Research on Mechanism Design Scheme of 500kV Fast Circuit Breaker

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***Abstract*—Reducing the fault isolation time of 500kV transmission line is of great significance for enhancing the transmission capacity of transmission line and improving the security and stability of power grid. In this paper, the CTY-5/10/20 series hydraulic operating mechanism is improved.The electromagnetic repulsion mechanism is used to drive the hydraulic valve directly in the 500kV fast circuit breaker mechanism, which cancels the response time of the primary valve of the original transmission hydraulic mechanism. Finally, the action time of the mechanism is reduced to 4ms to achieve the fast response of the mechanism, and then the breaking time of the circuit breaker is reduced.Through simulation and test verification, the average opening speed of the improved 500kV fast circuit breaker mechanism can reach 10m / s, and the opening time is about 8mm.The research results of this paper accumulate experience for the future engineering application of 550kV fast AC circuit breaker in China Southern Power Grid, and provide reference for the future planning and safe and stable operation of China Southern Power Grid.**

Keywords—550kV fast circuit breaker, electromagnetic repulsion mechanism, optimal design, dynamic simulation

I. Introduction

In the actual operation of China Southern Power Grid, the transmission capacity of AC transmission lines is mainly restricted by two aspects, one is the thermal stability constraint of the line, the other is the transient stability constraint of the system, including the transient power angle stability constraint, the transient voltage stability constraint and the transient frequency stability constraint[1-2].At present, there are many cases that the transient stability limit of 500kV AC lines (such as the AC channel of West to East power transmission) within the scope of China Southern Power Grid is lower than the thermal stability limit[3]. For example, in the calculation of peak load summer in 2018, the thermal stability limit of Guangdong AC entrance is 9300mw. During the maintenance of Yumao double line, due to the transient voltage instability of Wuzhou station after the main transformer failure of Shanhua N-2 and xianlingshan splitting, the thermal stability limit of Guangdong AC entrance is lower The transient stability limit is 6300mw, and the transmission capacity of the line has a large space to improve.When large capacity power plants in Guangdong, Guangxi and other regional power grids are sent out, it is easy to cause transient instability of power grid after system failure[4]. For example, in the calculation of peak load summer in 2018, in order to avoid angle instability of Longtan Power Plant after N-1 fault of 500kV Longping line during maintenance of Longhe line a, it is necessary to limit the output of Longtan Power Plant to no more than 3000MW[5]. When the transient stability limit is lower than the thermal stability limit, the transmission capacity of AC transmission line is determined by the transient stability limit.

For 500kV high-voltage AC transmission line, the fast protection fault clearing time adopted in the simulation calculation is considered as 90ms near the fault point side and 100ms far away from the fault point side[6]. In addition to leaving a certain margin, it includes 40ms switch breaking time and 35ms relay protection fault detection, discrimination and exit time[7]. According to a large number of simulation analysis of China Southern Power Grid, it is found that the transmission capacity of 500kV AC transmission lines in China Southern Power Grid is greatly limited based on the fault clearing time specified in the current guidelines[8-9]. At present, the technical specification for breaking time of 550kV AC circuit breaker requires less than 60ms. With the current circuit breaker manufacturing process and technical level, the breaking time of most manufacturers can reach about 40ms[10]. The conventional LW-550 / Y5000-63 circuit breaker adopts CTY-10 hydraulic spring mechanism to provide opening operation power. The opening time is 17.5ms, in which the mechanism action time is 8.7ms and the precompression time is 8.8ms[11]. In this paper, through the optimization and transformation of the hydraulic mechanism, the action time of the mechanism is reduced to 4ms, so as to achieve the rapid response of the mechanism, and then reduce the breaking time of the circuit breaker.

