State Diagnosis for Closing/Opening Spring in the Spring Operating Mechanism of Circuit Breaker

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Abstract. In order to ensure safe and reliable operation of the spring operating mechanism, a method of spring’s state diagnosis in spring operating mechanism is proposed. Through the analyze the spring’s operation characteristic in storing process and in closing/opening process, the effective output of motor in storing process and the closing/opening speed are extracted, and these are used as characteristic parameters to diagnose spring’s state. The diagnosis process of closing/opening spring’s state is specifically analyzed and described based on the judgment of characteristic parameters. The diagnosis system of closing/opening spring’s state is designed, and it is verified by combining with the CT20 spring operating mechanism. Through the contrast experiment of old and new closing/opening spring, the proposed diagnosis method for opening/closing spring is validated to be simple and accurate, and the result of the diagnosis is very well.

Introduction

The spring operating mechanism is widely used in HV circuit breaker due to its advantages of high reliability, simple mechanical structure and concise maintenance. In the long-term operation, closing/opening spring, which is the core component of spring operating mechanism, is under compression and extension states [1]. With the increase of running time, the fatigue, creep, stress relaxation and other phenomena could be occurred in closing/opening spring, which directly leads to the lower closing/opening speed, the longer closing/opening time and even the breaker rejecting act[2].

To solve the above problems, a diagnosis method for opening/closing-spring state is proposed in this paper. Through the analyzing the operation characteristics of the spring operating mechanism, the effective output work and closing/opening speed are used as the characteristic parameters to diagnosis spring’s state. Meanwhile, a diagnostic process is proposed based on the characteristic parameters. The CT20 spring operating mechanism is used as simulator test rig, the experimental samples, which select old and new sprig, are used for diagnostic verification. The results show that when not using the pressure parameters, the spring’s state can be effectively diagnosed by the proposed method [3,4].

Action Characteristic of Spring Operating Mechanism

Spring operating mechanism, which use spring as energy-storing element, is a kind of mechanical actuator. The action process of spring operating mechanism is shown in Figure 1 [5].

In closing operation, closing coil receives the closing-control signal, then lock catch trips with magnetic forces. The energy, which is stored in closing spring, is released and contact is moved by mechanical transmission unit [6]. A part of the closing energy is used to close spring, the other part is used to store energy for opening spring. After closing action, closing spring is immediately stored by the energy-storing motor. In opening operation, opening coil receives the opening-control signal, then lock catch trips with magnetic forces. The energy, which is stored in opening spring, is released and contact is moved by mechanical transmission unit [7,8].
The closing process
Energy-storing process
The Opening process
Pressure of closing spring
Pressure of opening spring
Positions of Contact
current

Figure 1. Action process of spring operating mechanism.  Figure 2. Schematic diagram of storing process.

Storing Process of Closing Spring

After closing action, the limit switch is closed and the motor is started to drive closing spring stored. After storing action, keep it in the storing state by locking system. The CT20 is used as an example to analyze force condition, as shown in figure 2.

A is the driving shaft which is driven by energy-storing motor, OB is the position of closing spring. B is the movable end of closing spring. When closing spring is stored with energy, rocker arm (AP) rotates clockwise with shaft (A) and guide rod of spring (BP) is pulled. Closing spring is compressed to store energy. The closing spring end point (B) moves with the change of angle ($\alpha$) on the X axis. When $\alpha$ is 0 degrees, the spring is in the energy-releasing state, when $\alpha$ is 180 degrees, the spring is in the energy-storing state. The energy-storing motor drives the A point rotated, so that $\alpha$ realizes the rotation from 0 degree to 180 degree. The spring’s force can be shown with (1)-(3) [9].

\[
\Delta x = \frac{r \cdot \sin(\alpha + \beta)}{\sin(\alpha)} \quad (1)
\]

\[
\Delta l = \frac{d+l - \Delta x}{\cos(\alpha)} \quad (2)
\]

\[
F = k \cdot \Delta l \cdot \sin(\alpha + \beta) \quad (3)
\]

In the above formula, the length of AP is $r$, the length of BP is $l$, and the distance of AO is $d$. $\Delta x$ is the distance of AB.$\Delta l'$ is the force stroke on the path of OB. $\Delta l$ is the force stroke on the path of BP. In the CT20 spring operating mechanism, the length of $r$ is 50mm, the length of $l$ is 600mm, and the length of $d$ is 150mm. According to equation (1)-(3) and the actual length of operating mechanism as well as triangular relation between $\alpha$ and $\beta$ in figure 2, the relationship between $F$ and $\alpha$ can be obtained, as shown in figure 3.

The work, which energy-storing motor does, turns into closing spring stored. It shows that the state, when closing spring is in storing state, can be reflected by the effective output of motor. According to equation (4), the output work of motor $W$, which is in the closing process, can be calculated through integration.

\[
W = \int F(\alpha) \Delta l(\alpha) d\alpha \quad (4)
\]
In the operating process of circuit breaker, the effective output of energy-storing motor is shown in Figure 4 [10].

