Motion Characteristic Analysis of High Voltage Circuit Breaker Transmission Mechanism

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***Abstract*—It is of great significance to analyze the opening and closing motion characteristics of the high-voltage circuit breaker transmission mechanism. Through the analysis of the dynamic characteristics of the opening and closing, the internal defects of the circuit breaker can be effectively detected, which provides a theoretical basis for the future health assessment, fault prediction and diagnosis of the circuit breaker. In this paper, from the perspective of theoretical modeling, the mathematical model of the hinge four-link and crank slider is established according to the structure of the circuit breaker transmission mechanism. Then, based on the same principle of the joint movement state, the two parts are integrated to obtain the overall motion model of transmission mechanism. Finally, the Matlab/Simulink software is used to simulate the displacement and acceleration curves of the main contacts during the opening and closing process, so that the motion characteristics are analyzed and compared with other literatures to verify the rationality of the results.**

Keywords-HV circuit breaker; Matlab/Simulink simulation; transmission mechanism; motion characteristics

I. INTRODUCTION

As the core equipment for control and protection in power systems, high-voltage circuit breakers play an important role in ensuring the stable operation of power systems. The circuit breaker is generally composed of a plurality of parts such as an operating mechanism, a transmission mechanism, an interrupting arc extinguishing element and an insulating support, and each part plays a different task and plays an indispensable role [1-2]. As the transmission link between the connecting mechanism and the contact mechanism, the transmission mechanism plays the role of transmitting power and energy, and is an important carrier for realizing the opening and closing operation[4]. Mastering the motion characteristics of the transmission mechanism can effectively analyze the opening and closing behavior of the circuit breaker, and provide a theoretical basis for the assessment of the health status of the circuit breaker, fault prediction and diagnosis. Therefore, it is necessary to analyze the motion characteristics of the high-voltage circuit breaker transmission mechanism.

At present, many scholars at home and abroad have conducted a lot of research on circuit breakers, mainly focusing on the study of current characteristics and the physical modeling and simulation of operating mechanisms and transmission mechanisms. In the study of circuit breaker discharge and current characteristics, in [3], the characteristics of the arc behavior and the interruption ability were investigated experimentally, obtaining the characteristics of the arc behavior and the interruption ability of the high-speed vacuum circuit breaker. Reference [4] used software ADAMS to build a model of a high voltage circuit breaker's mechanism, the electromagnetic force under short current is analyzed. And the analysis results are introduced into ADAMS. The behavior of the circuit breaker under short current is simulated. Reference [5] used software UG at first to build the 3D solid model of operating mechanism of high-voltage circuit breaker, which then is introduced into mechanical system dynamic simulation analysis software ADAMS. Finally, the dynamic performance curves of high-voltage circuit breaker are simulated and analyzed. Reference [6] established a linear spring model, a modal spring model and a node spring model for the springs of the operating mechanism, and the circuit breaker was simulated to compare the performance of the spring model.

In this paper, the transmission mechanism of a high-voltage circuit breaker is analyzed from the perspective of theoretical modeling. The four-link and crank-slider models are used to approximate the motion characteristics of the transmission mechanism. The displacement and acceleration characteristics of the main contact are obtained by Matlab/Simulink software simulation and compared with other literatures

II. WORKING PRINCIPLE OF TRANSMISSION MECHANISM

The transmission mechanism of the high- voltage circuit breaker is used to connect the contact structure and the operating mechanism, transmitting the energy and power provided by the operating mechanism to the contact, driving the contact action, and realizing the functions of the circuit breaker such as opening, closing and automatic reclosing.

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The structure of each part of the circuit breaker is shown in Fig. 1.