II. Optimal design scheme of circuit breaker mechanism

A. Design of circuit breaker mechanism

In this paper, the CTY-5/10/20 series hydraulic operating mechanism is improved. The middle design is a square working cylinder, and two groups of butterfly spring groups are arranged on both sides. The others are designed according to the functions of double split coil, double auxiliary switch, double travel switch, anti slow split device, overpressure protection, self-contained buffer structure, and manual pressure relief.

When the CYT-10 hydraulic spring operating mechanism is opened, the action time of the mechanism is 8.7ms, which is 5ms for the first stage valve and 3.7ms for the second stage valve. The electromagnetic repulsion mechanism based on the principle of electromagnetic induction eddy current has the advantages of short mechanical delay time and fast initial motion speed. In this project, the repulsive mechanism is used to drive the secondary valve directly, and then the response time of the primary valve is cancelled, and finally the action time of the mechanism is reduced to 4 ms. The schematic diagram of repulsion mechanism with secondary valve is shown in Figure 1. And Figure 2 shows the primary valve and secondary valve of circuit breaker mechanism.

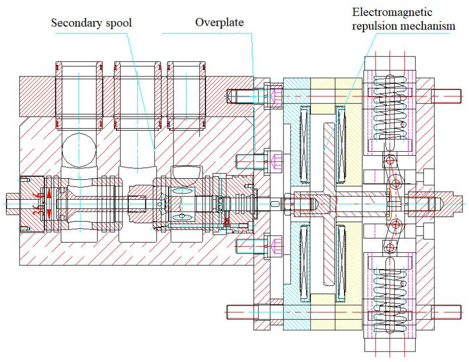
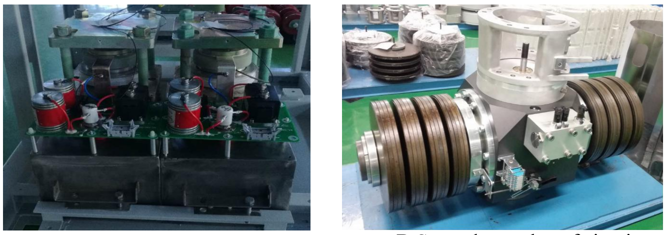


Figure1. Schematic diagram of electromagnetic repulsion mechanism with secondary valve of hydraulic mechanism



A.First class valve of circuit breaker

B.Secondary valve of circuit breaker mechanism

Figure2. Primary valve and secondary valve of circuit breaker mechanism

B. Working principle

The 500kV circuit breaker mechanism is mainly composed of valve core, electromagnetic repulsion mechanism, bistable spring holding device and control drive circuit. The electromagnetic repulsion mechanism includes opening coil, repulsion plate and closing coil. The whole structure adopts coaxial vertical layered arrangement, which can effectively improve the overall mechanical stability of the switch[12]. The specific structure is shown in Figure 3.

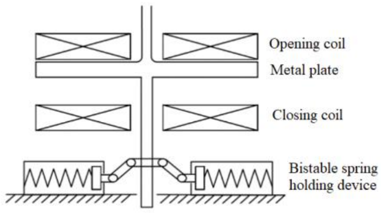


Figure 3.Schematic diagram of electromagnetic repulsion mechanism

The drive control circuit is shown in Figure 4[13]. C_1 and C_2 are respectively the pulse capacitors used in the opening and closing, R is the equivalent resistance of the line and coil, L_0 is the equivalent inductance except the coil in the circuit, D is the freewheeling diode, and K is the drive thyristor.

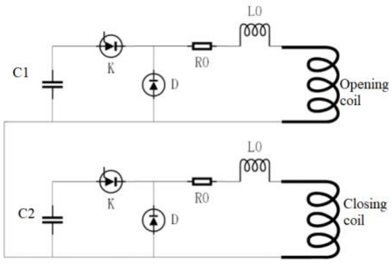


Fig.4 Schematic diagram of driving control circuit of electromagnetic repulsion mechanism

