutation is the process in which the current flows from the main contact to the arcing contact during the breaking process of the circuit breaker. During the process of commutation, the main contacts had been separated, but the arcing contacts were still in contact state, and there may be a transient arc between the main contacts. Since the main contact and arcing contact are in parallel connection, in order to study the current commutation process of circuit breaker contact, it can be simplified to the model shown in Figure 1.

![Figure 1. Schematic diagram of current commutation circuit model.](image)

In the figure above, the two current paths, n represents the main contact system, a represents the arcing contact system, both of which have resistance R and inductance L. There is a voltage $U_{LB,n}$ between the contact fractures, and the current $I_0$ is the total external inflow current, as well as the breaking current value of the circuit breaker. The current $I_n$ and $I_a$ are the currents flowing in the main and arcing contact systems. $U_{LB,n}$ refers to the arc voltage between the main contacts. With the separation of the main contacts, this voltage value can be considered as a function of time, which causes the commutation of electric current to the arcing contacts. $U_{LB,a}$ refers to the arc voltage between arcing contacts, but it can be considered zero during the process of commutation, because the arcing contacts are not separated and no arc is generated. In the early stage of the contact breaking process, it can be considered that the current basically flows through the main contact system. At this time, the current flowing through the main contact system can be considered as equal to the external current until all the current is converted to the arcing contact system. When the current commutation is completed, the current flowing through the arcing contact system can be considered as equal to the external current. According to the model in figure 1, the following equations can be listed:

$$I_0 = I_a + I_n \quad (1)$$

$$I_n R_n + L_n \frac{dI_n}{dt} + U_{LB,n} = I_a R_a + I_a \frac{dI_a}{dt} \quad (2)$$

$$U_{LB,n} = a + E \cdot v \cdot t \quad (3)$$

$$I_0(t) = \sqrt{2} I_{rms} \left[ \sin(\omega \cdot t + \phi) + I_{dc} \cdot e^{-t/\tau} \right] \quad (4)$$

Where $t$: time; $\omega$: angular velocity; $\phi$: the phase angle of the commutation process; $\tau$: the system attenuation constant; $a$: the anode and cathode voltage drop, which are usually determined only by the
contact material and the gas environment where the contact is located; $E$: the electric field intensity of plasma in SF6 gas; $\nu$: the contact separation speed; $\delta$: the asymmetry coefficient; $I_{dc}$: the effective value of external current.

Before the separation of the main contacts, although current flows through both the main and arcing contact circuits, the ratio of the current in the main contact circuit and the current in the arcing contact circuit is almost 100:1 [6]. It can be considered that $I_0 = I_n$. A prerequisite for an effective commutation process is that the arcing contacts remain closed during the separation of the main contacts, that is $U_{LB,a}$ is zero. Equations 1 to 4 can solve. The commutation current can be calculated from Equations 1 to 4, as shown in Equation 5:

$$I_{a,open}(t) = (-B - D - G) \cdot e^{-\frac{t_0 - t}{\tau}} + A \cdot \sin(\omega \cdot t) + B \cdot \cos(\omega \cdot t) + D \cdot e^{-\frac{t}{\tau}} + F \cdot t + G$$  (5)

The above equation describes the physical process of the current conversion process of circuit breaker. It also shows that the current between the main contacts will decrease from the same as the external current to zero, and the current between the arcing contacts will increase from zero to the same as the external current. This process time is the current conversion time.

2.2. Theoretical model of switching arc

The arc model is used as a black box model which treats the arc as a simple two-terminal component, ignoring its internal characteristics. By observing a large number of experimental data and conducting numerical statistics and analysis, the variation law of its external characteristics is obtained, and a mathematical equation describing its external characteristics is used to determine the transfer function. The black-box model only describes the relationship between the voltage $U(t)$ at both ends and the current $I(t)$ flowing through it, and the complex physical and chemical processes inside the arc generation process will not be taken into account.

The arcing process is divided into three phases: the pre-breakdown phase, the arc steady state phase and the arc-extinguishing phase. In the pre-breakdown phase of the arc, a simple exponential function time-varying resistance is used to simulate the change of arc path resistance, as in Equation 6:

$$R_a(t) = r_0 + R_0 e^{-\frac{t}{\tau}}$$  (6)

Where $r_0 = 0.5 \Omega$, simulation of arc static resistance; $R_0 = 10^{12} \Omega$, the resistance before the simulated arcing; $\tau = 1 \text{ns}$, the time constant of the resistance change of the arcing path. When the arc burns stably, the arcing path resistance is considered to be the static resistance $r_0$. In the arc-extinguishing phase, the influence of the arc gap recovery voltage is ignored, and an exponential rise function similar to that of arc burning is used to simulate the change of the arcing path resistance, as shown in Equation 7. $R_{a0}$ is the arc resistance when the arc current crosses zero.