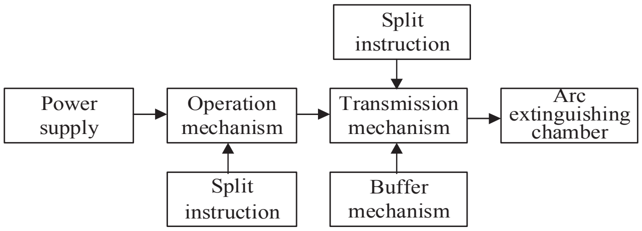

Figure 1. Schematic diagram of the circuit breaker

The analysis of the motion characteristics of the transmission mechanism is mainly to obtain the displacement, angular velocity and angular acceleration of the crank and the connecting rod in the mechanism. The key point is to obtain the motion trajectory, velocity and acceleration characteristics of the moving contact.

The actual engineering drawing of the transmission mechanism are transformed into motion diagram and decomposed to facilitate analysis and study of its motion characteristics. The space transmission mechanism of the high voltage vacuum circuit breaker is mainly composed of three parts, namely the input mechanism, the intermediate transmission mechanism and the main contact transmission mechanism. When the transmission mechanism is operated, the driving provided by the operating mechanism is applied to the arm 2-1 of the shaft 2 to rotate the shaft 2, and the arm 2-3 on the shaft 2 and the insulating push rod 3 and the connecting rod 4 constitute a four-bar mechanism, thereby, the motion of the shaft 2 is transmitted to the connecting rod 4. The rod 6 and the moving contact are regarded as a whole, and the connecting rods 4, 5 and the rod 6 and the moving contact can be regarded as a model of the crank slider mechanism, and the motion of the moving contact 7 transmitted from the member 4 to the member 5 is driven up and down in a straight line by the pull rod 6. The schematic diagram of the mechanism of the high voltage circuit breaker is shown in Fig. 2.

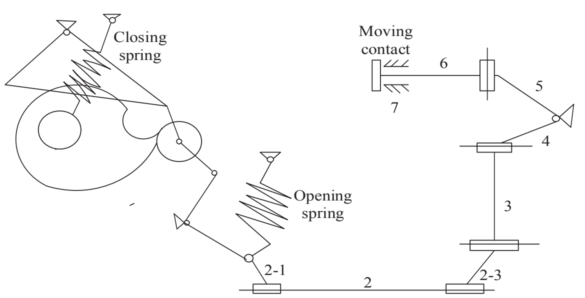

Figure 2. High-voltage circuit breaker mechanism diagram

III. TWO-LAYER MATHEMATICAL MODEL OF THE TRANSIMISSION MECHANISM

The operating mechanism of the circuit breaker is not directly connected to the arc extinguishing chamber, but the transmission of energy and motion through the intermediate mechanical transmission mechanism, driving the contacts to perform the opening and closing movement. Circuit breakers generally complete the opening and closing process in tens of milliseconds [7]. Because the circuit breaker has many components and large mass, in the process of energy transmission, each machine continuously mutually moves, impacts and rubs, and the whole process is high-speed movement, which is easy to produce shock, thus affecting the on-off characteristics. The mechanical parts of the circuit breaker are more complicated. If the overall mechanism of the transmission mechanism is kinematically analyzed, the calculation is very difficult, and some intermediate details are easily ignored. Therefore, this paper adopts the idea of first decomposition and then integration to analyze the motion characteristics of the transmission mechanism.

The input transmission mechanism is a crank slider mechanism, whose slider portion is connected to the operating mechanism. This article does not consider the operating mechanism part for the time being. It only studies the transmission mechanism of the intermediate transmission mechanism to the contact mechanism under the given initial speed of the input mechanism, and driving the contact to perform a series of opening and closing movement characteristics. Therefore, this paper does not analyze the input transmission mechanism. The two-layer mathematical model of the intermediate transmission mechanism and the contact mechanism in the transmission mechanism is established below.

A. Intermediate Transmission Mechanism

The schematic diagram of the mechanism is shown in Fig. 3. It can be equivalent to a hinged four-bar linkage [8]. As a bridge between the other two mechanisms, the crank AB and the rod CD move in exactly the same state, while the link BC is only a translational movement, which is characterized by neither changing the direction of rotation of the crank nor changing the angular velocity and the angular acceleration. They are connected by hinges without considering the friction loss between the hinges , so the kinematics analysis of the mechanism is relatively simple. .