According to figure 4, the electric energy consumed by the energy-storing motor can be converted to compressed energy in closing spring.

\[ W = E = U \int_{t_2}^{t_4} i(t) \, dt \]  

(5)

In the formula (5), \( U \) is the rated voltage of the energy-storing motor, and \( t_2-t_4 \) is the effective working time of the energy-storing motor. The effective work of the motor \( W \) can be used as the characteristic parameter. The energy-storing state of closing spring can be effectively diagnosed through the effective work of motor.

**Closing/Opening Process**

According to energy change of spring, the closing/opening process are specifically analyzed.

\[ E_s = E_f + E_0 \]  

(6)

In the formula (6), \( E_s \) is energy which is energy-storing motor stores in the closing spring, \( E_f \) is the energy which is stored in opening spring and used to open spring, \( E_1 \) is the energy which is stored in closing spring and used to closing spring. When circuit breaker is closed, a part of release energy in closing spring drives the operating mechanism and the insulating rod moved, so that the closing operation is completed. Another part of release energy in closing spring is used to compress the opening spring, so that the opening spring is stored. When circuit breaker is separated, the energy stored in the opening spring is released, so that opening operation is completed.

The relationship between the spring energy and the spring speed is analyzed by "Work and Energy". Physically, the object with mass of \( m \) overcomes the resistance \( F_z \) under driving force \( F \), moving a distance \( x \), speeding up from \( V_1 \) to \( V_2 \), then it can be concluded that:

\[ \int_0^x (F - F_z) \, dx = \frac{1}{2} mv_2^2 - \frac{1}{2} mv_1^2 \]  

(7)

The process of closing operation is simplified according to the load characteristics of the circuit breaker, as shown in Figure 5 [11].

![Figure 5. The simplified diagram of the closing spring and the load.](image)

Where \( m(x) \) is the equivalent mass of the spring load, of which the value depend on the mass, velocity and position of the transmission mechanism of the closing operation, and varies with the deformation of the spring. According to the kinematic equation, \( F(x) \) is a variable, and its value varies with the shape of the spring. So, the formula (8) can be changed into:

\[ \int_0^x \left[ F(x) - F_z \right] \, dx = \int_0^x \left[ \frac{1}{2} m(x) v^2 \right] \, dx \]  

(8)

As long as the spring force \( F(x) \) and the spring load equivalent mass \( m(x) \) can be obtained, the velocity \( v \) of spring with any stroke \( x \) can be calculated by using formula (9).

\[ v = \sqrt{\frac{2 \int_0^x [F(x) - F_z] \, dx}{\int_0^x [m(x)] \, dx}} \]  

(9)

The closing/opening speed can be calculated. So, the state of the opening spring can be reflected by the speed of opening spring \( v_f \) and the state of the closing spring can be reflected by the speed of
closing spring $v_h$. Meanwhile, according to equation (6), the state of opening spring also can be reflected by the speed of closing spring $v_h$. So, the opening speed (including opening speed at the separating instant and average opening speed) and closing speed (including closing speed at the separating instant and average closing speed) can be selected as feature parameters. The state of closing/opening spring can be diagnosed by detection of closing/opening speed.

**Diagnosis Method**

**The State Diagnosis of Closing/Opening Spring**

Through analyzing the process of energy-storing spring and the closing/opening process, effective output work of motor and closing/opening speed can be used as characteristic parameters to diagnose the state of closing/opening spring.

The diagnostic process is divided into the following steps, as shown in figure 6.

1. The effective output work of motor, closing/opening speed and other characteristic parameters are collected and extracted after closing/opening process and energy-storing process.

2. According to figure 3, the state of closing spring is reflected by effective output work of motor. So, the first diagnosis of the closing spring can be obtained through the analysis of effective output work of motor. When effective output work of motor is within the range of the standard, the closing spring in good condition, then proceed to the next diagnosis. When effective output work of motor is not in the range of the standard, the closing spring state has been unable to meet the requirements of the circuit breakers. Diagnosis ends and diagnosis results are that the closing spring need to timely repair or replace.

3. According to the formula (12), the state of opening spring is reflected by the opening speed. So, the first diagnosis of the opening spring can be obtained through the analysis of opening speed. When opening speed is within the range of the standard, the opening spring in good condition, then proceed to the next diagnosis. When opening speed is not in the range of the standard, the opening spring state has been unable to meet the requirements of the circuit breakers. Diagnosis ends and diagnosis results are that the opening spring need to timely repair or replace.

4. According to equation (7) and (12), the state of closing/opening is also reflected by the closing speed. The state of closing/opening spring can be secondly diagnosed by the closing speed. The first misdiagnosis, which caused by the measurement error, can be effectively avoided by the second diagnosis. When closing speed is within the range of the standard, the closing/opening spring in good condition, then proceed to the next diagnosis. When closing speed is not in the range of the standard, the closing/opening state have been unable to meet the requirements of the circuit breakers. Diagnosis ends and diagnosis results are that the closing/opening spring need to timely repair or replace.

