Study on Closing Spring Fatigue Characteristics of High Voltage Circuit Breaker

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Abstract. One of the most causing closing fault of high voltage circuit breaker is closing spring failure. In order to avoid such closing fault, this paper analyzed the relationship between energy of closing spring and its load, as well as the experiment carried out to get the minimum energy when closing. The time-varying static stress relaxation curve of closing spring force was obtained by analogy the real working condition of high voltage circuit breaker which closing spring is compressed for a long time, the operation time-varying dynamic stress relaxation curve of closing spring force was also obtained by carrying mechanical endurance test. In the end, established the model of closing spring storage life and fatigue life, closing spring life prediction and fault early warning of high voltage circuit breaker was then realized.

1. Introduction
High voltage circuit breaker is one of the most important control and protection equipment in the power system. It can open, close and carry the normal current of the running line, and also carry, close and open the specified abnormal current within the specified time[1]. As one of the important equipment of power system, its reliability directly affects the safe operation of the whole power grid[2-4]. A large number of field cases show that most of the faults of high-voltage circuit breakers are caused by internal mechanical faults, and most of them are caused by the reasons of operating mechanism, such as refusing to open or close. The closing spring is the only energy source of the high-voltage circuit breaker, which is an important element to ensure the normal operation of the high-voltage circuit breaker. In recent years, it is common to report that the high-voltage circuit breaker cannot work normally due to the spring failure: the breaking of the closing spring causes the failure of the high-voltage circuit breaker to act[5-6], the fatigue of the closing spring causes the slow closing speed of the high-voltage circuit breaker[7], the insufficient energy released by the closing spring causes the failure of opening and closing.

As one of the core components of the high-voltage circuit breaker, the closing spring produces stress relaxation phenomenon[8-9] due to material fatigue and creep during long-term operation, especially the spring fracture, which reduces the energy storage of the spring, resulting in the decrease of opening and closing speed of the high-voltage circuit breaker or even the failure of opening and closing. This directly reduces the arc extinguishing ability of the high-voltage circuit breaker. In serious cases, the explosion of the arc chamber occurs, which seriously threatens the stable operation of the power grid.

Therefore, this paper first analyzes the energy distribution mechanism of the closing spring of the high-voltage circuit breaker. On this basis, the minimum energy required for the normal closing of the high-voltage circuit breaker is obtained through the test, which provides a reliable basis for the on-line monitoring and fault warning of the closing spring. Then, the static stress relaxation curve and
dynamic stress relaxation curve of the closing spring are obtained by simulating the two operating conditions of the actual operation of the high-voltage circuit breaker, i.e. the long-term non action operating condition and the frequent action operating condition. Finally, by establishing the storage life model and fatigue life model of the closing spring of the high-voltage circuit breaker, the life prediction and fault warning of the closing spring of the high-voltage circuit breaker can be realized.

2. Energy Distribution Mechanism Of Closing Spring Of High Voltage Circuit Breaker

When the high-voltage circuit breaker completes the opening and closing function, the power provided by the operating mechanism must be greater than the resistance to complete the action, and the work done by the power must be greater than the work done by the resistance, and the load characteristics and dynamic characteristics shall match as much as possible.

The closing process is divided into two stages before and after the closing. Before the collision between the moving contact and the fixed contact, the operating mechanism mainly overcomes the opening spring force \( F_e \) and the friction resistance \( F_f \) to do work, and there is energy loss before and after the collision between the energy storage lever and the driving lever; after the collision between the moving contact and the fixed contact, the operating mechanism mainly overcomes the contact resistance \( F_z \), the opening spring force \( F_e \), the contact spring force \( F_t \) and the friction resistance \( F_f \), the electric repulsion force \( F_d \) generated by the inrush current between the contacts when the switch is closed does work. There is energy loss before and after the collision of moving and fixed contacts. When closing, the closing spring force is the power.

