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New Structure Design for 126kV HV Vacuum Circuit Breaker

Xie Jiuming[1,2], Sun Dengyue[1], Wang Jianzhong[2], Cao Jianbo[2] and Liu Wenping[2]

[1]*National Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Yanshan University, Qinhuangdao, 066004*

[2]*Research Institute of Tianjin Benefo Machinery & Electric Holding Group LTD, Tianjin, 300350*

lxjmzxt@126.com

Abstract

This paper analyzes the advantages of double breaks under series connection for 126kV HV vacuum circuit breaker. It makes efforts in the break designing to avoid hidden danger brought by voltage-sharing capacitor. Voltage is evenly distributed in the shape of ▽ at the basic break that asks for no voltage-sharing capacitors. Permanent magnetic actuator is used to ensure the synchronization of opening and closing of double breaks. Based on this layout, this paper designs a new actuator and motion system for vacuum circuit breaker optimized by virtual prototype software ADAMS and genetic algorithm. Laboratory tests have proved that the opening and closing speed of the breaker meets the speed standard and that the 126kV HV vacuum circuit breaker is feasible.

Keywords: *double breaks, voltage-sharing, synchronization, motion system, optimization*

1. Introduction

With economic development and the rise of people's living standard, the demand of electricity is surging, promoting the rapid growth of power grid enterprises. Grid capacity is enlarging and voltage class is increasing. Safer and more reliable electrical facilities have been put into use [1]. State Grid proposes that electric facilities are expected to be" outdoor-oriented, small in size, low in cost, safe and reliable with advanced technology" [2]. Currently, grid of 126kV voltage class is widely used in urban areas with SF6 switch as the main kind of switch. In 1997, SF6 was confirmed as a greenhouse gas at the Kyoto Conference. It is able to exist in the air for3200 years and its Global warming Potential (GWP) is 24900 times of that of CO2. Thus, its usage and release must be limited [3]. Under high voltage, with the increasing understanding about vacuum circuit breaker and manufacturing technology, many researchers agree that high-voltage vacuum circuit breaker is the future of breakers [4-7]. The problem will be addressed by substituting vacuum for SF6.

Vacuum circuit breaker is a kind of machinery equipment with electrical properties. Its electrical properties rely on machinery a property, which means to ensure the opening and closing speed of the vacuum circuit breaker especially. Vacuum circuit breaker designed aims at realizing electrical properties according to which machine parameters are designed to guarantee the machinery properties. Machinery properties rest upon motion system whose quality will affect the reliability of the equipment [8-10]. Therefore, it is necessary to control the design of the motion system.

This paper analyzes the advantages of double breaks under series connection for 126kV HV vacuum circuit breaker. Two vacuum arc interrupters of 72.5kV constitute the 126kV vacuum circuit breaker under series connection. Through a new layout, the voltage can be

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evenly distributed at the breaks and permanent magnetic actuator makes the synchronization of two breaks possible. The motion system of the vacuum circuit breaker is designed and optimized and its opening and closing speeds improved as a result. Laboratory experiments have proved that the opening and closing speed of the breaker meets the speed standard.

2. Theoretical Analysis of 126kV Vacuum Circuit Breaker with Double Breaks

Researchers, both home and abroad, pointed out that there were two R&D way of vacuum circuit breaker. One is to develop vacuum circuit breaker with single breaker. The other is to develop vacuum circuit breaker with double or multiple breakers [11-13]. In this paper, two vacuum arc interrupters of 72.5kV are the parts of the 126kV vacuum circuit breaker under series connection.

2.1. Insulation Breakdown Characteristic of Vacuum Circuit Breaker

Vacuum insulation breakdown is a complicated physical phenomenon. It is affected by many factors. Currently, there are three theories, namely, electron discharge theory, particle exchange theory and corpuscular theory [14-16]. Through theoretical analysis and large amount of tests, researchers concluded that vacuum insulation breakdown was caused by electrode. Though the breakdown voltage varies from research to research, it is found commonly that there was a relationship between the breakdown voltage, breakdown electric field intensity and gap length [17], as is shown in Figure 1.