The electromagnetic repulsion mechanism adopts a relatively mature dual coil drive eddy current disk structure. When the switching unit is in the opening operation, the thyristor turns on after receiving the opening trigger signal, and the pulse energy storage capacitor discharges to the opening coil[14]. The opening coil generates millisecond pulse current, which induces a great eddy current on the surface of the metal disc, and its direction is opposite to that of the opening coil. At the same time, the metal disc instantly generates a downward electromagnetic repulsion force. When the downward electromagnetic repulsion force is greater than 0 When the device generates upward closing holding force, the metal disc drives the connecting rod and valve core to start opening. When the opening is in place, the device generates downward opening holding force. At this time, the opening process of the electromagnetic magnetic mechanism of the secondary valve is completed. The principle of closing process is the same as opening process.

III. Calculation and Analysis

A. Parameter design

Based on the traditional AC circuit breaker, this paper optimizes the design of high-power hydraulic spring operating mechanism for 550kV fast circuit breaker. The fast circuit breaker adopts three fracture series connection, and the designed output stroke of the mechanism is 202mm. The designed moving mass of the interrupter is about 80kg, the designed average closing speed is 4 ± 0.5m/s, the designed average opening speed is 13 ± 1m/s, the designed maximum closing speed is about 5.5m/s, and the possible maximum opening speed is 14~15m/s. The total travel of repulsion mechanism is 13mm, the opening resistance is 2710.5N, the opening holding force is 780N, the closing resistance is 2795.4N, and the closing holding force is 780N.

B. Calculation of main parameters of hydraulic system

After many times of optimization calculation, the output piston rod diameter of the hydraulic mechanism is 34 mm, the working piston diameter is 75 mm, and the stroke is 202 mm; the energy storage piston diameter is 75 mm, and the stroke is 83.5 mm. With a total of six energy storage pistons, the total piston area is 26507.2 square mm. According to the flow rate of hydraulic oil, the stroke of energy storage piston is 26.7mm when opening and 6.9mm when closing. The total stroke of energy storage piston is about 60.4mm to complete an O-C-O cycle.

In order to make the hydraulic mechanism fully serialized, according to the calculation, CYT-20 type disc spring of hydraulic mechanism can be used. In application, each side disc spring is overlapped by 2 pieces and matched by 8 groups (that is, each disc spring group is 16 disc springs), and the disc spring parameters are 550mm×200mm×17mm ×38.5mm. When the pre-compression stroke is 52mm (30% of the total compression), the effective stroke is 83.5mm, and the total compression stroke is 135.5mm (72% of the total compression). In this way, the maximum force of disc spring is 753.7KN, and the rated oil pressure is 56.8Mpa. At the maximum force of disc spring, the stress at point I is - 2807Mpa, the stress at point II is 545Mpa, the stress at point III is 1184Mpa and the stress at point III is - 969Mpa.

According to the requirements of design input, the mechanism should meet the O-CO operation cycle. The locking point of O-CO operation is set to be 10 mm smaller than the calculated stroke (The reserved operation leakage safety margin). The total stroke of energy storage piston is 60 mm in O-CO cycle, so that the remaining stroke after operation is 13.5 mm, it can meet the requirements of O-CO operation at full energy. In addition, in order to ensure the opening speed, the opening locking point is set below 39.9mm stroke, with a little margin, and the opening locking point is set at 39mm stroke. The compression size of the disc spring corresponding to the locking point is 91mm, and the size of the disc spring is 64.3mm after a split. At this time, the corresponding force values of the disc spring are about 669.4kn and 554.3kn respectively, so the output operation work (minimum opening work) of the disc spring is about 32672.8J. When the disc spring is opened under rated pressure, the disc spring force is 772.1kN and 719.2kN respectively when the disc spring is lowered from 135.5mm to 108.8mm, so the output work of disc spring is about 39817J under rated pressure.