Before contact collision, closing composite load force:

\[
F_i = F_e + F_f
\]  

After contact collision, the resultant closing load force is:

\[
F'_i = F_e + F_f + F_t + F_z + F_d
\]  

When opening, in the contact stroke stage of opening, both the opening spring force and the contact spring force are the power. As the opening time goes on, the contact spring has no effect on the opening movement, and the moving contact only moves under the force of the opening spring. The load combination force during opening includes the self closing force \( F_p \) of vacuum arc extinguishing chamber, friction force of parts and components \( F_f \), buffer force \( F_h \) provided by buffer, electric power \( F_d \), etc. the load combination force of opening can be obtained as follows:

\[
F_z = F_p + F_f + F_h + F_d
\]  

In the process of opening and closing, there is electric power, which is composed of two parts: one is Lorentz force \( F_l \) generated by current under the action of magnetic field; the other is Holm force \( F_m \) generated by current line contraction at the contact. When opening, there is self closing force. The so-called self closing force is a force that makes the moving contact close to the static contact in the inner cavity under the action of atmospheric pressure without external force. Its size depends on the port diameter of the bellows.

In the process of high-voltage circuit breaker movement, the spring force of closing spring, opening spring and contact spring affects the movement characteristics of high-voltage circuit breaker. Generally, the spring force can be calculated as follows:

\[
F_s = F_0 - C \frac{dl}{dt} + k(l_0 - l)
\]  

In formula: \( F_0 \) is the preliminary force of spring, \( l \) is the length after deformation of both ends of spring, \( \frac{dl}{dt} \) is the relative speed of both ends of spring, \( C \) is the damping coefficient of spring, \( k \) is the stiffness coefficient of spring, and \( l_0 \) is the length after preliminary applied force of both ends of
spring.

The energy source of the spring operating mechanism is the electric energy of the energy storage electric device, which is mainly transformed into the mechanical energy of the moving contact through the spring and the driving mechanism. When closing, the closing spring transfers the stored energy to the opening spring and contact spring, i.e. one part is used for the opening spring and the other part is used for closing. This part of energy used for closing passes through the contact spring in the process of transmission. The contact spring absorbs part of the energy, which is used to maintain the contact pressure, and transforms the other part into the kinetic energy of the moving contact to make the moving contact work, namely:

\[ W_{hc} = E_p + W_{ct} + E_f \]  \( (5) \)

\[ W_{ct} = E_{dc} + E_p \]  \( (6) \)

In formula: \( W_{hc} \) is the output power of the closing spring, \( E_p \) is the energy stored by the opening spring, \( E_f \) is the energy loss of the transmission mechanism when closing, \( W_{ct} \) is the work done by the contact spring, \( E_{dc} \) is the function of the moving contact before collision, and \( E_p \) is the energy stored by the contact spring to maintain the contact pressure.

The output power \( W_{hc} \) of the closing energy storage spring of the operating mechanism is related to the spring stiffness coefficient \( k \) and the spring deformation. Without considering the spring damping, there are:

\[ W_{hc} = \frac{1}{2} k (\Delta l^2 - \Delta l_0^2) \]  \( (7) \)

In formula: \( \Delta l \) is the deformation of the closing spring during energy storage, and \( \Delta l_0 \) is the deformation of the spring after closing.

When closing, the output power of three-phase contact spring is as follows:

\[ W_{ct} = 3 \int_{0}^{\Delta x} (F_0 - k \Delta x) \Delta x = 3 (F_0 \Delta x - \frac{1}{2} k \Delta x^2) \]  \( (8) \)

In formula: \( k \) is the spring stiffness coefficient, \( \Delta x \) is the deformation of the contact spring, \( F_0 \) is the pre force provided by the operating mechanism to each phase of the contact spring, which is the preliminary force of the spring, and the spring damping is not considered here.

In the closing process, it is assumed that the real-time speed of the moving contact is \( v_{dc} \), and the normalized mass of the moving system including the complex multi bar mechanism and the insulated pull rod is \( m_d \) before the collision of the moving contact and the fixed contact. According to the law of conservation of energy and the theorem of kinetic energy, there are:

\[ W_{hc} - E_p - E_{dc} = E_{dc} = \frac{1}{2} m_d v_{dc}^2 \]  \( (9) \)

Before the collision, \( v_{dc} \) increases with time and reaches the maximum at the moment before the collision. Before and after the collision between the moving contact and the fixed contact, they can ensure a certain closing pressure under the action of the contact spring pressure. Finally, the real-time speed of the moving contact \( v_{dc} = 0 \), that is, the kinetic energy of the moving contact is finally exhausted under the action of the spring damping, and converted into heat energy and other forms of energy.