$$R_a(t) = r_0 + R_{a0} e^{rac{t}{\tau}}$$  (7)

The characteristic curve derived from the theory of piecewise time-varying arc model is shown in Figure 2.
3. Simulation calculation of current commutation

3.1. Selection of arc model
Using the MODELS module and language of ATP-EMTP software, the control function of the dynamic arc model is realized based on the above theoretical basis. The calculation results are output by nonlinear resistance element \( R(TACS) \) Type91 to realize the construction of the arc model, as shown in Figure 3:

![Realization of dynamic arc model](image)

In the figure above, the Arcing Model component is the SUP module corresponding to the arc resistance change control system programmed by the MODELS language. Firstly, the initial value of the constants and the describing function of arc resistance during different stage are set. Then, the phase of arc process is determined by the comparison of time and the comparison of line current with critical value. At last, an appropriate description function is selected for output through a TACS resistance of access lines.

3.2. Simulation model of current commutation
According to the theory of circuit breaker contact current commutation, the main contact circuit and the arcing contact circuit have switches representing their contact or separation. When the switch is opened, an arc model will appear, and it can be described by the dynamic arc model established by Model and TACS. It should be noted that only the main contact resistance will generate an arc during the contact current commutation process. The arcing contact is still in contact state at this time, and it can be considered as closed, so the switch in the arcing contact circuit can be considered as always closed. There is no need to reflect it in the simulation calculation model. The simulation calculation model of current commutation established in ATP-EMTP is shown in Figure 4.
In the simulation model, a current source is used to output current, and the external input current remains stable during the breaking process of the circuit breaker. $L_0$ is the external circuit accessory inductance of the circuit breaker contact, which only depends on the gas environment, so it is set to a fixed value in this simulation[7]. $L_m$ is the main contact circuit inductance, usually very small, or negligible. In this simulation, it is selected as $3\, \text{nH}$ according to the empirical value of literature. $L_a$ is the inductance of arcing contact circuit, which is determined by the material inductance and the gas environment, with little change. Therefore, the empirical value of 200$nH$ is always taken in this simulation. $R_m$ and $R_a$ are the main contact circuit resistance and arcing contact circuit resistance. The test data in literature[8] is used. An arc model in series in the main contact circuit represents the arc generated by the process of current commutation. Since the current commutation time is mainly obtained through the relationship between the current in the contact circuits and the external current, a current pointer is in series in both the main and arcing contact circuits.

4. Analysis of commutation process parameters effect

4.1. Calculation of main contact resistance effect
The literature simulates the erosion test of the 126kV circuit breaker with its rated short circuit breaking current of 40kA. If only the influence of main contact resistance on its current commutation time is considered, the 126kV main contact resistance change is placed in the current commutation simulation model. The influence of the 126 kV main contact resistance changes on the current commutation time is obtained during the electrical life degradation process. In the simulation calculation, the arc contact resistance is always taken as its initial test value of $309.38\, \mu\Omega$.

By comparison, it can be found that in the three group circuit breaker electrical life degradation tests, the influence trend of the main contact resistance on the current commutation time is consistent with the main contact change trend. When the resistance of the main contact increases, the current commutation
time also increases, but the influence of the main contact resistance on the current conversion time is small.

4.2. Calculation of arcing contact resistance effect

If only the influence of arc contact resistance on its current commutation time is considered, the 126kV arcing contact resistance change is placed in the current commutation simulation model. The influence of arcing contact resistance changes on the current commutation time is obtained during the electrical life degradation process. In the simulation calculation, the main contact resistance is always taken as its initial test value of 71.64μΩ.

By comparison, it can be found that the current commutation time has a strong tracking effect on the arcing contact resistance trend, similar to the change trend of the arcing contact resistance, the arcing contact resistance gradually increasing. The current commutation time shows a trend of increase with contactor ablation deepening. There is a turning point in the data of the three groups. At the beginning of the electric life test, the current commutation time increasing degree is not big, but after a certain number times of the accumulative breaking currents, the current commutation time increases sharply, almost reaching 3~4 times of the initial value. During the entire process of electrical life degradation, only the arcing contact resistance change is considered, when the breaking current is large, the current commutation time is also large.

5. Conclusion

The current commutation process of SF6 circuit breaker was calculated with the model established in ATP-EMTP in this paper. The computational formula of current commutation time was obtained and the piecewise time-varying arc model was established with MODELS module. Then the influence of contact state degradation on current commutation process was simulated. Results showed that the current commutation time of SF6 circuit breaker increases with the increase of main and arcing contact resistances. The main contact resistance has little influence on the current commutation time, but the arcing contact resistance has a significant influence on the value.

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