Improving the cam profile of the spring operating mechanism of vacuum circuit breaker based on energy matching

Fuqiang Li, Shufen Wang¹, Yuguang Li and Zhenzhen Sun

College of Mechanical Engineering, Dalian University, Dalian, Liaoning 116622, China

¹ E-mail: wangshufen@dlu.edu.cn

Abstract. High-voltage circuit breakers are important protection and control equipment in power systems. In order to understand the mechanical characteristics of vacuum circuit breaker, the mathematical relationship between the released energy of closing spring, the stored energy of opening spring and overtravel spring and the rotation angle of output crank arm is studied. The characteristic curve between the released energy of closing spring and the rotation angle of output crank arm and the characteristic curve between the stored energy of opening spring and overtravel spring and the rotation angle of output crank arm are drawn by MATLAB. In order to improve the matching of energy release and energy storage characteristic curves, a method of improving cam profile is proposed. The dynamics simulation model of spring operating mechanism of high voltage circuit breaker is established and the original cam and adjusted cam are imported into the dynamics simulation model of mechanism. The simulation results show that the adjusted cam improves the closing speed of vacuum circuit breaker. This helps to reduce the stress on the parts of the vacuum circuit breaker and increase the service life of the vacuum circuit breaker.

1. Introduction

Vacuum circuit breaker is an important control and protection equipment in power system. Spring operating mechanism is an important part of vacuum circuit breaker. Its dynamic characteristics are an important factor to determine the breaking performance of circuit breaker [1]. Improving the closing efficiency of spring operating mechanism can reduce the cost and improve the reliability of operation [2]. The reasonable matching between the output force characteristics of the spring operating mechanism and the load characteristics of the vacuum circuit breaker depends on the reasonable design of the cam mechanism [3-5]. In order to study the dynamic characteristics of spring operating mechanism, in Literature [1], the overall model of spring operating mechanism of high voltage circuit breaker was imported into ADAMS for dynamics simulation analysis. In Literature [6], the principle of energy distribution of circuit breaker was analyzed and the mathematical model of energy distribution of high voltage circuit breaker was established. In Literature [7], the cam profile was optimized to improve the transmission characteristics and mechanical properties of the spring operating mechanism. In Literature [8], a closing cam was designed to make the dynamic characteristics and load characteristics of high voltage circuit breaker match well. In Literature [9], using a negative feedback design method, the designed cam can make the dynamic characteristics of the circuit breaker accurately match the load characteristics. In order to avoid the contact fusion welding when the closing speed is lower than the critical speed, the closing cam profile curve was
designed according to the determined closing speed and the energy required by the closing spring in Literatures [10-11].

This paper studies the relationship between the energy of closing spring, opening spring, overtravel spring and the angle of output crank arm. The relationship between the energy of closing spring and the angle of output crank arm is regarded as the output characteristic of high voltage circuit breaker and the relationship between the energy of opening spring and overtravel spring and the angle of output crank arm is regarded as the load characteristic. The output characteristic curve and load characteristic curve were drawn by MATLAB. In order to improve the matching of output characteristics and load characteristics, the closing cam profile was improved. In order to understand the influence of the improved cam on the performance of vacuum circuit breaker, the simplified model of high-voltage circuit breaker was imported into ADAMS and set parameters. The dynamics simulation model of high-voltage circuit breaker was established and the improved cam was imported into the dynamics simulation model.

2. Vacuum circuit breaker

2.1. Working principle of vacuum circuit breaker

As shown in Figure 1, during the closing process of vacuum circuit breaker, the cam is driven by the closing spring through the output crank arm and the connecting rod mechanism to close the vacuum interrupter. At the same time, the overtravel spring is compressed, the moving contact is compressed and the energy stored in the opening spring is increased to prepare for the opening. The point E in Figure 1 will be held by the closing frame.

