International Journal of Multimedia and Ubiquitous Engineering
Vol.11, No.2 (2016), pp.57-68
http://dx.doi.org/10.14257/ijmue.2016.11.2.08

Mechanical Characteristics of Vacuum Circuit Breaker: A Simulation Based Experimental Study

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Abstract

Electrical industry is with the rapid development. Vacuum circuit breaker, with advantages of good arc resistance, suitable for frequent operation, long electrical service life, high reliability, long maintenance cycle, has been widely used in many applications. Modern conditions need high voltage vacuum circuit breaker and it has a difference with common vacuum circuit breaker. Mechanism characteristics are a most important aspect for the vacuum circuit breaker and more attention should be paid attention. In this paper, mechanism characteristics are studied for a certain model of vacuum circuit breaker and a simulation method is developed. With the method, curves variation of travel, speed, length increasing of contact spring with time has been developed and given in the paper. With responsible device, some parameters are tested in the experiment. The test results show that the simulation results are coincidence with the test results, which mean the effect of the simulation method. Mechanism characteristics can be well described with the model the paper proposed.

Keywords*: vacuum circuit breaker, mechanism characteristics, simulation method, experimental test*

1. Introduction

With the development of electrical industry, vacuum circuit breaker, with advantages of good arc resistance, suitable for frequent operation, long electrical service life, high reliability, long maintenance cycle, has been widely applied in the voltage circuit system. Vacuum circuit breaker can generally be divided into multi voltage levels. And the low voltage level is often used for explosion-proof electrical use.

There are three main parts exist in vacuum circuit breaker: (1) the vacuum interrupter, which is the unit for the arc extinguishing; (2) the electromagnetic or spring operating mechanism, which is the operation unit to control the vacuum interrupter working, and (3) frame and other parts, and this part is to support and cooperate with other parts in the operating process. With the development of applications of high voltage power transmission, vacuum circuit breaker for high voltage condition has been developed rapidly. Its range is from tens of kilovolt (kV) in the past to hundreds of kilovolt today. High voltage vacuum circuit breaker has its own characteristics, and some structures also have a big difference with the vacuum circuit breaker commonly used. Aiming to this difference, various research should be developed.