![Figure 6. The diagnostic process of closing/opening spring.](image)

![Figure 7. The closing stroke-time curve.](image)
Acquisition and Extraction of Characteristic Parameters

According to the process of closing/opening spring and the energy-storing process, the current-time curve in the energy-storing process can be obtained by using the current transformer, and the stroke curve of closing/opening spring can be obtained by angular displacement sensor.

The collected data are analyzed by mathematical operation, and the characteristic parameters that reflect the state of spring are extracted [12].

(1) Effective output work of motor

The current-time curve of AC motor need to Hilbert transform, extract envelope curve, filter and de-noising. Then, waveform in the effective working time of the motor is selected. According to formula (5), the effective output work $W$ is obtained by processed waveform. For the DC motor, the current-time curve can be directly integrated to get the effective output work of the motor $W$.

(2) Closing/opening speed

From the closing stroke-time curve, the average closing speed can be obtained. According to figure 7, the closing stroke-time curve is removed with beginning or end each 10% stroke, 80% of the remaining stroke is used to calculate the average closing speed.

$$V_{p1} = \frac{0.8H}{\Delta t} (m/s)$$

In the formula (10), $V_{p1}$ is the average closing speed, and $\Delta t$ is the time corresponding to the 80% stroke.

The closing stroke-time curve is differentiated to obtain the closing speed-time curve, the closing speed at the separating instant can be obtained by analyzing the closing speed-time curve and closing time.

In the same way, the opening speed at the separating instant and the average opening speed also can be obtained from opening speed-time curve and the opening stroke-time curve.

Experimental Verification

Experimental Platform

The experimental platform is the CT20 operating mechanism equipped with a simulated load, as shown in Figure 8. The weight of simulated load is similar to the load of LW25-126, which was equipped with the CT20 operating mechanism. The measurement device supplies diagnose for the opening/closing spring, which is designed by author.

![Figure 8. Measurement device and CT20.](image)

![Figure 9. CT20 spring operating mechanism.](image)

Experimental Verification

Two groups of closing/opening spring are selected, which come from the same manufacturer, and it is shown in figure 9.

In Figure 9, the A group are new spring. It shows that the structure of closing/opening spring is complete. There are no cracks in its surface and the spring has not deformed. The surface is smooth without rust. The parameters of opening spring are shown in Table 2.
In Figure 9, the B group are old spring which is running for 17 years. It shows that the structure of opening closing is also complete. There is no crack in surface and the spring has not deformed. But its running time is long, the action is frequent, and there is some rust on its surface. There may have phenomenon of fatigue and stress relaxation. The A and B groups of closing/opening spring are detected, and the results are shown in Table 1.

|                          | standard value | A Group | B Group |
|--------------------------|----------------|---------|---------|
| the opening speed        |                |         |         |
| at the separating instant (m/s) | 3.5~4.2        | 3.88    | 2.97    |
| the closing speed        |                |         |         |
| at the separating instant (m/s) | 1.0~1.6        | 1.42    | 1.57    |
| the average opening speed (m/s) | 4.2~4.8        | 4.55    | 3.86    |
| the average closing speed (m/s) | 1.4~2.4        | 1.98    | 2.38    |
| Effective output work of motor (KJ) | 3.0~4.0        | 3.57    | 3.64    |

According to the method proposed in this paper, the state of closing/opening spring is diagnosed. In A group, the mechanical parameters of the closing/opening spring are in the standard range. In B group, the effective output work of motor is in the standard range, which indicates the good performance of the closing spring, and the opening speed at the separating instant and the average opening speed is lower than the standard value, which indicates that the opening spring has been unable to meet the requirements of circuit breaker and it needs to replace and maintain.

In order to verify the state of the opening spring in the B Group, the opening spring is compressed to storing height 342mm in pressure tester, and its measured pressure is 15800N. Compared with the standard parameters, the energy-storing value of the closing spring is decreased, and there may have phenomenon of fatigue and stress relaxation. Therefore, the speed of closing speed is reduced.

The above results can draw a conclusion that the actual state of closing and opening spring and the diagnosed results are basically identical by performing the verifying experiment. The effectiveness of the diagnostic method has been further verified.

Conclusion
In this paper, the state of closing/opening spring is mainly studied, and it draws the following conclusions:

1. According to the operating characteristics of the spring operating mechanism, the relationship between the effective output work of motor and the closing spring, and the relationship between closing/opening speed and closing/opening spring are analyzed.

2. The angular displacement sensor and current transformer are used for data acquisition in closing/opening process and storing process. The collected data is uploaded to the host computer for extraction of characteristic parameter. A method to diagnose the spring state based on characteristic parameters is proposed.

3. The measurement device is used in CT20 experimental platform for diagnostic test. The experiment shows that the proposed method is used to effectively evaluate spring’s state of HV circuit breaker. It provides reference for the maintenance of spring in circuit breaker.

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