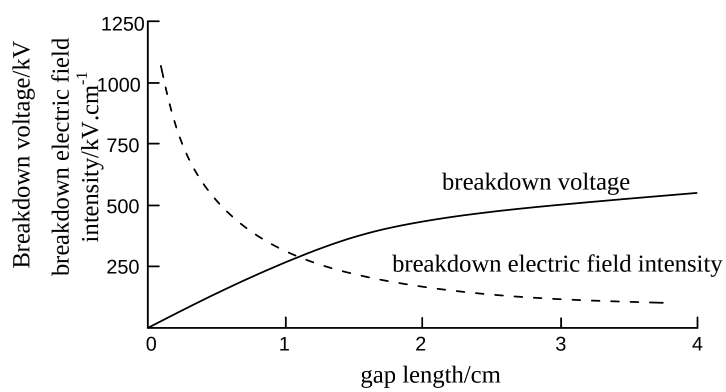


Figure 1. Relationship between the Breakdown Voltage, Breakdown Electric Field Intensity and Gap Length

Through many tests [18] and Figure 1, it is clear that when the gap distance is smaller than 0.5cm, the breakdown voltage has a linear relationship with the gap distance. There is:

$$U=Kd$$

In the expression, d—refers to gap length; K—refers to ratio coefficient.

As the gap distance increases, the breakdown voltage is denied of the linear relationship with the gap distance. And it becomes:

$$\mathrm{U} = \mathrm{Kd}^{\alpha}$$

In the expression, α is the exponent, an important factor? It is usually between 0.4~0.7.

From Figure 1, it is also clear that as the gap length increases, the exponent α is getting small. The breakdown voltage and the gap length are saturated. Therefore, it becomes difficult to enhance the voltage grade simply by increasing the gap distance.

Thus, double breaks are more reliable for 126kV vacuum circuit breaker than single break in that they have larger gap distance.

2.2. Static Insulation Characteristic of Vacuum Circuit Breaker

Insulation characteristic of the vacuum circuit breaker is used under the condition when there is no large cut-off current. Researchers mainly focus on static breakdown, static breakdown statistical analysis and static insulation breakdown mechanism [19]. Static insulation characteristic of vacuum circuit breaker with double breaks is fundamental to the design of insulation structure in vacuum circuit breaker with multiple breaks.

GIERE S and others have made comparison studies of static breakdown characteristic between double breaks and single break by applying the vacuum arc interrupter to alternating voltage and lightening impulse voltage. Results showed that when total gap length was certain, vacuum circuit breaker with double breaks had higher breakdown voltage than that with single break [20].

SHIOIRI T studied the breakdown statistical characteristic of vacuum circuit breaker. Compared to vacuum circuit breaker with single break, vacuum circuit breaker with double breakers were less likely to be breakdown under the same gap distance. Thus, vacuum circuit breaker with double breaks had higher breakdown voltage [21].

LIAO Minfu, and ZOU Jiyan [22] proposed the concept of breakdown voltage gain and worked out the expression for gain multiplier K_n of breakdown voltage with multiple breaks:

$$K_n = \frac{U_n}{U_s} = n^{(1-\alpha)}$$

In the expression, n—refers to the number of the break.

For double breaks, the gain multiplier is $2^{(1-\alpha)}$. If α is 0.5, then the gain multiplier is 1.414.

From the analysis above, double breaks have higher static insulation characteristic than single break for 126kV vacuum circuit breaker.

