Research on the wear and life of copper tungsten alloy contacts of high voltage SF$_6$ circuit breakers

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Abstract. Three phase short circuit and two phase short circuit grounding fault of power system have a significant influence on the electrical life of circuit breaker contact. In this paper, the mathematical model of each component is established by Power System Analysis Software Package (PSASP), and the simulation model is built to simulate the dynamic state of the circuit breaker after different short-circuit faults. The simulated result confirms that contact electrical wear quantity related to the type of short circuit fault and the position of short circuit point. The size of short circuit current will directly impact electrical wear quantity and electrical life of circuit breaker contact.

1. Introduction
In power system operation, high voltage circuit breaker is switching current device. Its electrical life is generally shorter than the overall life of high voltage circuit breakers. The electrical life of the high voltage circuit breaker is decided by the contact and the arc extinguishing chamber, and the maintenance and replacement are relatively easy. On the one hand, through the on-line monitoring of the electrical life of the high voltage circuit breaker, the service life of the high voltage circuit breaker can be extended when its performance decline in time to repair or replace. On the other hand, it can also avoid blind maintenance to extend the use of equipment. With the continuous development of condition based maintenance, wear of high voltage circuit breaker contact analysis is very necessary, the production and manufacture of high voltage circuit breaker also has certain reference[1-3].

2. Simulation model of high voltage circuit breaker based on PSASP

2.1. Power System Simulation Model
The network structure of power system simulation model is illustrated in Figure 1, including generator system (power system stability system (PSS), excitation regulation system, speed control system) and power network.
Figure 1. Power system simulation model.

2.2. Mathematical model and PSASP simulation model

\[ T_{d0} \frac{dE_s}{dt} = E_{sd} - [E_q + (x_d - x_q)I_d + (K_{d1} - 1)E_q] \]  
(1)

\[ T_{q0} \frac{dE_q}{dt} = -E_d + (x_d - x_q)I_q \]  
(2)

\[ T_j \frac{d\omega}{dt} = P_t \frac{1}{\omega} - (\psi_d I_q - \psi_q I_d) - D(\omega - \omega_0)2\pi f_0 \]  
(3)

\[ \frac{d\delta}{dt} = (\omega - 1)2\pi f_0 \]  
(4)

\( x_d \), generator d-axis synchronous reactance; \( x_{dq} \), generator d-axis transient reactance; \( K_{d1} \), saturation coefficient; \( D \), equivalent damping coefficient; \( x_q \), generator q-axis transient reactance; \( \psi_d \) and \( \psi_q \), stator winding flux; \( T_{d0} \), the open circuit time constant of generator rotor d-axis excitation winding stator; \( T_{q0} \), the open circuit time constant of generator rotor q-axis damper g winding stator; \( T_j \), generator rotor inertia time constant \( T_s = 2H \); \( I_d \), generator rotor d-axis winding current; \( I_q \), generator rotor q-axis winding current; \( E_{sd} \), excitation voltage; \( E_q \), transient potential saturation value.

2.3. Power system stability model (PSS)

Figure 2. Power system stability model (PSS).

\( K_{s1} \), rotating speed error amplification factor; \( K_{e1} \), electromagnetic power error amplification factor; \( K_{e2} \), voltage deviation amplification factor; \( T_e \), blocking link time constant; \( T_{e1} \), \( T_{e2} \), \( T_{e3} \), \( T_e \) phase shift link time constant; \( K \), change link coefficient of type; \( K=0 \), the straight link (inertial differential link); \( K=1 \), the phase shift link; PSS output, these amounts are shown in the Figure 2.
2.4. Excitation system model

\[ V_i \rightarrow \Sigma \rightarrow K_r \frac{1}{1+T_r s} \rightarrow 1+T_s s \rightarrow \frac{1}{K_s+1+T_s s} \rightarrow K_a \frac{1}{1+T_a s} \rightarrow E_{\omega_0} \rightarrow E \]

Figure 3. Power system stability model (PSS).

\( V_i \), machine terminal voltage; \( V_{o_i} \), the initial voltage of the machine; \( K_r \), the amplification factor of the measuring link; \( K_s \), the amplification factor of the amplifying link; \( K_a \), transformation link type parameter; \( T_r \), measurement link time constant; \( T_s \), amplification link time constant; \( T_a \), intermediate link time constant, these amounts are shown in the Figure 3.