ISSN: 1975-0080 IJMUE

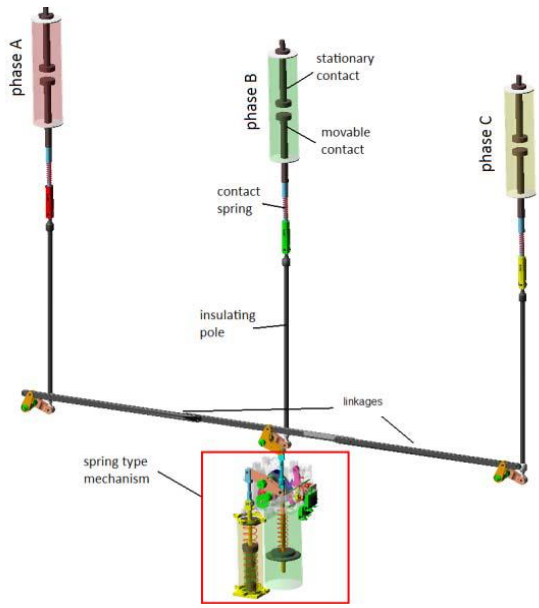

Figure1. Model of Vacuum Circuit Breaker

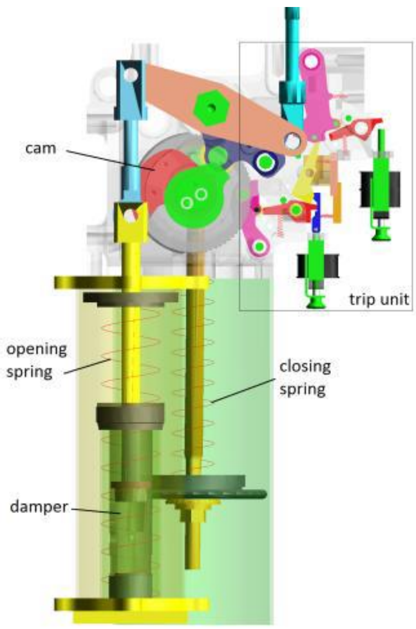

Figure 2. Spring Type Operating Mechanism

In the high-voltage vacuum circuit breaker (VCB), two components have the greatest influence on the performance: vacuum interrupter and operating mechanism. Operation mechanism is used in the operation contacts in the vacuum interrupters. Vast of studies have been done in a vacuum arc and contact materials. Performance has been improved greatly. However, not so many studies focus on the operation of high-voltage vacuum circuit breaker mechanism. So, it is necessary to study vacuum arc control for high-voltage vacuum circuit breaker to obtain better mechanical properties. Structures of vacuum circuit breaker are shown in Figure 1 and Figure 2 [1].

Lots of papers on the vacuum circuit breaker have been published in the past years [2-5]. Recently, Multi break vacuum circuit breaker is considered reasonable and feasible choice [6-8], and responsible research on it has also been developed [9-11]. The concept of multi vacuum circuit breaker based on light control module type has also been proposed [12-13].

When the high current vacuum arc extinguished, a lot of residual charge still exists in the contact gap. One of important research contents is the diffusion characteristics of the residual charge in dynamic dielectric recovery process in vacuum circuit breaker [14-16].

With the development of technology, characteristics of permanent magnetic keeping, permanent magnetic actuator in electronic control for vacuum circuit breaker are concerned [17-19], permanent magnetic actuator operation for its high stability is becoming more and more popular [20-23]. Furthermore, precision issues in operating mechanism is still the focus of researchers [24-25]. Dispersion is influenced by the factors of the motion, the environmental temperature and control voltage is the two most important factors affecting the performance.

There are several main developing trends of vacuum circuit breaker: (1) the small vacuum interrupter, (2) vacuum circuit breaker with large capacity and high voltage, (3) the new contact materials, (4) new contact structure, (5) intelligence, (6) high mechanical operating performance, (7) advanced row sealing process, (8) improved interrupter technology and comprehensive performance, (9) specialized breaker, (10) low voltage

Because of alternating environment of low temperature and high temperature, high wet or dry working conditions, the vacuum circuit breaker is tested by comprehensive properties. Generally, vacuum circuit breaker needs to ensure the high reliability in order to ensure the normal operation of power supply or other purposes, so the mechanical properties under different conditions are quite necessary.

This article focuses on the mechanical properties of vacuum circuit breaker and its high temperature mechanical properties. According to the research, working characteristics of the vacuum breaker can be effectively understood. Corresponding products with special researched would be sold in a certain market. This can reduce the production cost of the condition of meeting the general requirements of consolidation.

The main contribution of this paper is studying the mechanism characteristics of vacuum circuit breaker permanent magnetic actuator and proposed a simulation method. This simulation method is composed of two parts: simulation of the mechanism characteristics and simulation of coil current. With the simulation method, performance of closing and opening processes have been studied for a certain vacuum circuit breaker. The remainder of the paper is organized as follows: Description of the model would be listed in section 2. Simulation results are shown in section 3. The verification is shown in section 4. And the conclusion is described in section 5.

2. Models

2.1. Geometric Model

Mechanical parameters of vacuum circuit breaker is shown in Table 1.

Table 1. Main Parameters of Vacuum Circuit Breaker

Items	Value
Break distance/mm	60
Contact closing force/N	170±50
Just opening speed /m/s	＞2.5
overrun/mm	25
Average closing speed/mm	1.4±0.2
Average opening speed/mm	3.1±0.2
stiffness coefficients of contact spring/N/mm	50
Preloading of contact spring/N	5000

2.2. Static Simulation Model

Magnetic field of the vacuum circuit breaker can be calculated with the finite element method, while magnetic field distribution can be described with the Maxwell equation:

$$\frac{\partial}{\partial r}\left(\frac{1}{\mu \cdot r}\frac{\partial(rA_\theta)}{\partial r}\right)+\frac{\partial}{\partial r}\left(\frac{1}{\mu \cdot r}\frac{\partial(rA_\theta)}{\partial z}\right)=-J_\theta \tag{1}$$