![Figure 1. Working principle diagram of vacuum circuit breaker.](image)

2.2. Performance of vacuum circuit breaker

The performance index of vacuum circuit breaker includes contact speed and service life. As far as the electrical performance of vacuum circuit breaker is concerned, the higher the contact speed is, the better. However, the increase of contact speed will increase the stress of mechanical parts and reduce the service life of circuit breaker. This paper focuses on the reasonable matching of output characteristics and load characteristics of vacuum circuit breaker to improve the performance of vacuum circuit breaker. Improving the performance of the vacuum circuit breaker means to increase the service life of the vacuum circuit breaker without reducing the closing speed. In this paper, the output characteristic of vacuum circuit breaker refers to the relationship between the energy of closing spring and the rotation angle of output crank arm and the load characteristic refers to the relationship between the energy of overtravel spring and opening spring and the rotation angle of output crank arm.
3. Load characteristic curve

3.1. Movement analysis of moving contact pushed by output crank arm

The transmission principle diagram of the double four bar linkage with the output arm pushing the moving contact is shown in Figure 1. In order to analyze the relationship between $\angle XCF$ and $\angle XMK$, the double four bar mechanism is split into two four bar mechanisms, as shown in Figure 2(a) and Figure 2(b). The calculation process of the relationship between $\angle XCF$ and $\angle XMK$ is as follows.

![Figure 2. Split diagram of double four bar mechanism.](image)

![Figure 3. Analysis diagram of stored energy of opening spring and overtravel spring.](image)

In Figure 2(a), the relationship between $\angle XCF$ and $\angle XIG$ satisfies the following relationship.

$$l_{CF} \cos \angle XCF + l_{FG} \cos \angle XFG = l_{CI} \cos \angle XCI + l_{IG} \cos \angle XIG$$  \hspace{1cm} (1)

$$l_{CF} \sin \angle XCF + l_{FG} \sin \angle XFG = l_{CI} \sin \angle XCI + l_{IG} \sin \angle XIG$$  \hspace{1cm} (2)

Solving equations:

$$\angle XIG = 2 \arctan \left( \frac{A + \sqrt{A^2 + B^2 - C^2}}{B - C} \right)$$  \hspace{1cm} (3)

$$A = 2l_{IG}(l_{CI}\sin \angle XCI - l_{CF}\sin \angle XCF)$$  \hspace{1cm} (4)

$$B = 2l_{IG}(l_{CI}\cos \angle XCI - l_{CF}\cos \angle XCF)$$  \hspace{1cm} (5)

$$C = l_{CF}^2 + l_{CI}^2 + l_{IG}^2 - 2l_{CI}l_{CF}\cos (\angle XCI - \angle XCF)$$  \hspace{1cm} (6)

Using the same method, the relationship between $\angle XIF$ and $\angle XMK$ can be obtained and the relationship between $\angle XMK$ and $\angle XCF$ can be obtained.

### Table 1. Calculation process of stored energy of opening spring.

| Parameters                                           | Value                        |
|------------------------------------------------------|------------------------------|
| Abscissa of point $L$ $x_L$/ (mm)                    | $l_{ML} \cos (\angle XML)$   |
| Ordinate of point $L$ $y_L$/ (mm)                    | $l_{ML} \sin (\angle XML)$   |
| The distance between point $P$ and point $L$ during closing process $l_{PL}$/ (mm) | $\sqrt{(x_L - x_P)^2 + (y_L - y_P)^2}$ |
| Initial state, the distance between point $P$ and point $L$ $l_{PL0}$/ (mm) | 122.3                        |
| Original length of opening spring $x_{f0}$/ (mm)      | 92.3                         |
| Opening spring compression $\Delta x_f$/ (mm)        | $l_{PL} - x_{f0}$            |
| Equivalent stiffness coefficient of opening spring $k_f$/ ($N$/mm) | 56.25                        |
| Initial state, energy stored in the opening spring $E_{f0}$/ (J) | 25.3                         |
| During the closing process, energy stored in the opening spring $E_{f1}$/ (J) | $1 \frac{1}{2} k_f \Delta x_f^2$ |
| During the closing process, increase of stored energy of opening spring $E_f$/ (J) | $E_{f1} - E_{f0}$           |
3.2. Calculation process of stored energy of opening spring and overtravel spring