2.3. Dynamic Insulation Characteristic of Vacuum Circuit Breaker

Dynamic insulation characteristic of vacuum circuit breaker refers to dielectric strength characteristic and repeated breakdown characteristic under large cut-off current. LIAO Minfu and ZOU Jiyan [22] worked out a repeated breakdown model for vacuum circuit breaker with double breaks and concluded that the statistical probability of repeated breakdown of double breaks was much smaller than of single break. For double breaks, when one break is breakdown, the other one can still bear the voltage for some time and leaves the previous break time to recover. As a result, two breaks can complete the cut-off together and the vacuum switch can avoid being breakdown. What's more, researchers also found out that vacuum circuit breaker with double breaks had higher cut-off capability that was 1~1.3 times more than the single break [23-25].

Therefore, 126kV vacuum circuit breaker is expected to be equipped with double breaks as they have higher dynamic insulation characteristic that makes the fault current cut-off easier.

2.4. Functions of Moving Contact

Recovery of the insulation medium quickly requires the breaker to complete displacement distance in a short time when vacuum circuit breaker disconnects the fault current. For vacuum circuit breaker with double breaks, the kinetic energy W_d of the moving contact in the arc interrupter is:

$$W_d = 2 \times \frac{1}{2} m \left(\frac{s}{t}\right)^2 = m \left(\frac{s}{t}\right)^2$$

In the expression, m—refers to the quality of the arc interrupter for each break; s—refers to the distance of the moving contact.

For vacuum circuit breaker with single break, the quality of the moving contact is M. the distance of the moving contact is 2s. The kinetic energy W_s of arc interrupter is:

$$W_s = 2 \times \frac{1}{2} M \left(\frac{2s}{t}\right)^2 = 2M \left(\frac{s}{t}\right)^2$$

As vacuum arc interrupter of single break is much larger than that of double breaks, for the quality of the moving contact, there is M> m. Thus, the kinetic energy of double breaks is smaller than that of single break, that is, $W_d < W_s$. This does well to the actuator. The lower the output efficiency the actuator is, the easier it is to move and the more reliable it is.

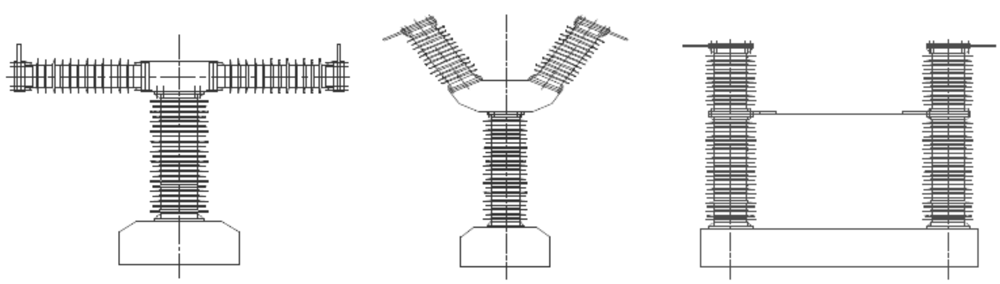
Therefore, double breaks have more advantages in terms of mechanical movement for 126kV vacuum circuit breaker.

3. Key Problems of 126kV Vacuum Circuit Breaker with Double Breaks

For vacuum circuit breaker with double breaks, voltage is evenly distributed at the basic break is the foundation and the key problem as same as the synchronization of opening and closing of double breaks.

3.1. Break Voltage-sharing of 126kV Vacuum Circuit Breaker with Double Breaks

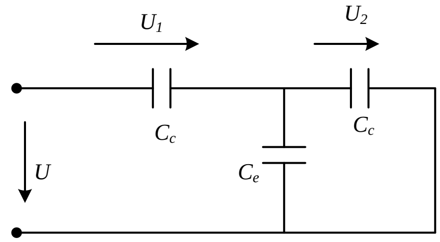
Currently, vacuum circuit breaker with double breaks is mainly in the shape of T type, Y type and H type, as is shown in Figure 2.