Where, A is the magnetic vector at each node; u is the magnetic permeability; J is the density of current. The magnetic attraction of the plunger can be expressed as the following:

$$F=\iint_s\left[\frac{1}{\mu}(\vec{n}\cdot B-\frac{1}{2\mu}B^2\vec{n}\right]ds \qquad B=\nabla\times A \tag{2}$$

Where, $\vec{n}$ represents the unit vector of the plunger surface; s is the outer surface area; B represents the induction strength of magnetic. Then, plunger magnetic attraction and total magnetic flus linkage can be calculated.

According to the principle of permanent magnet mechanism and during the moving process, magnetic attraction F can be calculated by:

$$F=F(s,i) \tag{3}$$

And flux linkage ψ can be got by:

$$\psi=\psi(s,i) \tag{4}$$

Equation of (3) and (4) are nonlinear functions, and both current and displacement would be varied to acquire the desired functions.

2.3. Dynamic Simulation Model

This model is used to solve the problem of changes of parameters of electromagnetic and mechanism. In this model, two side effects should be taken into consideration: electromagnetic parameters of magnetic attraction of plunger and magnetic force of mechanical parameters.

Differential equations (5), (6), and (7) can be used to express the dynamic behavior of the permanent magnetic actuator.

$$\frac{d\psi(s,i)}{dt}=U_c-i(t)\cdot R \tag{5}$$

$$m\frac{d^2s}{dt^2}=F_m(s,i)-F_f(s,\frac{ds}{dt}) \tag{6}$$

$$\frac{ds}{dt}=v \tag{7}$$

Where, ψ represents the magnetic flux linkage of the active coil;
R represents the coil resistance; i represents the coil current;
U_c represents the capacitor voltage;
F_m and F_f represent the magnetic attraction and the reaction force on the plunger ;
M represents the plunger mass; S represents moving plunger displacement;
V represents the plunger moving velocity.

The reaction force of the designed for vacuum circuit breaker is shown in Figure 3. In the Figure, f_c is the reaction force of the circuit breaker and the G_m is the weight of moving part of the circuit breaker.

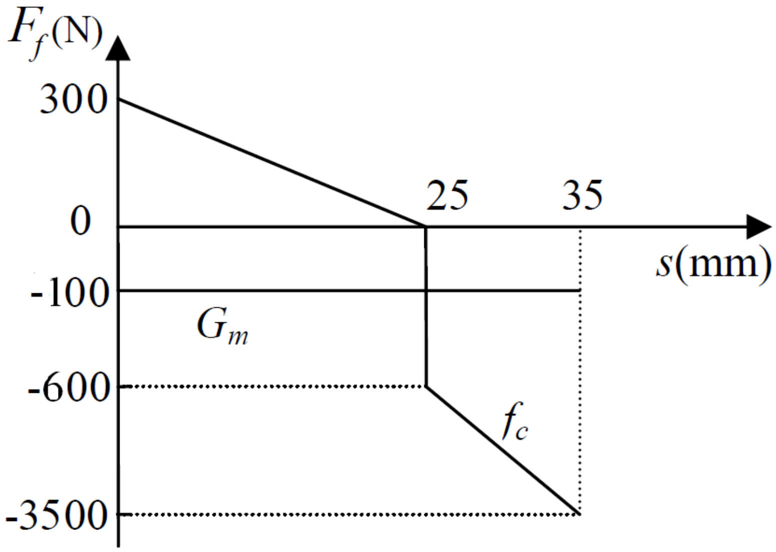

Figure 3. Characteristic of Vacuum Circuit Breaker in Reaction Force

In order to analyze the problem easily, equation (5) can be studied more detailed. ψ which represents the total flux linkage can be divided into two parts: (1) ψ_m , which is generated by a permanent magnet; (2) ψ_c , which is generated by the current. Then,

$$\psi = \psi_m + \psi_c \tag{8}$$

The flux linkage ψ_m is just influenced by the mover position, $\psi_m = \psi_m(s)$. And the ψ_i is influenced by the position and current. $\psi_c = \psi_c(s, c)$. Then, we can get:

$$\frac{d\psi_m(s, c)}{dt} = \frac{\partial \psi(s, c)}{\partial t} \cdot \frac{dc}{dt} + \frac{\partial \psi(s, c)}{\partial s} \cdot \frac{ds}{dt} \tag{9}$$