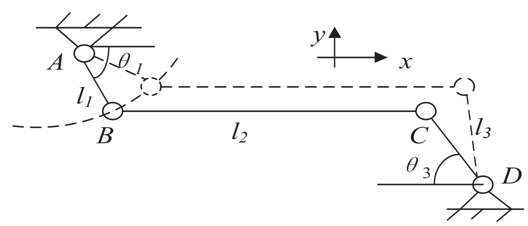

Figure 3. Intermediate transmission mechanism

According to the above structural diagram, the relationship of each component can be obtained:

$$\begin{cases} l_1 cos\theta_1 + l_2 + l_3 cos\theta_3 = x_D \\ l_1 sin\theta_1 + l_3 sin\theta_3 = y_A \end{cases} \tag{1}$$

Equation (1) takes the first derivative of time t and get the speed as:

$$\begin{cases} -l_1\omega_1 sin\theta_1 - l_3\omega_3 sin\theta_3 = 0 \\ l_1\omega_1 cos\theta_1 + l_3\omega_3 cos\theta_3 = 0 \end{cases} \tag{2}$$

Equation (1) takes the second derivative of time t, get the acceleration, and write it into matrix form:

$$\begin{pmatrix} -l_1 sin\theta_1 & -l_3 sin\theta_3 \\ l_1 cos\theta_1 & l_3 cos\theta_3 \end{pmatrix}\begin{pmatrix} \alpha_1 \\ \alpha_3 \end{pmatrix} = \begin{pmatrix} l_1 cos\theta_1 & l_3 cos\theta_3 \\ l_1 sin\theta_1 & l_3 sin\theta_3 \end{pmatrix}\begin{pmatrix} \omega_1^2 \\ \omega_3^2 \end{pmatrix} \quad (3)$$

The connecting rod l_2 performs translational motion without changing its speed and acceleration magnitude and direction, so $\omega_1=\omega_3$, $\alpha_1=\alpha_3$ can be obtained.

B. Main Contact Mechanism

The main contact mechanism is one of the important components of circuit breakers. The contact part of the high-voltage circuit breaker transmission mechanism adopts the straightening transmission mechanism, as shown in Fig. 4.

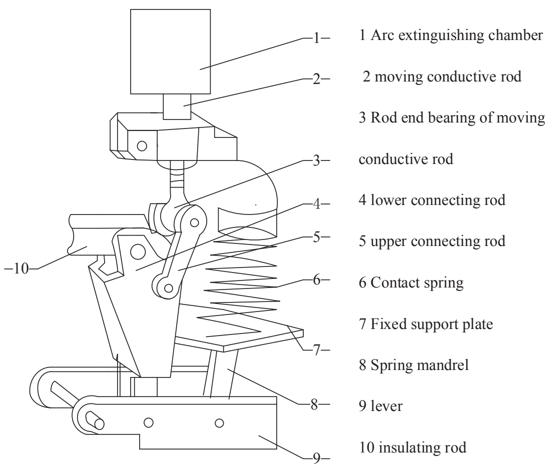

Figure 4. Straightening transmission mechanism

Where, the moving conductive rod 2 is connected with the moving contact, and the mechanism composed of it and the upper connecting rod 5 and the lower connecting rod 4 can be regarded as a crank slider model [8].

When the switch is closed, under the action of the closing signal, the spindle arm drives the insulating rod 10 to move, and the insulating rod transmits the energy and motion to the lower link 4, the upper link 5 and the moving conductive rod 2 to move in sequence, thereby driving the moving contact to do a linear motion upwards to achieve closing. At the moment when the moving contact and the static contact are just in contact, the moving conductive rod does not move temporarily. At this time, the spindle drives the insulating rod to rotate the lever 9 counterclockwise, compressing the contact spring until the end of lever rotates, and the contact spring is provided a certain degree of spring force, the elastic force is transmitted to the moving contact through the upper and lower connecting rods and the movable conductive rod to realize the closing of the over-travel portion of the contact. Similarly, when opening, under the action of the opening signal, the spindle arm transmits the drive and energy provided by the operating mechanism and the energy storage mechanism to the insulating rod, the lower link, the upper link and the moving rod in turn, pulling the contact moves straight down to achieve the opening. At the same time, the contact spring is released, and the opening is accelerated in the over-travel stage, which is beneficial to improve the arc-extinguishing ability to a certain extent.