The maximum tension of output piston rod is 199965n and the maximum pressure is 51725.5N. The safety factor of buckling is greater than 7.5, and the safety factor of tensile strength is greater than 3.6. Figure 5 shows the strength check results of ANSYS. The diameter of the pull rod is 34mm, the diameter of the smallest structure is 33.5mm, and the maximum stress point is 524Mpa.

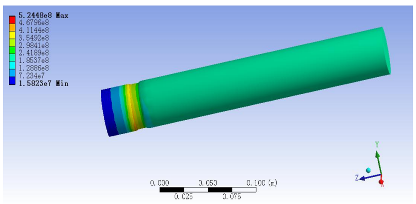


Fig.5 Strength checking simulation of mechanism pull rod

C. Parameters of electromagnetic repulsion mechanism

As the structure of electromagnetic repulsion mechanism is simple and symmetrical, the axisymmetric model can be used for equivalent simulation calculation, and the simulation model is shown in Figure 6[15]. In order to approach the actual structure, the setting of relevant parameters in the simulation is consistent with the prototype structure. The aluminum repulsion plate has a radius of 90mm and a thickness of 12mm; the cross-sectional area of the drive coil is 1mm×7mm, the inner diameter of the coil is 25mm, the outer diameter is 107mm, the number of turns is 55, and the material is copper; the total mass of the moving parts is 2kg (including the mass of the valve core, the metal disc and other moving parts); the total travel is 13mm. In the closing position, the initial gap between the opening coil and the metal disc is 4.5mm, and in the opening position, the initial gap between the opening coil and the metal disc is 4.5mm The initial gap between the closing coil and the metal plate is 5mm when the switch is in the position of the switch. The capacitance of c-opening and c-closing is 0.0025mF, the line stray inductance L_0 is 0.07mH, and the equivalent resistance on the line is 0.03 Ω.

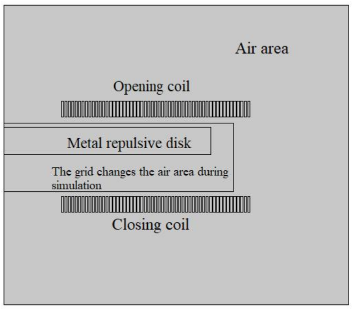


Fig.6 Simulation geometry model of electromagnetic repulsion mechanism

When the electromagnetic repulsion mechanism operates, according to the law of conservation of energy, the energy *dAs* provided by the power supply should be equal to the sum of the work done by the mechanism *dA*, the change of energy in the magnetic field *dw* and the heat loss *dQ*, as follows:

$$dA_s = dA + dw + dQ \tag{1}$$

There is magnetic coupling between the repulsive coil and the repulsive plate, and the energy balance equation as follows:

$$e_1 i_1 dt + e_2 i_2 dt = dA + dw + i_1^2 R_1 dt + i_2^2 R_2 dt \tag{2}$$

Where, e_1 and e_2, i_1 and i_2, R_1 and R_2 are the voltage, current and resistance of repulsive coil and metal plate respectively.

The magnetic energy w of the two coils depends on the following equation:

$$w = \frac{1}{2} i_1^2 L_1 + \frac{1}{2} i_2^2 L_2 + i_1 i_2 M \tag{3}$$

Where L_1 is the inductance of the repulsive coil; L_2 is the repulsive plate inductance; M is mutual inductance.

Combining equations (1) - (3), the work done by the mechanism can be obtained as follows:

$$A = \frac{1}{2} i_1^2 dL_1 + \frac{1}{2} i_2^2 dL_2 + i_1 i_2 dM \tag{4}$$

Because L_1 and L_2 are constant, the electromagnetic repulsion force of the mechanism is as follows:

$$F = \frac{dA}{du} = \frac{i_1 i_2 dM}{du} \tag{5}$$

It can be seen from equation (5) that the electromagnetic repulsion force F is directly proportional to the derivative *dM* /du of the repulsive metal displacement caused by the repulsive coil current i_1, the induced current i_2 on the repulsive metal plate and the mutual inductance between the coil and the copper plate.