Coil equation can be described as the following:

$$\frac{dc}{dt} = \frac{U_c - c \cdot R - \frac{\partial \psi(s, c)}{\partial s} \cdot \frac{ds}{dt}}{\frac{\partial \psi(s, c)}{\partial c}} \tag{10}$$

The equation (10) is the dynamic description of electrical circuit.

The other mechanism characteristics of vacuum circuit breaker would be calculated with the ordinary nonlinear or linear dynamic theory.

2.4 Flow Chart of Simulation

In the modeling process, the clearance between the parts and accessories will not be taken into consideration, and friction forces between the different parts are neglected. Assumption of rigid connection between the components are adopted.

Modeling and simulation ability is quite great with Matlab/simulation software. Modeling and simulation processes is as shown in Figure 3. In work environment of Matlab, geometrical model of vacuum circuit breaker is designed with the actual size. Constraint and load are added to the working state of vacuum circuit breaker status. Distinguish between constraint types should be especially paid attention.

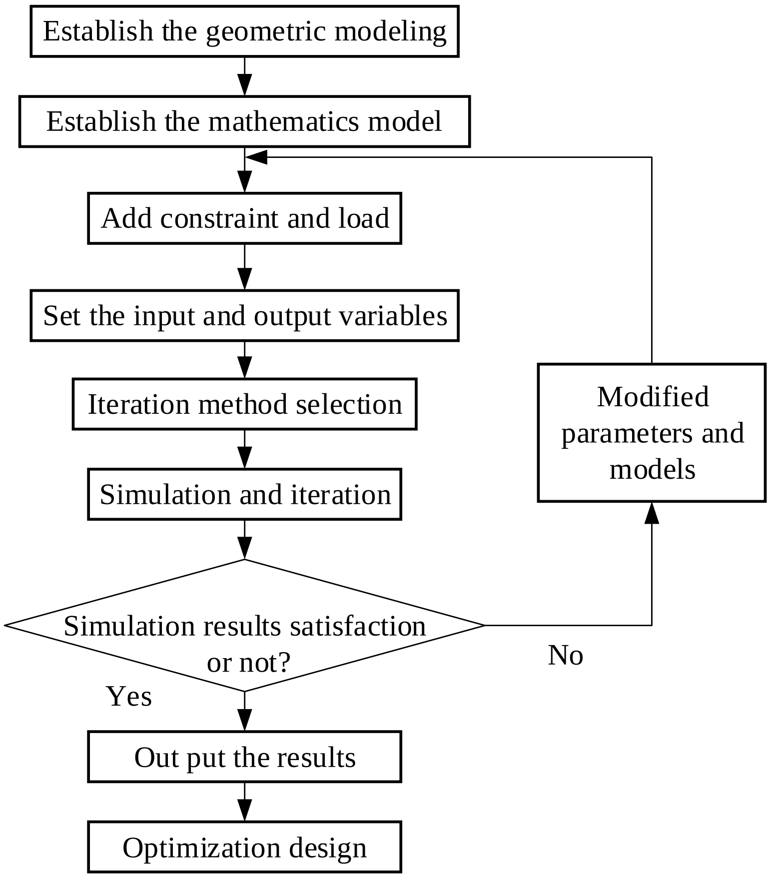