The above is the energy distribution principle of the closing spring when the high-voltage circuit breaker is closed.
3. Dynamic Stress Relaxation Test Of Closing Spring

3.1. High-voltage Circuit Breaker for Test
In order to reflect the changing law of closing spring force in the whole life cycle of the high-voltage circuit breaker from the operation, a new factory 12kV high-voltage circuit breaker was used for the test. Meanwhile, the high-voltage circuit breaker was tested and controlled by the combination of the running in control system and the signal acquisition system.

3.2. Test Results and Discussion
According to the test data, draw the dynamic stress relaxation test curve of closing spring, as shown in figure1.

It can be seen from figure1 that the stress of closing spring changes little at first. With the increase of action times of high-voltage circuit breaker (about 5000 times later), the force of closing spring begins to decrease.

![Curve of dynamic stress relaxation for closing spring](image)

3.3. Fatigue Life Prediction of Closing Spring
In order to fit the dynamic stress relaxation test data with primary function, secondary function and tertiary function respectively, as shown in figure1, it can be seen from the fitting results that the fitting effect of tertiary function is good, so it can be approximately considered that the relationship between the closing spring stress and the action times of high-voltage circuit breaker conforms to the tertiary function distribution:

\[
F = 1.2 \times 10^{-11}n^3 - 3.4 \times 10^{-7}n^2 + 4.5 \times 10^{-4}n + 3800 \tag{10}
\]

In formula: \( F \) is the stress value, \( n \) is the action times of high-voltage circuit breaker, and equation (10) is the fatigue life equation of closing spring.

3.4. Determination of Minimum Energy Required for Closing
During the test, adjust the three-phase contact pressure to make the high-voltage circuit breaker just close. Record the three-phase contact pressure, corresponding over travel and closing spring force at this time, as shown in Table 1.
Table 1. Three-phase contact pressure, overpass, closing-spring force

| Operation times | Phase A contact pressure | Phase A over travel | Phase B contact pressure | Phase B over travel | Phase C contact pressure | Phase C over travel | Working position Pressure | Working position pressure |
|-----------------|--------------------------|--------------------|--------------------------|--------------------|--------------------------|--------------------|---------------------------|---------------------------|
| 0               | 3786                     | 4.84               | 3349                     | 4.81               | 3283                     | 4.33               | 2498                      | 3764                      |
| 1000            | 3796                     | 4.85               | 3332                     | 4.79               | 3292                     | 4.34               | 2495                      | 3762                      |
| 2000            | 3789                     | 4.85               | 3346                     | 4.81               | 3288                     | 4.34               | 2494                      | 3762                      |
| 3000            | 3787                     | 4.84               | 3333                     | 4.79               | 3291                     | 4.34               | 2492                      | 3764                      |
| 4000            | 3786                     | 4.84               | 3331                     | 4.79               | 3285                     | 4.33               | 2489                      | 3760                      |
| 5000            | 3781                     | 4.84               | 3307                     | 4.76               | 3286                     | 4.33               | 2485                      | 3759                      |
| 6000            | 3782                     | 4.84               | 3301                     | 4.76               | 3280                     | 4.33               | 2482                      | 3757                      |
| 7000            | 3773                     | 4.83               | 3279                     | 4.73               | 3282                     | 4.33               | 2478                      | 3753                      |
| 8000            | 3776                     | 4.83               | 3262                     | 4.71               | 3285                     | 4.33               | 2479                      | 3748                      |
| 9000            | 3770                     | 4.83               | 3259                     | 4.71               | 3290                     | 4.34               | 2475                      | 3749                      |
| 10000           | 3755                     | 4.81               | 3247                     | 4.70               | 3299                     | 4.35               | 2470                      | 3743                      |
| 11000           | 3752                     | 4.81               | 3234                     | 4.68               | 3443                     | 4.49               | 2465                      | 3744                      |
| 12000           | 3740                     | 4.80               | 3221                     | 4.67               | 3470                     | 4.52               | 2460                      | 3744                      |
| 13000           | 3728                     | 4.78               | 3199                     | 4.64               | 3506                     | 4.56               | 2457                      | 3739                      |
| 14000           | 3715                     | 4.77               | 3170                     | 4.61               | 3551                     | 4.60               | 2455                      | 3739                      |
| 15000           | 3680                     | 4.73               | 3162                     | 4.60               | 3594                     | 4.65               | 2451                      | 3737                      |
| 16000           | 3668                     | 4.72               | 3153                     | 4.59               | 3616                     | 4.67               | 2447                      | 3730                      |
| 17000           | 3652                     | 4.71               | 3147                     | 4.59               | 3639                     | 4.69               | 2441                      | 3727                      |
| 18000           | 3644                     | 4.70               | 3144                     | 4.58               | 3650                     | 4.70               | 2431                      | 3724                      |