2.5. Speed control system model

\[ \omega \rightarrow K_f \rightarrow \frac{1}{2} K_r \rightarrow 1+T_f s \rightarrow \frac{1}{1+T_x s} \rightarrow K_\delta \rightarrow 1-\omega \frac{1}{1+T_x s} \rightarrow P_1 \]

Figure 4. Speed control system model.

\( K_f \), measurement link amplification factor; \( K_r \), negative feedback amplification factor; \( K_\delta \), negative feedback amplification factor; \( \varepsilon \), governor dead zone; \( \alpha \), turbine over heat coefficient; \( T_x \), soft feedback time constant of turbine; \( T_f \), time constant of servo mechanism; \( T_\varepsilon \), the time constant of the steam volume; \( T_s \), water hammer effect time constant; \( T_\alpha \), turbine intermediate superheating time constant; \( \mu_0 \), guide vane (valve) initial opening; \( K_{ao} \), equivalent to the ratio of the generator's rated power to the system reference capacity in fact, \( K_{ao} = \frac{P_e}{S_a} \), \( P_e \), System reference capacity, \( S_a \), rated power of generator, these amounts are shown in the Figure 4.

3. Study on calculation method for electrical wear and electrical life of high voltage circuit breaker contact

3.1. Main calculation method for electric wear of circuit breaker contact

The main characteristic parameter of electric life of circuit breaker is electric wear, this paper discusses the circuit breaker electrical wear refers to the wear amount of circuit breaker contact, not including the wear of arc extinguishing chamber and arc extinguishing media. At present, the main methods to calculate the electrical life of circuit breaker contacts are:

3.1.1. The cumulative breaking current method or the cumulative arc energy method

\[ \frac{d\delta}{dt} = (\omega - 1)2\pi f_0 \]
\[ Q = \sum_{i}^{N} I_{ikd}^2 t_i \]  

(6)

$Q$, the total electrical wear of circuit breaker; $N$, rated breaking current of circuit breakers to allow the number of open and broken; $I_{ikd}$, single breaking current value of circuit breaker; $t_i$, single break time of circuit breaker.

This method is widely used in the early detection of circuit breaker, although it only needs to measure the current effective value, but its sensitivity is not high.

3.1.2. The method of weighted cumulative current

\[ Q = \sum_{i}^{N} (I_{ikd})^\alpha \quad (1 < \alpha < 2) \]  

(7)

$Q_s$, absolute total electrical wear of circuit breakers; $I_{ikd}$, single break current of circuit breaker considering the material and the arc extinguishing medium; $I_{bkd}$, single rated breaking current of circuit breaker considering the material and the arc extinguishing medium; $\alpha$, a constant, value between 1~2, generally take 2, which is related to the circuit breaker contact material.

This method is widely used, which considers the influence of the material of the circuit breaker, the arc extinguishing medium and other factors on the electrical wear of the circuit breaker contact. This method is relatively simple, but the disadvantage can only be found out of the electrical wear.

3.1.3. The arc time weighted evaluation method

\[ Q_s = N \times (I_{bkd})^\alpha \quad (1 < \alpha < 2) \]  

(8)

$Q_s$, absolute total electrical wear of circuit breakers; $I_{bkd}$, single rated breaking current of circuit breaker considering the material and the arc extinguishing medium; $\alpha$, a constant, value between 1~2, generally take 2, which is related to the circuit breaker contact material.

This method can accurately judge the electrical life of circuit breakers, mainly due to respectively cumulative metering the three-phase contact electrical wear condition and the arc burning time is considered. Category was used to calculate the single disconnect current wear amount. But in the course of using, the need to install the device to measure the arc time is cumbersome.