Figure 4. Flow Chart of Simulation Process

3 Simulation Results

3.1 Closing Process

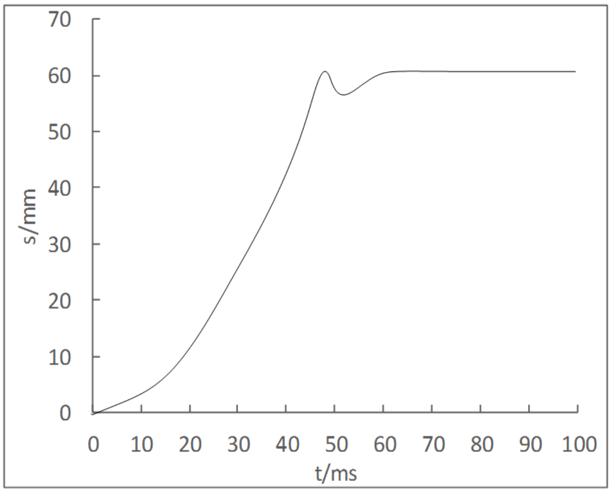

Figure 5. Closing Travel-Time Curve

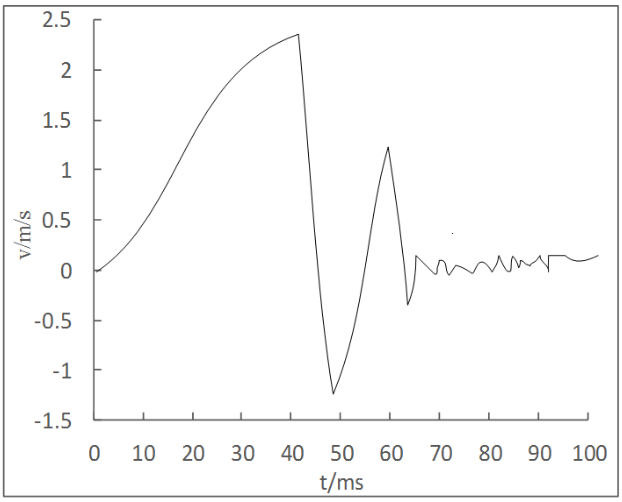

Figure 6. Closing Speed-Time Curve

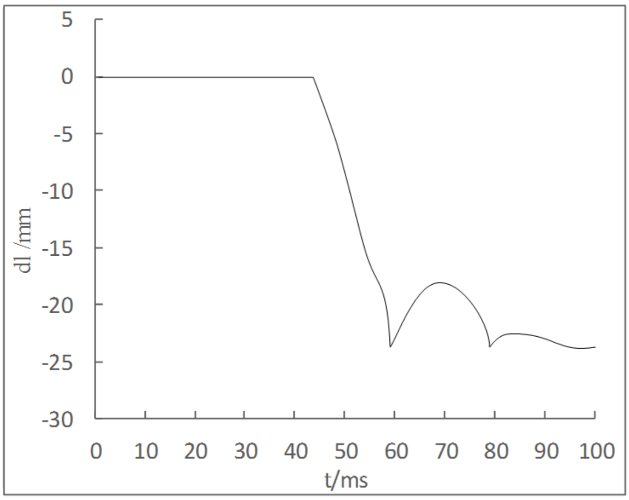

Figure 7. The Decrease of the Length of Contact Spring

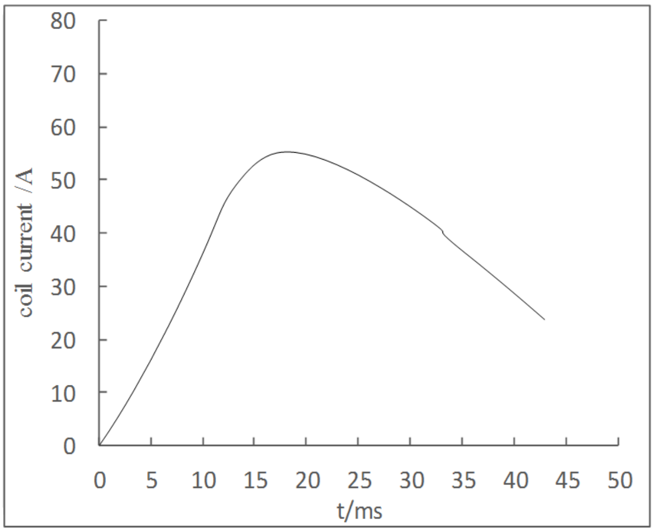

Figure 8. Current Variation with Time

From Figure 5 to Figure 7, the moving contact began to touch together with the static contact at the time of 48ms, then the contact spring would be compressed till the overrun time is finished. There is a slight wobble happened at the left end of the characteristic curve of the contact position. This is mainly because of the influence caused by the contact bounce. The closing operation process would last about 58ms. The average closing speed is 1.29 m/s . Maximum displacement of closing bounce is 2.3mm. From the simulation results, motor transmission device to meet the requirements of mechanical properties in the closing operation process. The current variation can be seen as Figure 8.