(a) T type (b) Y type (c) H type

Figure 2. Vacuum Circuit Breaker with Double Breaks

Though the voltage at each break is similar to each other, it is unevenly distributed due to the distributed capacitance. Equivalent circuit of vacuum circuit breaker with double breaks is shown in Figure 3.



U—Supply Voltage; U_1, U_2—Break Voltage; C_c—Break Capacitance; C_e—Earth Capacitance

Figure 3. Equivalent Circuit of Vacuum Circuit Breaker with Double Breaks

Therefore, the voltage at two breaks is distributed as:

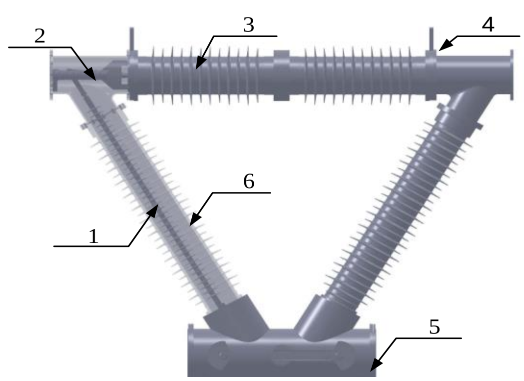
$$U_1 = U\frac{C_c + C_e}{2C_c + C_e}$$

$$U_2 = U\frac{C_c}{2C_c + C_e}$$

C_c and $C_e$are at μF level. If $C_c = C_e$, there are $U_1 = \frac{2U}{3}, U_2 = \frac{U}{3}$.

From the expression, we can see that the voltage at one break is twice as at the other, which results in an uneven distribution of voltage during the cut-off. This will makes the break under higher voltage easier to breakdown and relight the arc after cut-off and brings the equipment down. Therefore, the voltage-sharing capacitor is introduced to each break and these capacitors are under parallel connection. However, parallel connection of voltage-sharing capacitors may bring hidden danger to insulation or ferromagnetic resonance [26-28].

The layout design of 126kV vacuum circuit breaker with double breaks is based on the abovementioned principles. ▽ type is adopted to optimized the voltage distribution at two breaks, as is shown in Figure 4.



1—insulated pulling level; 2—reversing mechanism; 3—vacuum arc interrupter;
4—connecting terminal; 5—actuator; 6—insulation terminals

Figure 4. Layout of the New 126kV Vacuum Circuit Breaker with Double Breaks

From this layout, it can be seen that two vacuum arc interrupters are directly connected in a short distance. The connection point is at least 1000mm away from the earth point. So the earth capacitance of the conductor can be neglected. The equivalent circuit is shown in Figure 5.

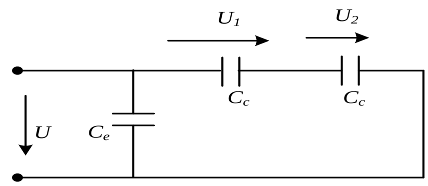


Figure 5. Equivalent Circuit for the New 126kV Vacuum Circuit Breaker with Double Breaks

In this layout, the voltage distribution at two breaks is basically the same. And they are freed from parallel connection and thus the negative influence of voltage-sharing capacitor is avoided.

3.2. Break Synchronization of 126kV Vacuum Circuit Breaker with Double Breaks

One of the key concerns of the design of the 126kV vacuum circuit breaker with double breaks is the synchronization of opening and closing. According to researches on dynamic medium recovery and the cut-off ability [29-30], breaks are not synchronized at millisecond level, which may result in significant disparity of arcing time under cut-off current. As a result, the voltage at the breaks is unevenly distributed. It would further lead to that the electric wear varies from moving contacts and that the vacuum arc would be reignited. The cut-off may even turn out to be a failure.

In the switch of HV, spring mechanism and hydraulic mechanism are common actuators. But as these two mechanisms contain many parts and are less stable during the drive, it is hard to ensure the synchronization of the opening and closing of the break. An electron-drive permanent magnetic actuator is widely used in the vacuum equipment of medium-voltage. Such actuator has few parts and only one moving part. Besides, it is high in movement accuracy at μs level and long mechanical longevity [31-33]. Therefore, permanent magnetic actuator is used as the actuator of the 126kV vacuum circuit breaker with double breaks.