From the above analysis, we know the functional relationship between \( \angle XMK \) and \( \angle XCF \). Next, the functional relationship between the energy storage of opening spring and overtravel spring and \( \angle XMK \) is studied. As shown in Figure 3, during the closing process, with the decrease of \( \angle XMK \), the stored energy of the opening spring is increasing. The stored energy of the overtravel spring is zero before the collision between the moving contact and the static contact. After the collision between the moving contact and the static contact, the stored energy of the overtravel spring begins to increase. The calculation method of the relationship between the stored energy of the opening spring and the angle of the output crank arm \( \angle XCF \) is shown in Table 1. The calculation method of the relationship between the stored energy of the overtravel spring and the angle of the output crank arm \( \angle XCF \) is shown in Table 2.

| Parameters                                           | Value                       |
|------------------------------------------------------|-----------------------------|
| Abscissa of point \( N \) \( x_N \)/(mm)             | \( l_{MN} \cos(\angle XMN) \) |
| Compression of overtravel spring \( \Delta x_c \)/(mm) | 3.70 \( - x_N \)            |
| Equivalent stiffness coefficient of overtravel spring \( k_c \)(N/mm) | 3000                        |
| Energy stored in overtravel spring \( E_c \)/(J)      | \( \frac{1}{2} k_c \Delta x_c^2 \) |

3.3. Load characteristic curve

Bring the relevant data into the formula, the load characteristic curve calculated and drawn by MATLAB is shown in Figure 4. In Figure 4, the value of abscissa is the rotation angle of the output crank arm, and the value of ordinate is the sum of the energy stored by the opening spring and the energy stored by the overtravel spring. In the figure, with the rotation of the output crank angle, the energy stored in the opening spring and overtravel spring increases suddenly after the contact is just closed.

![Figure 4. Matching of characteristic curve.](image)

4. Output characteristic curve

The output characteristic curve refers to the relationship between the energy stored in the closing spring and the rotation angle of the output crank arm. The principle of cam pushing output crank arm is shown in Figure 5. Closing spring pushes cam to rotate and cam pushes output crank arm to rotate.
4.1. Relationship between cam energy release and cam rotation angle

The relationship between cam energy release and cam rotation angle is analyzed. The calculation process of the relationship between the stored energy of the closing spring and the angle of cam $\angle A0_B$ is shown in Table 3.

| Parameters                              | Value |
|-----------------------------------------|-------|
| Length of closing spring connecting accessories $a/(\text{mm})$ | 18.1  |
| Initial length of closing spring $x_h/(\text{mm})$ | 175   |
| Cam rotation angle $\alpha/(\degree)$    |       |
| The distance between point A and point B $l_{AB}/(\text{mm})$ | $\sqrt{l_{AO_A}^2 + l_{BO_B}^2 - 2l_{AO_A}l_{BO_B}\cos\alpha}$ |
| Closing process, closing spring length $x_h/(\text{mm})$ | $l_{AB} - a$ |
| Closing process, closing spring compression $\Delta x_h/(\text{mm})$ | $x_{h_0} - x_h$ |
| Initial state, energy of closing spring $E_{h_0}/(\text{J})$ | 192   |
| Equivalent stiffness coefficient of closing spring $k_h/(\text{N/mm})$ | 50    |
| Closing process, energy of closing spring $E_{h_1}/(\text{J})$ | \( \frac{1}{2}k_h\Delta x_h^2 \) |
| Energy released by cam $E_h/(\text{J})$ | $E_{h_0} - E_{h_1}$ |

4.2. The relationship between the rotation angle of output crank arm and that of cam

In order to find out the relationship between the rotation angle of the output crank arm and the rotation angle of the cam, it is necessary to analyze the transmission process of the cam and the output crank arm. As shown in Figure 6, the closing cam is composed of five arcs. Taking the first arc $Z_1Z_2$ as an example, in the process of transmission between cam arc profile and output crank arm, the distance between point $D$ and point $O_1$ remains unchanged. Therefore, the transmission process of first arc $Z_1Z_2$ and output crank arm can be transformed into four-bar mechanism $O_0O_1 DC$ transmission.