Equation (6) is the motion equation of electromagnetic repulsion mechanism.

$$\frac{\partial v}{\partial t} = \frac{F_{em} - F_g - F_x - Ft}{m} \qquad (6)$$
$$\frac{\partial u}{\partial t} = v$$

Where v is the velocity of the repulsive plate; F_{em} is the electromagnetic force on the repulsive plate; F_g is the gravity of the whole moving part; F_x is the minimum opening force required to improve the secondary valve; F_t is the force exerted by the bistable spring retaining mechanism; m is the mass of the whole moving part; u is the stroke of the repulsive plate from zero.

D. Curves of various applied forces in simulation

Figure 7 shows the curve of the holding force of the bistable spring retainer changing with the stroke of the repulsion plate. The holding force of the retainer used in this simulation is 780N at the opening and closing position.

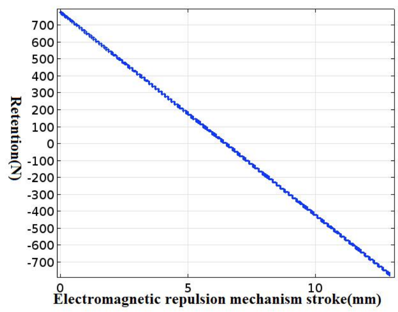


Fig.7 Curve of the retention force of the bistable spring with the travel of the repulsion plate

Figure 8 shows the curve of the opening starting force of the electromagnetic repulsion mechanism changing with the stroke. It can be seen from the curve that 2710N is the resistance before the repulsion plate moves to 4.5mm, and it becomes the power of 2795N after the repulsion plate moves to 4.5mm.

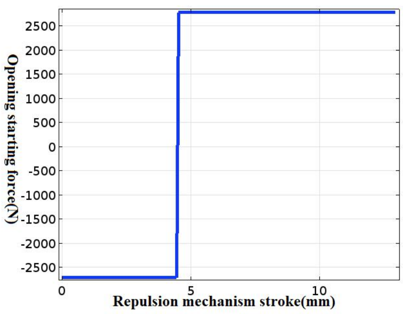


Fig.8 Curve of opening force changing with stroke of electromagnetic repulsion mechanism

Figure 9 shows the change curve of the closing starting force of the electromagnetic repulsion mechanism with the stroke. It can be seen from the curve that 2795N is the resistance before the repulsion plate moves to 8.5mm, and it becomes the power of 2710N after the repulsion plate moves to 8.5mm.

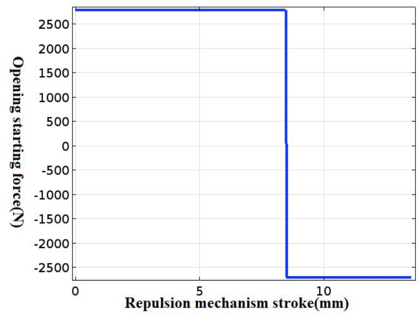


Fig.9 Curve of closing force of electromagnetic repulsion mechanism changing with stroke

E. Simulation results of multi physical fields for electromagnetic repulsion mechanism

The opening process of the electromagnetic repulsion mechanism is simulated under the conditions of capacitor charging voltage of 700V, 750V, 800V, 850V and 900v respectively. Figure 10 shows the curve of the stroke changing with time under the five conditions.

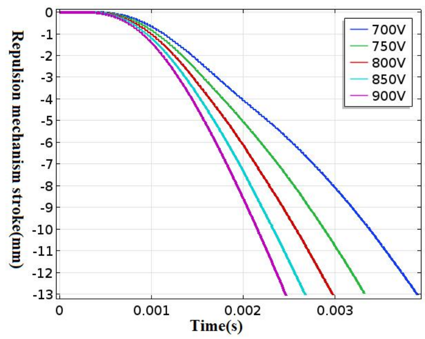


Fig.10 Curve of stroke changing with time when opening

Figure 11 shows the curve of velocity versus stroke under five kinds of voltage conditions, and Figure 12 shows the curve of electromagnetic force versus stroke in vertical direction. It can be concluded from the curve that with the increase of capacitor voltage, the shorter the time to reach the rated stroke of 13mm, the greater the average speed and the greater the vertical electromagnetic force.