4. Determining the Motion System for 126kV Vacuum Circuit Breaker with Double Breaks

Motion system is the main body of the vacuum circuit breaker, including drivetrain system and dynamic system. The acquisition of the electrical properties is mainly controlled by the motion system.

4.1. Determining the Stress Propagation of Insulating Bar

As 126kV vacuum circuit breaker adopts double-breaks under series connection and is far from the ground, the insulating bar, thin and long, is comparatively large in size. Also, the arc interrupter of the breaker requires stronger contact force. Therefore, if we apply the mode of pressure-power transmission to control the closing of the vacuum circuit breaker, the deflection of the insulating bar must be unstable. This problem can be avoided by increasing the diameter of the bar, which will definitely increase its size and weight. As a result, more ready-made materials and power are demanded, and the inertial force of the drivetrain system will be increased. This would lead to the inevitable reduction of opening and closing speed of the vacuum circuit breaker for permanent magnetic actuators with certain output power. This does no good to the electrical properties. In comparison, the mode of tension-power transmission can free the insulation bar from deflection. Moreover, transmission parts should be kept as few as possible during the designing.

4.2. Measures to Improve the Opening Speed

For 126kV HV vacuum circuit breaker with double breaks, increasing the opening speed is beneficial for the arc to break. The characteristic of the permanent magnetic actuator power is that it becomes stronger as the air gap between the moving core and the static core narrows, which is not good to increasing the opening speed.

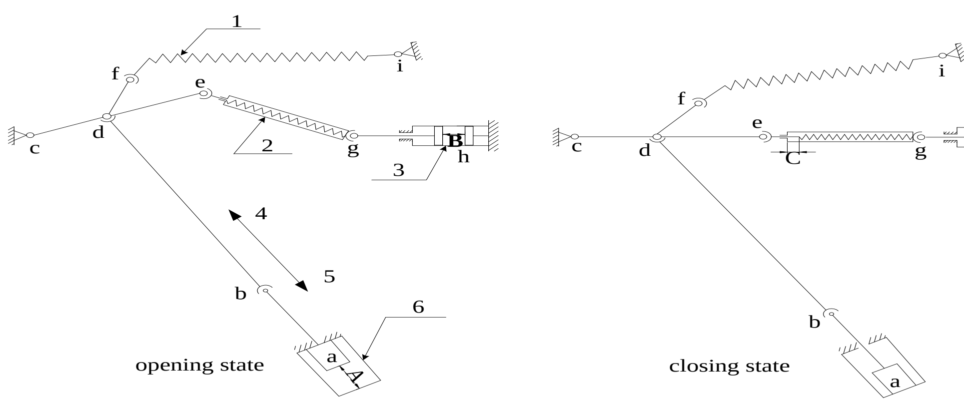
After the spring breaks and stores power, the output format of the spring force is just the opposite of that of the permanent magnetic actuator. When the spring releases its energy, the more it breaks, the stronger the energy is. In order to increase the opening speed of the 126kV vacuum circuit breaker, especially the initial speed when the contacts just starts to open, we can add more breaking springs in the motion system.

4.3. Design of the Breaking Spring

When the breaking spring is added to the motion system, the retentivity of the permanent magnetic actuator will distribute part of its power to the breaking spring to make it store the energy. The other part is given to the moving contact of the arc interrupter to make the contact have certain amount of pressure to sustain the power and thermal stability of the vacuum circuit breaker. But the breaker has high requirements for both two parts of the power. In order to ensure the closing, the retentivity of the actuator should be tremendously huge. And the strength of the retentivity is related to the cross sectional area of the moving core and the magnetic field intensity of the permanent magnetic actuator. Therefore, increasing the size of the actuator would lead to a waste of materials and the enlargement of the size of the whole system.