In the working process of the cam pushing the output crank arm, the multi segment arc of the cam pushes the output crank arm to rotate. Therefore, it is necessary to study the value range of the cam rotation angle from the beginning to the end of the contact between each segment of the cam arc and the output crank arm. Taking the first section of cam arc as an example, the relationship between the arc parameters and cam angle is studied. The cam arc transmission is shown in Figure 7(a).
At the contact stage between the first arc of the cam and the roller of the output crank arm, the calculation steps of the relationship between the rotation angle of the output crank arm and the rotation angle of the cam are as follows.

Step 1: As shown in Figure 7(b). Record the value of $\angle XO_0O_1$, $\angle XO_0W_0$ and $\angle XO_0W_2$ when the energy of closing spring is not released.

Step 2: When the first arc begins to contact, calculate the value of the angle $\angle XO_0W_0^1$ between $O_0W_0$ and the horizontal direction.

Step 3: When the first segment of arc starts to contact, $\angle XO_0O_1^1 = \angle XO_0O_1 + (\angle XO_0W_0^1 - \angle XO_0W_0)$.

Step 4: When the first segment of arc ends contact, calculate the value of angle $\angle XO_0W_2^1$ between $O_0W_2$ and horizontal direction.

Step 5: When the first arc ends contact, $\angle XO_0O_1^2 = \angle XO_0O_1 + (\angle XO_0W_2^1 - \angle XO_0W_2)$.

Step 6: According to the above analysis, the value range of $\angle XO_0O_1$ is $[\angle XO_0O_1^1, \angle XO_0O_1^2]$, as shown in Figure 6, according to the four bar mechanism $O_0O_1CD$ motion law, solve the relationship between $\angle XO_0O_1$ and $\angle XCD$.

When other arc segments contact, the calculation process of the relationship between $\angle XO_0O_2$, $\angle XO_0O_3$, $\angle XO_0O_4$ and $\angle XCD$ is similar to that of the first arc contact.

### 4.3. Output characteristic curve

The output characteristic curve refers to the relationship between the energy stored in the closing spring and the rotation angle of the output crank arm $\angle XCF$. According to the above analysis, the relevant data is brought into the formula, and the output characteristic curve of the vacuum circuit breaker is drawn by MATLAB. The output characteristic curve is shown in Figure 4.

### 5. Improving cam profile based on characteristic matching

#### 5.1. Matching of output characteristics and load characteristics

Draw the output characteristic curve and load characteristic curve on a graph, as shown in Figure 4. Through the analysis of the characteristic curve matching, it is found that the difference between the energy release of closing spring and the energy storage of load spring increases slowly in the early stage and rapidly in the late stage. In order to balance the difference between output energy release and load energy storage, in this paper, the energy release of closing spring is increased by adjusting the cam profile in the early stage of closing.
5.2. Improvement of cam profile

The relationship between cam structure and energy release of closing spring and rotation angle of output crank arm is analyzed. As shown in Figure 8(a), the length of \( OW_0 \) and \( OW_2 \) determines the rotation angle range of the output crank arm when the cam pushes the output crank arm to rotate. The rotation angle of the cam during the contact between the first section of arc and the roller of the output crank arm is determined by \( \angle W_0O_0W_2 \), which also determines the energy release of the closing spring. In order to make the output crank arm rotate at the same angle, the cam rotates more, the lengths of \( OW_0 \) and \( OW_2 \) remain unchanged, \( \angle XO_0W_0 \) remains unchanged and \( \angle W_0O_0W_2 \) is added. The modified cam profile is shown in Figure 8(b).