A schematic diagram of the structure of the contact mechanism is shown in Fig. 5.

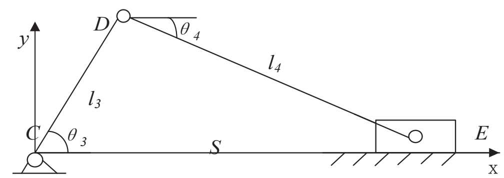

Figure 5. Schematic diagram of the contact mechanism

According to the coordinate system constructed in Fig. 5, the equations can be written as follows:

$$\begin{cases} l_3 cos\theta_3 + l_4 cos\theta_4 = S \\ l_3 sin\theta_3 + l_4 sin\theta_4 = 0 \end{cases} \quad (4)$$

Equation (4) take the first derivative of time t and get the speed relationship:

$$\begin{cases} -l_3\omega_3 sin\theta_3 - l_4\omega_4 sin\theta_4 = \dot{S} \\ l_3\omega_3 cos\theta_3 + l_4\omega_4 cos\theta_4 = 0 \end{cases} \quad (5)$$

Write in matrix form:

$$\begin{pmatrix} l_4 sin\theta_4 & 1 \\ -l_4 cos\theta_4 & 0 \end{pmatrix}\begin{pmatrix} \omega_4 \\ \dot{S} \end{pmatrix} = \begin{pmatrix} -l_3\omega_3 sin\theta_3 \\ l_3\omega_3 cos\theta_3 \end{pmatrix} \quad (6)$$

Equation (4) is used to find the second derivative of time t, and the acceleration relationship is obtained:

$$\begin{pmatrix} l_4 sin\theta_4 & 1 \\ -l_4 cos\theta_4 & 0 \end{pmatrix}\begin{pmatrix} \alpha_4 \\ \ddot{S} \end{pmatrix} = \begin{pmatrix} -l_3 sin\theta_3 & -l_3 cos\theta_3 \\ l_3 cos\theta_3 & -l_3 sin\theta_3 \end{pmatrix}\begin{pmatrix} \alpha_3 \\ \omega_3^2 \end{pmatrix} - \omega_4^2\begin{pmatrix} l_4 cos\theta_4 \\ l_4 sin\theta_4 \end{pmatrix} \quad (7)$$

In (1)~(7) , l_i is the length of rod, θ_i is the angular among links and the x or y direction, ω_i, α_i are respectively the angular velocity and the angular acceleration of rods, where i equal to 1,2,3,4. S, $\dot{S}$, $\ddot{S}$ are respectively the displacement, the velocity and the acceleration of the slider.

IV. SIMULINK SIMULATION

The vacuum circuit breaker of model ZN65-12 is used as the research object. The closing and closing response is very fast, and the opening and closing operation can be completed in 50~70ms. The average speed can reach 1.3m/s during the opening process. The average closing speed is about 0.6m/s [7]. The following is a simulation analysis of the transmission mechanism using Simulink.

The main algorithm of the Simulink tool module used in this paper is numerical integration, so you need to set the initial value of the integrator first. The Simulink simulation diagram is built based on the motion characteristics and initial conditions.

A. Simulink Simulation of Intermediate Transmission

A four-link model is used, setting the crank of the four-bar linkage l_1=100mm, the connecting rod l_2=250mm, l_3=175mm, the crank l_1 rotates at the uniform angular velocity ω_1=246rad/s, α_1 =0, and then the initial value of other bars is obtained in (3). According to the initial conditions of the above equation and the equation of motion, the Simulink simulation diagram as shown in Fig. 6 is established. The angular acceleration at the hinge C and the angular acceleration curve of the rod 3 are obtained by simulation.