From the above test data and the law of conservation of energy, we can get:

Total energy released by closing spring = energy consumed by compression three-phase contact spring + energy consumed by tension opening spring + gravity work of moving part + energy consumed by friction and collision.

Through calculation, the relationship between the energy consumed by friction and collision of high-voltage circuit breaker and the action times of high-voltage circuit breaker is shown in figure 2.

Figure 2. Relationship between energy of friction and number of action

From the above test results, it can be calculated that the minimum energy required for high-voltage circuit breaker to close is: energy consumed by compression of three-phase contact spring + energy consumed by tension opening spring + gravity work of moving part + energy consumed by friction and collision ≈ 96.95 J.
Among them: the energy consumed by the compression contact spring
\[ E = 3 \times \left[ \frac{1}{2} \times (2500N + 3700N) \times (3.5mm \times 10 - 3) \right] = 32.55J; \]

The energy consumption of the tension opening spring (design value) is 20.8J;

Because the mass and displacement of the moving parts are small, the energy consumed by the gravity work of the moving parts can be ignored;

The energy consumed by friction and collision is taken as the average value within the life cycle of high-voltage circuit breaker, which is 43.6J.

The force of closing spring under the minimum energy required for closing of high-voltage circuit breaker is the minimum force allowed. When the force of closing spring \( f = 2656.2N \) (energy of closing spring 96.95J, compression distance 36.5mm) is substituted into the fatigue life equation of closing spring, the fatigue life of closing spring under the minimum limit closing spring force is 56958 times.

To sum up, with the increase of operation time and operation times of high-voltage circuit breaker, the energy of closing spring decreases continuously due to the phenomenon of stress relaxation. When the energy of closing spring decreases to the minimum energy required for closing, the high-voltage circuit breaker cannot be closed normally. At this time, an alarm shall be given to take effective measures Standard measures (such as replacement of closing spring) shall be taken to avoid closing fault of high-voltage circuit breaker.

4. Static Stress Relaxation Test Of Closing Spring

4.1. Closing Spring Parameters

The closing spring material is VDSiCr spring steel, which is composed of outer spring and inner spring. See Table 2 for relevant spring parameters.

| Item                  | External spring | Inner spring |
|-----------------------|-----------------|--------------|
| External diameter D/mm| 50.1            | 36.5         |
| Line diameter d/mm    | 6.3             | 5.5          |
| Free length l/mm      | 230             | 177          |
| Pre-pressure P1/N     | 1431.78         | 1016.26      |
| Working position pressure P1/N | 1954.12 | 1734.60 |