3.2 Opening Process

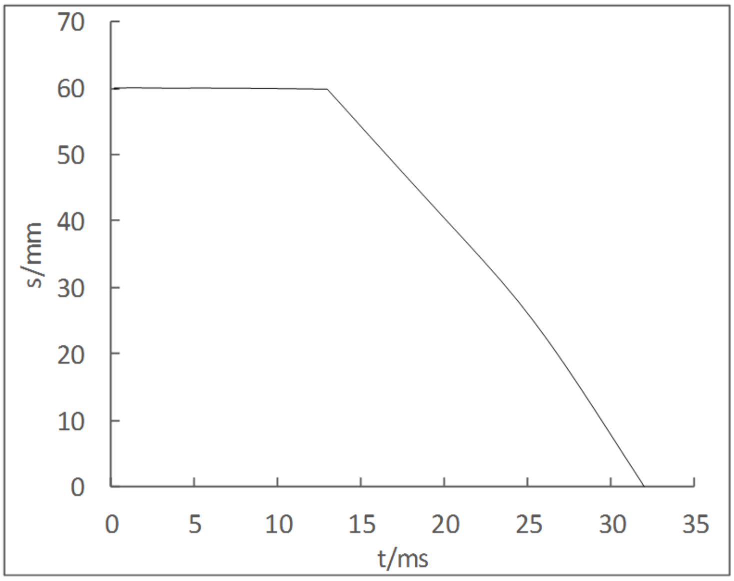

Figure 9. Opening Travel-Time Curve

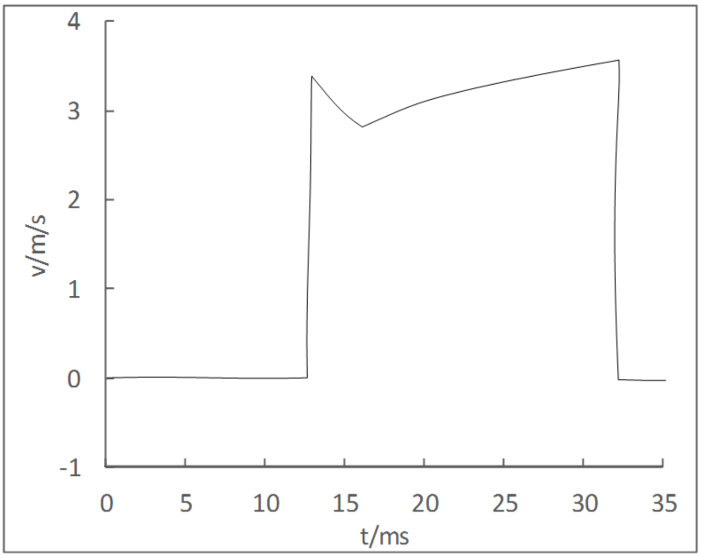

Figure 10. Opening Speed-Time Curve

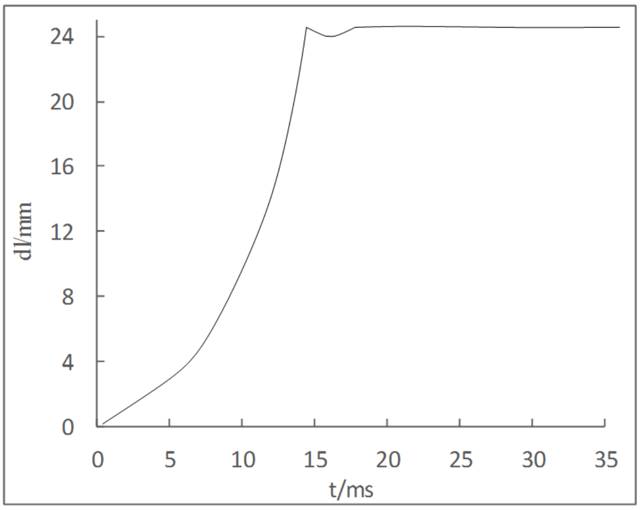

Figure 11. The Increases of the Length of Contact Spring

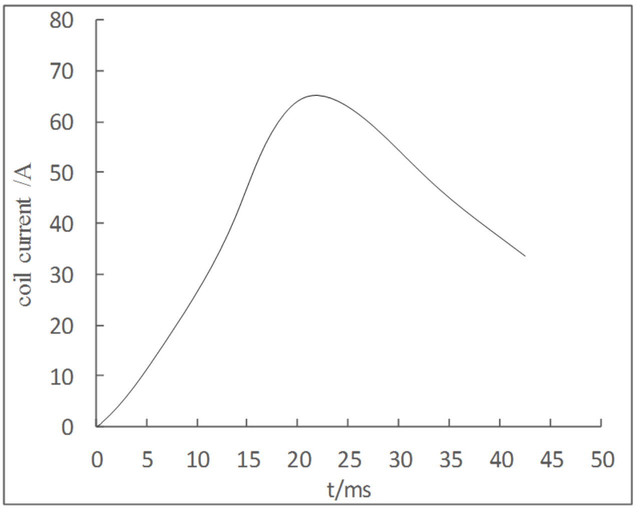

Figure 12. Current Variation with Time

Curves of variation of travel, speed, length increasing of contact spring with time for opening the process is shown in Figure 9 to Figure 11. As can be seen, it is a static moving contact, moving contact is static, and the moving contact keeps the touch with static contact all the time. The conducting rod would move down the reaction of motor actuator. After knock the moving contact at time of 12.5ms, the conduct rod would move upside rapidly with the speed of $3.13\,m/s$. The duration time of opening operating process would last some 31.4ms. And from the simulation results we can see that the motor actuator can meet the demand of the mechanical characteristics when the breaker is in the open process. The current variation in open process is shown in Figure 12.

4. Verification Experiment

In order to verify the simulation results, some experimental device is used to test some key parameters. Voltage and coil current are tested by Hall voltage and current sensors. Models of which are VSM500 and CSM200L respectively. Linear displacement sensor with high test accuracy is used to test the displacement of the moving plunger of the actuator. 8 channels with 32bit device would use to receive the signal from the voltage and current signals. A virtual software would use to display and store the data.

Both test and simulation results of contact of the vacuum circuit breaker are shown in Table 2. We can see that the simulation results have little difference with the test results. This means that the simulation method proposed in the article is effective to simulate the mechanism characteristics of the vacuum circuit breaker.

Table 2. Comparison of Simulation and Test Results

Items	Simulation results	Test results
Average closing velocity (m/s)	0.87	0.82
Average opening velocity (m/s)	1.73	1.62
Maxim current of closing coil (A)	70	75
Maxim current of opening coil (A)	78	85

5. Conclusion

Electrical industry is with the rapid development and vacuum circuit breaker has been much more widely applied in various conditions. It can be divided into different classes and each class can be applied in a certain field. Modern conditions need high voltage vacuum circuit breaker and many key technologies should be developed. Mechanism characteristics are a most important aspect for the vacuum circuit breaker.

In this paper, mechanism characteristics are studied for a certain model of vacuum circuit breaker. Curves of variation of travel, speed, length increasing of contact spring with time has been given in the paper. With responsible device, some parameters are tested with the experiment. The test results show that the simulation results are coincidence with the test results. The simulation method is effective and mechanism characteristics can be described with the model of the paper proposed.

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