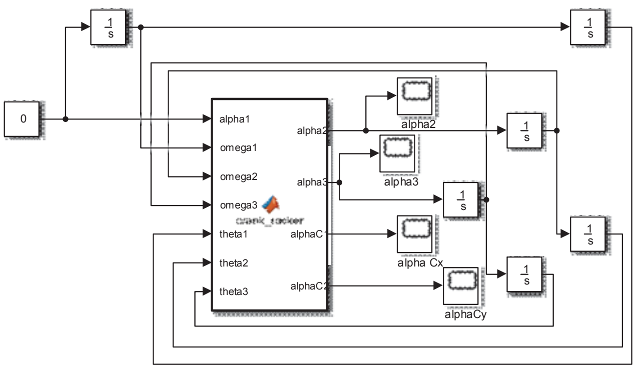

Figure 6 Simulink simulation of four-link

B. Simulink Simulation of Contact Mechanism

The crank slider mechanism is adopted, because the intermediate transmission mechanism does not change the magnitude and direction of the angular velocity and the angular acceleration, so ω_3=ω_1=246rad/s, α_3=α_1=0. It is known that crank l_3=175mm, the connecting rod l_4=350mm, moving conductive rod l= 525mm. The length of the moving conductive rod is long, which is beneficial to reduce the rotation angle of the moving conductive rod, so that the opening and closing has a larger transmission force, and the movement of the moving contact is closer to a linear motion. Therefore, the crank slider mechanism takes the moving contact and the moving conductive rod as a whole, as the mechanism E in Fig. 5. According to the initial condition, the relevant parameters of other components in the initial position are obtained, and a Simulink simulation diagram as shown in Fig. 7 is established to obtain the motion characteristics of the object E.

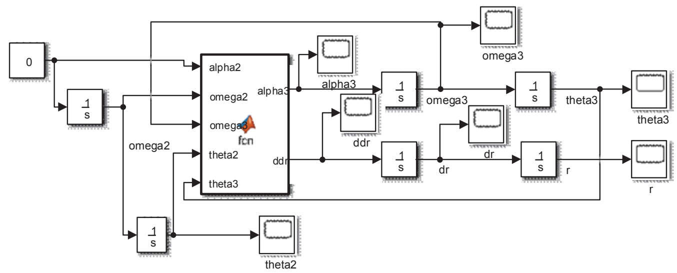

Figure 7 Simulink simulation of the crank slider

C. Simulink Simulation of the Transmission Mechanism

The four-bar linkage is combined with the crank slider to obtain a five-bar mechanism. This structure is taken as the model of the circuit breaker transmission mechanism, and the initial value of the motion of the transmission mechanism in the on-off process of the studied circuit breaker is set according to the ratio of the four-link and crank-slider models. The Simulink diagram as shown in Fig. 8 is established. The opening time is set to t=0.07s, and the closing time is set to t=0.05s, the displacement and acceleration characteristics of the opening and closing of the moving contact is obtained.

D. Result Analysis

According to the simulation Fig. 8, the opening and closing displacement curve and the acceleration curve of the moving contact can be obtained, as shown in Fig. 9 to Fig. 10:

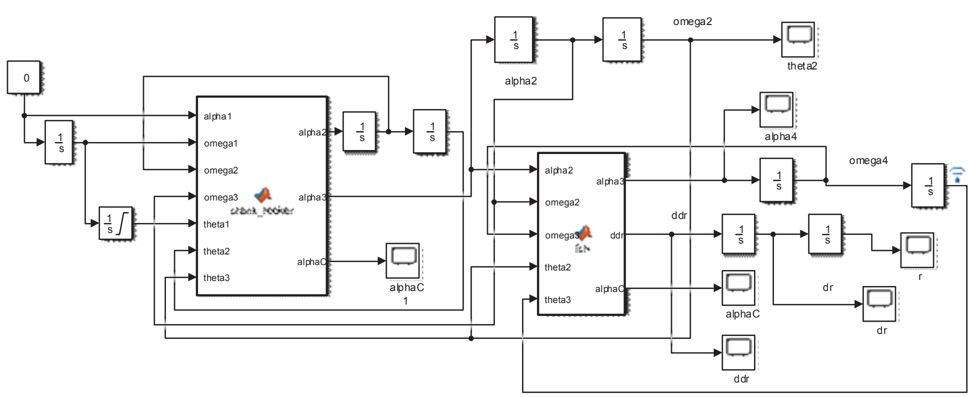

Figure 8 Simulation of the transmission mechanism Simulink

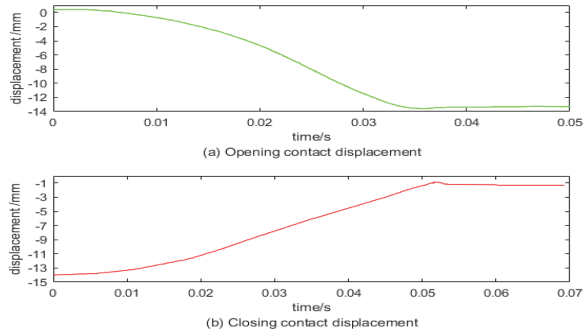

Figure 9 Contact displacement curve

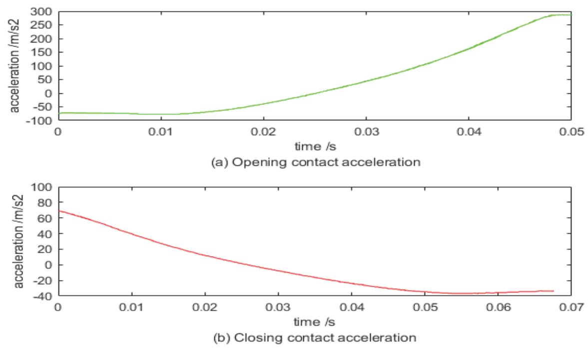

Figure 10 Contact acceleration curve

From the above-mentioned moving contact motion characteristic graph, it can be known that:

1) The results of the displacement of the moving contact are shown in Fig. 9. Figs. (a) and (b) respectively represent the opening displacement curve and the closing displacement curve. The abscissa represents the time of the on-off operation, the unit is s, and the ordinate represents the displacement of the moving contact, the unit is mm. It can be seen from the figure that the opening displacement of the contact is close to 14mm and the closing displacement is 13mm, which may be caused by the error in the initial value setting and calculation process of the model.

2) The results of the dynamic contact acceleration are shown in Fig. 10. Figs. (a) and (b) represent the opening and closing acceleration curves and closing acceleration curves of the circuit breaker. The abscissa indicates the opening and closing operation time, the unit is s, and the ordinate indicates the change of acceleration during the opening and closing process of the moving contact, and the unit is m/s^2. It can be seen from the figures that the accelerations at the start and end of the opening are $-73m/s^2$ and $275m/s^2$ respectively; when closing, the acceleration is from about $70m/s^2$ at the beginning to about $-38m/s^2$ at the end. At about 25ms, the acceleration of the opening and closing is about 0, and the direction of acceleration changes, mainly because the force provided by the buffer and the driving force provided by the operating mechanism work together.

3) It can be seen from Figs. 9 and 10 that the opening operation time is shorter than the closing operation time, which is consistent with the actual situation, because the opening operation has higher requirements for arc extinguishing characteristics, and the contact displacement is approximately the same, the brake time is shorter, indicating that the opening speed is faster, and it can better meet the arc extinguishing requirements of the circuit breaker.

E. *Rational Discussion*

The simulation results are compared with the literature [9][10] and the closing displacement and acceleration are shown in Figs. 11 to 14.

Figs. 11 and 12 respectively show the comparison curve of the opening and closing displacement. Figs. 13 and 14 respectively represent the comparison curve of the opening and closing acceleration. The curves are divided according to the movement of the contact opening and closing using to the different color boxes.