The pressure sensor manufactured by Ningbo Keli Sensor Technology Co., Ltd. is selected as the measuring device, and the parameters of the pressure sensor are shown in Table 3. In order to realize the continuous band temperature measurement of the stress relaxation of the closing spring at a certain temperature, the schematic diagram of the designed test device is shown in figure 3.
Table 3. Parameters of pressure sensor

| Parameter                        | Unit | Value         |
|----------------------------------|------|---------------|
| Rated load                       | kN   | 6             |
| Sensitivity                      | mV/V | 0.7±0.1       |
| Comprehensive error              | %F.S | ±0.1          |
| creep (30 min)                   | %F.S | ±0.1          |
| Zero balance                     | %F.S | ±1            |
| Zero temperature effect          | %F.S/10℃ | ±5          |
| Output temperature effect        | %F.S/10℃ | ±5          |
| Input impedance                  | Ω    | 400±50        |
| Output impedance                 | Ω    | 352±3         |
| Insulation resistance            | MΩ   | ≥5000         |
| Operating temperature range      | °C   | -4 to 250     |
| Safety overload                  | %F.S | 150           |
| Ultimate Overload                | %F.S | 200           |
| Recommended excitation voltage   | V DC | 10~12         |
| Maximum excitation voltage       | V DC | 15            |
| Seal level                       |      | IP65          |
| Texture of material              |      | Alloy steel   |

Figure 3. Test device for stress relaxation

4.2. Test Results and Discussion

The pre-pressure of closing spring of high-voltage circuit breaker without energy storage is 2448.04N, and the length of closing spring without energy storage is 130mm; the pressure of closing spring with energy storage is 3688.72N, and the length of closing spring with energy storage is 93.5mm. According to the actual working condition of the closing spring of the high-voltage circuit breaker, during the test, compress the closing spring to the energy storage position (at this time, the closing spring pressure is 3688.72N and the length is 93.5mm), and then according to the recovery temperature of the closing spring material, set five temperature points below this temperature for five groups of tests, the test temperature is as follows: 100℃, 110℃, 120℃, 130℃ and 140℃.

According to the curve fitting of the test data under different test temperatures, as shown in figure4, it is obtained that the stress and time of the closing spring under the same temperature are in accordance with the distribution law of logarithmic function \( y = a \ln t + b \), where \( y \) is the stress value, \( t \) is the time, \( a \) and \( b \) are constants.
Taking the stress drop of closing spring as 5% as the failure index, the corresponding failure time of closing spring under the failure index is calculated according to the experimental data and stress relaxation function, and the results are shown in Table 4.

Table 4. Failure time under different temperatures

| Temperature (℃) | Time for stress reduction to 5% (day) |
|-----------------|--------------------------------------|
| 100             | 34.9                                 |
| 110             | 16.7                                 |
| 120             | 9.7                                  |
| 130             | 6                                    |
| 140             | 3.4                                  |

4.3. Fatigue Life Prediction of Closing Spring

According to the requirement of life prediction by Arrhenius equation, if the logarithm \( \ln t \) of failure time is linear with the reciprocal \( 1/T \) of absolute temperature, then the failure time can be calculated by using this equation at room temperature.

Figure 5 shows the relation curve between \( \ln t \) and \( 1/T \) in this test. It can be seen from the figure that \( \ln t \) and \( 1/T \) are basically linear.

By curve fitting of \( \ln t \) and \( 1/T \), the life prediction equation of closing spring stress reduced to failure index is obtained.

\[
\ln t = \frac{8762}{T} - 19.98
\]
In formula: $t$ is time in days; $T$ is absolute temperature in $K$.

From equation (11), the storage life of closing spring at room temperature (25℃) is 27.86 years.

5. Conclusion

(1) Many researchers have analyzed and calculated the matching of spring energy and load of spring operating mechanism of high-voltage circuit breaker, but they have not carried out theoretical research and experimental verification on the minimum closing energy of high-voltage circuit breaker. In this paper, the matching between the closing spring energy and the load of the operating mechanism of the high-voltage circuit breaker is analyzed in detail, and the minimum energy required for the closing of the high-voltage circuit breaker is obtained through the test, so as to realize the early warning of the closing spring fault of the high-voltage circuit breaker.

(2) The static stress relaxation curve of the closing spring force with time is obtained by simulating the closing spring in the compressed state under the long-term operation condition of the high-voltage circuit breaker, so as to realize the storage life prediction of the closing spring.

(3) Through the mechanical life test of the high-voltage circuit breaker, the relationship curve between the closing spring force and the action times of the high-voltage circuit breaker is obtained, and the fatigue life prediction of the closing spring is realized.

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