In this paper, the "dead point" principle is followed. The closing retentivity of the actuator meets the standard as long as it reaches the required amount of power of the breaking spring. It is also required that the reaction of the contact force of the vacuum arc interrupter does not act on the actuator. Based on that, the design of the actuator can be optimized.

Based on the analysis above, mechanical principles for the new motion system of 126kV vacuum circuit breaker are shown in Figure 6.



1—opening spring; 2—over-travel bar; 3—vacuum arc interrupter; 4—opening direction; 5—closing direction; 6—permanent magnetic actuator.

Figure 6. The Schematics of the Motion System of the 126kV Vacuum Circuit Breaker with Double Breaks

The picture shows that while the system is closing, the contact distance of the interrupter is B. When the vacuum circuit breaker completes closing, core a of the actuator is moving downward, driving insulating bar bd to move and sway, then the rocker arm cdf and fde sway. In this process, arm fde sways and drives the over-travel bar to move and sway, leading the moving contact of the interrupter to make linear motion. Then the moving and static contacts touch each other and close the system. Also, the swaying arm cdf extends the breaking spring that stores energy. When the system completes closing, the spring in the over-travel bar is extruded and provides contact force for the vacuum arc interrupter. At this point, the arm and the bar can reach the mechanically "dead point". The torque of the spring in the over-travel bar to the former de is zero. When opening, the motion sequence of the system is just opposite to the closing process.

4.4. Optimizing the Motion System for 126kV Vacuum Circuit Breaker

After setting the motion system for the vacuum circuit breaker, it is necessary to optimize the design of the parts. In this way, the system can be as light as possible with the minimum consumption of power while still serving the mechanical function required by the vacuum circuit breaker. In the dynamic system, the acquisition of the mechanical properties mainly depends on the operating force of the permanent magnetic actuator, the force of the breaking spring and the extruded force of the spring in the over-travel bar. With the effect of the dynamic system, the moving core of the vacuum arc interrupter completes the opening and closing process at certain speed.

Optimizing the 126kV vacuum circuit breaker motion system is in essence to make the opening and closing speed of the breaker satisfy the requirement of the arc interrupter in order to clarify the tension of the breaking spring in the dynamic system and the output power of the permanent magnetic actuator For the former,

$$\mathrm{F_t = F_0 + ks_t}$$

In the expression, $\mathrm{F_t}$—the tension of the breaking spring; $\mathrm{F_0}$—the initial tension of the breaking spring; *k*—elasticity coefficient of the spring; $\mathrm{s_t}$— the elongation of the spring.

For the force $\mathrm{F_c}$ of the permanent magnetic actuator, as the changing process is complicated, we simplify it as the constant force to make the analysis more convenient.

This paper employs the virtual prototyping technology together with ADAMS software. The variable of the motion system is defined as $\mathrm{F_t}$ $\mathrm{F_c}$ and *k*. Inputting different variables can produce different motion parameters so that we can know the optimal variable values.

Also, as described in document [34], the spring of the over-travel bar can be optimized by adopting optimized genetic algorithms, adjusting crossover and mutation probability and second cross, specifying genetic variation and developing immigration policy. The laboratory tests prove that the optimizing result meets the requirement for the initial and final pressure between the contacts in the vacuum arc interrupter.

5. Test of Opening-closing Speeds of 126kV Vacuum Circuit Breaker

Test the opening and closing speed of the optimized 126kV vacuum circuit breaker by Tianjin Benefo High Voltage Electric Co. Ltd. R. The instrument is a high voltage switch tester produced by Shi Jiazhuang Handy Electrical Instruments Co. Ltd. The model number is GCHD410E. A displacement sensor is used to measure the displacement data of the contact in the interrupter and the data is later applied to the computer for processing. There is no anomaly in the experiment. Testing results are shown in Figure 7 in which a represents the result of the opening and b, the closing.