According to the calculation method of the output characteristic and load characteristic of the vacuum circuit breaker, the output characteristic curve and load characteristic curve of the original cam and the modified cam are drawn by using MATLAB. The matching of their output characteristic and load characteristic is shown in Figure 9. It can be seen from the figure that after modifying the cam profile, the difference between the output energy release and the load spring energy storage tends to be balanced during the closing process.

![Figure 9. Matching of characteristic curve after adjusting cam.](image)

5.3. Influence of adjusting cam profile on performance of vacuum circuit breaker

In order to understand the influence of adjusting cam profile on the performance of vacuum circuit breaker, according to the transmission principle of vacuum circuit breaker, a dynamics simulation analysis model is established in ADAMS, and the original cam and adjusted cam model are introduced into the analysis model. The simulation results are shown in Figure 10. After adjusting the cam, the maximum speed in the closing process changes from 0.84m/s to 0.89m/s. The average closing speed is changed from 0.77m/s to 0.81m/s.

![Simulation results](image)
6. Conclusions

Through the theoretical analysis of vacuum circuit breaker closing process, the mathematical models of output characteristics and load characteristics are established. Using MATLAB to draw the output characteristic curve and load characteristic curve, it is found that the increase of the difference between the output characteristic curve and the load characteristic curve is small in the early stage of closing and large in the late stage of closing.

In order to make the difference between the output characteristic and the load characteristic nearly constant, by improving the cam profile, the value of output characteristic curve in the early stage of closing increase. The improved cam is imported into the dynamics simulation model of vacuum circuit breaker. The simulation results show that the maximum closing speed of the vacuum circuit breaker with improved cam is increased by 6%, and the average closing speed is increased by 5.2%. In other words, if the closing speed remains unchanged, the closing energy can be reduced, which can reduce the force on the vacuum circuit breaker parts and help to improve the service life of the vacuum circuit breaker.

References

[1] Zheng Xin, Liu Ronghai and Yang Yingchun 2017 Dynamics simulation analysis on CT14 Spring operating mechanism of high-voltage circuit breaker based on adams High voltage apparatus 53(7) 118-124
[2] Liu Wei 2019 Closing efficiency of spring operating mechanism High voltage apparatus 55(4) 245-249
[3] Fan Shun 2001 High-voltage circuit breaker spring operating mechanism China Machine Press
[4] Yan Jing, Ma Zhiying and Jin Li 2004 Optimum design of the spring operating mechanism in vacuum circuit breaker High voltage apparatus 40(6) 420-423
[5] Xiong Xianzhi and Wang Ping 2020 Cam optimization design of spring operating mechanism of vacuum circuit breaker High voltage apparatus 56(11) 116-123
[6] Yang Qiuyu, Peng Yanqing and Zhang Zhijian 2018 Dynamic simulation and failure analysis of spring mechanism of high-voltage circuit breaker based on ADAMS High voltage apparatus 54(6) 67-80
[7] Wang Lianpeng and Wang Erzhi 2006 Simulation and optimization of the spring actuator for vacuum circuit breaker High voltage apparatus 32(2) 27-29
[8] Guo Liangchao, Han Hui and Liu Yu 2019 Optimum design of the closing cam in spring operating mechanism of high-voltage circuit breaker High voltage apparatus 55(10) 13-18
[9] Zhao Yuzhi, Zhang Jie and Zhang Peng 2017 Optimum design of the spring actuator cam during closing operation in vacuum circuit breaker High voltage apparatus 53(3) 205-210
[10] Li Yonglin, Yu Li and Li Xuxu 2017 Optimization design of operating mechanism cam profile
for a 126 kV vacuum circuit breaker based on an optimal closing velocity. *High voltage apparatus* **53**(3) 197-204

[11] You Yimin, Chen Degui and Zhang Yinchang 2004 Study of the influence of the closing velocity and the pre-strike on synchronous closing in a vacuum circuit breaker *Transactions of China Electrotechnical Society* **19**(7) 85-89