3.1.4. Relative electrical wear and relative electrical life of the contacts

Considering the circuit breaker in the actual operation process, when the breaking current value difference is large, the difference of AC and DC components of the breaking current is also great and the extent of burning contact is different. But even if the same size of the current, the contact erosion degree is not the same due to the randomness of arc quenching process. Using the method of cumulative breaking current to calculate the amount of contact burning is not careful. In determining the electrical life of the circuit breaker, the cumulative current weighted method and the weighted method of time weighted all considered that electrical wear is related not only to the arc energy, also with the contact points off speed and arc quenching medium factors. This improved than before. But from the point of view of engineering practice and accuracy of judgment, it is feasible to calculate the relative electrical wear and relative electrical life of the contact.
3.2. Method for calibrating electrical life of circuit breaker contact

Contact by repeatedly opening and closing, the contact surface will gradually occur deformation, welding, surface potholes and other phenomenon, this phenomenon called the abrasion of the contact. The wear of the contact is mainly electrical wear, the core of which is the metal volatilization of contact material, transfer, chemical corrosion and the net loss of contact material. The energy of arc breaking current and arcing time mainly determines the wear contact, Fusing or pneumatolytic contact surfaces will cause the loss of contact by the fluid medium washing or spattering. In the course of each opening and closing of breaker, arc combustion can not be the same, but from a statistical point of view, it still follows a certain law. Considering the actual operation of the circuit breaker, the average time of the circuit breaker tends to be stable when the number of open and close circuit breakers is more frequent, from this point of view, the breaking current can be used as a reference to determine the cumulative effect of circuit breaker, and the randomness of arcing time is not considered.

The definition of electrical wear of rated short circuit breaking current is \( M_a \), the allowable number of breaks is \( N_a \), from the cumulative effect and statistical analysis, it can be concluded that the total amount of the circuit breaker wear is \( M_a N_a \). Setting the total wear of a new breaker contact is 100\%, and its relative electrical life is 100\%, the relative wear of the corresponding single rated short circuit breaking current is \( 1/N_a \), it will be defined as \( Q_a \). According to the \( N - I_c \) curve of different type circuit breakers, the allowable breaking times \( N \) corresponding all the different size of the breaking current value \( I_c \) can be calculated. The absolute amount of electrical wear about a single break is \( M \), the relative wear is \( 1/N \), which is defined as \( Q \).

Based on the above definition, the relative wear amount of circuit breaker contact in one break:

\[
Q_a = \frac{1}{N_a} \quad (10)
\]

\[
Q = \frac{1}{N} \quad (11)
\]

Since the total amount of absolute electric contact wear is a constant value, the formula as following:

\[
Q_a N_a = QN 
\]

\[
MN = M_a N_a \quad (13)
\]

\[
Q/Q_a = N_a / N = M / M_a \quad (14)
\]

\[
Q = Q_a (M / M_a) = M / M_a N_a \quad (15)
\]

Therefore, the relative electrical life of the circuit breaker is:

\[
L = L_N - \sum Q 
\]

(16)

In the above formula, the \( L_N \) is defined as the starting value of the relative electrical life of the circuit breaker contact, which is a number of less than or equal to 1, and the operating conditions of the circuit breaker determine its value. Just after the overhaul, replacement or newly installed circuit breaker, \( L_N \) can take 1.

3.3. Calculation method of residual electrical life of SF\(_6\) circuit breaker

Known a SF\(_6\) circuit breaker allows the number of consecutive break current \( I_{sn} \) is \( N \), then contact burning amount corresponding to a single break is \( 1/N \). In any breaking current \( I_s < 0.35I_{sn} \), are discussed in this paper from the front, with a break burning \( I_{sn} \) the equivalent \( I_s \) breaking times for \( N_{sl} \).

\[
N_{sl} = 1.83 \left( 0.35 \times \frac{I_{sn}}{I_s}\right)^3 \times \left( 0.5 \times \frac{I_{sn}}{I_s}\right)^{-1.7} = 5.95 \left( 0.35 \times \frac{I_{sn}}{I_s}\right)^3 \quad (17)
\]

Corresponding to an breaking \( I_s \), the contact burning amount should be:
The contact burning amount should be:

\[ Q_{s1} = \frac{1}{N_{s1}} \times \frac{1}{N} \times (0.35I_{sn}/I_s)^{\alpha} \times \frac{1}{N} \]  \hspace{1cm} (18)

Corresponding to any breaking \( I_s \geq 0.35I_{sn} \), the contact burning amount should be:

\[ Q_{s2} = \frac{1}{N_{s2}} \times \frac{1}{N} \times (0.5I_{sn}/I_s)^{\beta} \times \frac{1}{N} \]  \hspace{1cm} (19)