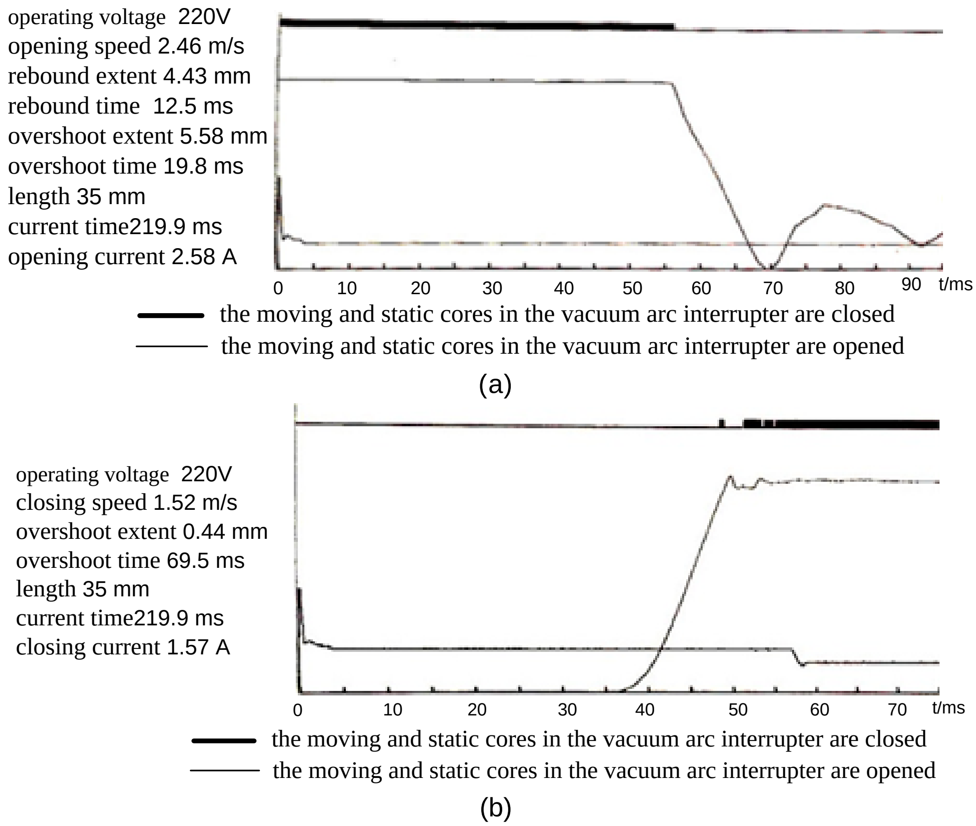


Figure 7. The Testing Result of the Opening and Closing System of the Vacuum Circuit Breaker

The result shows that the opening and closing speed of the optimized 126kV vacuum circuit breaker with double breaks satisfies the requirement of the mechanical properties.

6. Conclusions

(1) This paper expounds the advantages of 126kV HV vacuum circuit breaker with double breaks under series connection. Two 72.5kV vacuum arc interrupters constitute 126kV HV vacuum circuit breaker.

(2) It designs a new layout of the double breaks—the ∇shaped structure, making the voltage evenly distributed to avoid the harms brought by voltage-sharing capacitors under parallel connection. The actuator adopts permanent magnetic technology whose precise transmission can ensure the synchronization of the double breaks movement.

(3) Under the "dead point" principle, it proposes the mode of tension-power transmission and the breaking spring and designs a new movement pattern of 126kV vacuum circuit breaker with double breaks which can reduce the operating power of the electric magnetic actuator. Also, ADAMS and genetic algorithms are used to optimize the mechanism.

(4) The laboratory tests prove that the opening and closing speed of the 126kVvacuum circuit breaker satisfies the requirements of the mechanical properties, verifying the feasibility of the new design.

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