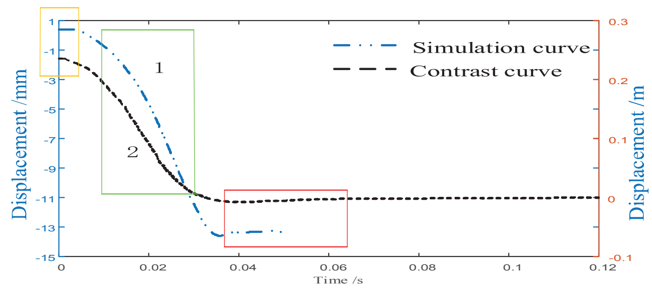

Figure 11 Comparison curve of the opening displacement

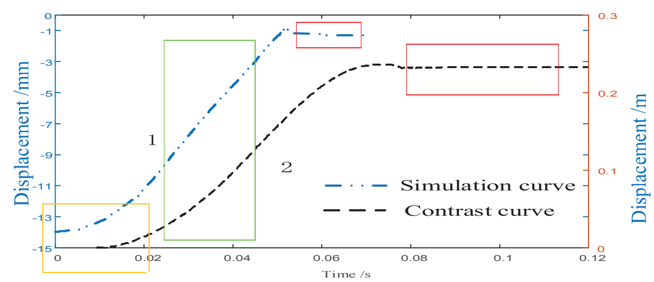

Figure 12 Comparison curve of the closing displacement

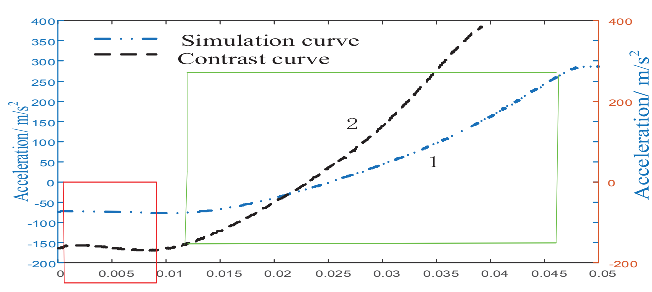

Figure 13 Comparison curve of the opening acceleration

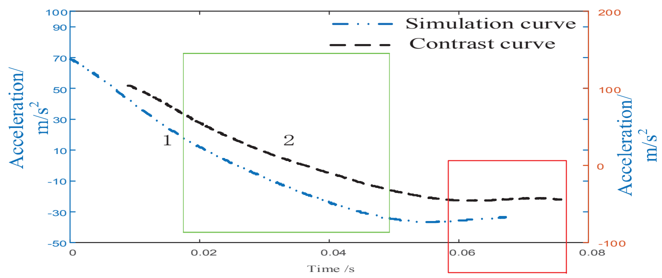

Figure 14 Comparison curve of the closing acceleration

1) It can be seen from Figs. 11 to 14 that the trends of the two curves in each box are almost the same, which are consistent with the movement behavior of the circuit breaker contacts, and verifying the four-bar linkage and crank slider model rationality.

2) On the whole, there is a big difference between the simulation curve and the comparison curve, which is caused by the difference in the type of circuit breakers studied, so that the basic parameters such as the opening and closing action time and the contact opening distance are different, thus resulting in the overall difference between the two curves.

V. CONCLUSION

From the perspective of theoretical modeling, this paper uses Matlab/Simulink to analyze the motion characteristics of the circuit breaker transmission mechanism. Firstly, the four-link and crank-slider motion model is established for the circuit breaker transmission mechanism, and the motion simulation of the member is carried out in Simulink. Then the four-link and crank slider motion functions are combined in Simulink to simulate the motion characteristics of the transmission mechanism. Finally, the simulation results are analyzed.

Through the analysis of the displacement and acceleration characteristic curves during the opening and closing operation of the moving contact and the comparison with the related literature, it can be seen that the established model has certain rationality, which roughly conforms to the change trend of the displacement and acceleration of the circuit breaker opening and closing operation.

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