Make new circuit breaker relative electrical life is 1, running after a period of time the cumulative relative loss is \( \sum Q_s \), relative surplus electrical life:

\[ L = L_N - \sum Q_{si} \]  \hspace{1cm} (20)

In the above formula, \( L_N \) is the initial value of the relative electrical life of the circuit breaker, and the average value is 1. \( \sum Q_s \) is the contact wear was calculated by the former. \( L > 0 \), can consider the circuit breaker status is normal, \( L \leq 0 \) cannot continue to run, need maintenance.

4. Simulation calculation analysis of SF\(_6\) circuit breaker contact relative wear amount

Simulation model selection of high voltage SF\(_6\) circuit breaker types for LW-252/4000-40, rated voltage of 220kV, 4000A of rated current, rated short-circuit breaking current 40kA, rated short circuit currents of 100kA, rated breaking number 20, inherent closing time 100ms, split time 33ms. Take the parameters \( \alpha = 3 \), \( \beta = 1.7 \), and when \( 0.15I_{sn} \leq I_s < 0.35I_{sn} \) there is no wear of \( Q_m \).

\[ Q_m = \frac{1}{5.95N(0.35I_{sn}/I_s)^{\alpha}} \]  \hspace{1cm} (21)

When: \( 0.15I_{sn} \leq I_s < 0.35I_{sn} \)

\[ Q_m = \frac{1}{3.25N(0.5I_{sn}/I_s)^{\beta}} \]  \hspace{1cm} (22)

When: \( I_s \geq 0.35I_{sn} \)

In the simulation of different short circuit (three-phase short-circuit and two-phase short circuit) fault, by changing the length of the line at both ends of the short circuit point to change the location of the fault point. Short circuit current values under different fault types are shown in Figure 5 and Figure 6.

![Figure 5. Fault current value of different fault point in three phase short circuit fault](image)

![Figure 6. Fault current value of different fault point in two phase short circuit fault](image)
Comparison of relative electric wear and breaking frequency of circuit breaker under different fault conditions is shown in Table 1.

**Table 1.** Comparison of relative electric wear and breaking times of circuit breaker under different fault condition.

| Fault type                  | Fault point distance DL(%) | Fault current $I_{sn}$ (kA) | $I_{sn}/I_s$ (%) | The relative amount of wear $Q_{sw}$ (%) | Breaking frequency N |
|-----------------------------|----------------------------|------------------------------|-----------------|----------------------------------------|---------------------|
| Three phase short circuit fault | 0%                         | 40                           | 100%            | 0.05                                   | 20                  |
|                              | 5%                         | 19.8                         | 49.5%           | 0.015123                               | 66                  |
|                              | 10%                        | 13.1                         | 32.75%          | 0.006885                               | 145                 |
|                              | 15%                        | 9.8                          | 24.5%           | 0.002882                               | 347                 |
|                              | 20%                        | 7.8                          | 19.5%           | 0.001453                               | 688                 |
|                              | 25%                        | 6.5                          | 16.25%          | 0.000841                               | 1189                |
|                              | ≥30%                       | ≤5.6kA                       | ≤14%            | /                                      | No wear             |
| Two phase short circuit fault | 0%                         | 12.6                         | 31.5%           | 0.006126                               | 163                 |
|                              | 5%                         | 7.6                          | 19%             | 0.001344                               | 744                 |
|                              | ≥10%                       | ≤5.5                         | ≤13.75%         | /                                      | No wear             |

5. Conclusion

The first paragraph after a heading is not indented (Bodytext style). 1) Contact wear quantity was related with the short circuit type and the position of the short circuit point, and the size of short circuit current directly affect the wear amount of contact.

Relative wear volume becomes larger when the current becomes larger, and at the same point the three phase short circuit fault is larger than that of two phase short circuit fault, thus the relative wear increases. Due to the non periodic component of short-circuit current, the total effective value of the short circuit current will increase, and the arc energy will be more than no the non periodic components. According to the relation between energy and burning, DC component will also affect the degree of contact wear, so in the actual calculation breaking times should be left a certain margin.

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