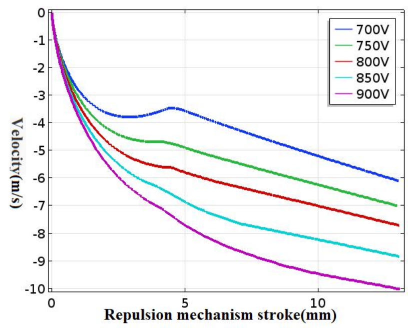


Fig.11 Change curve of speed with stroke during opening

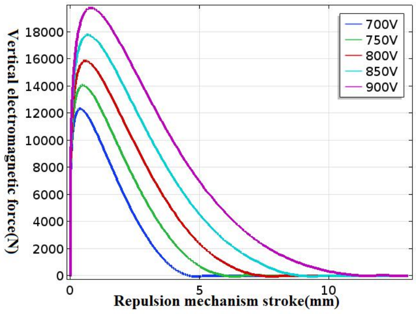


Fig.12 Curve of electromagnetic force in vertical direction changing with stroke when opening

The closing process of the electromagnetic repulsion mechanism is simulated under three conditions of 675V, 700V and 725V capacitor charging voltage respectively. Figure 13 shows the curve of the stroke changing with time under three conditions of closing.

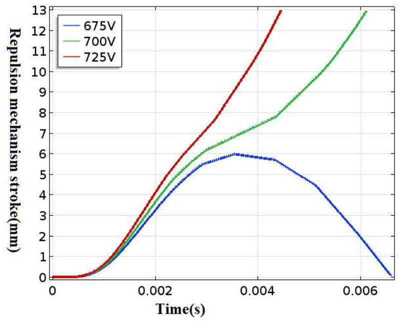


Fig.13 Curve of stroke changing with time when opening

Figure 14 shows the curve of the speed changing with the stroke under three kinds of applied voltage, and Figure 15 shows the curve of the vertical electromagnetic force changing with the stroke under three kinds of applied voltage. It can be concluded from the curve that with the increase of capacitor voltage, the shorter the time to reach the rated stroke of 13mm, the greater the average speed, the greater the vertical electromagnetic force, and the stroke returns at 675V.

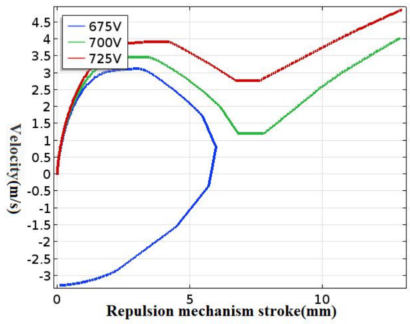


Fig.14 Curve of speed with travel during closing

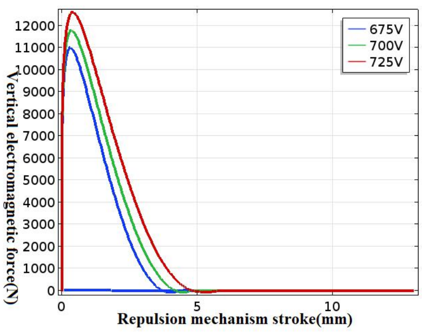


Fig.15 Curve of electromagnetic force in vertical direction changing with stroke when switching on

IV. MECHANICAL CHARACTERISTIC TEST

In this paper, the opening and closing mechanical characteristics of the improved electromagnetic repulsion mechanism of the secondary valve are tested. Under rated operating voltage DC990V and rated oil pressure 45-49Mpa, make and break operation for 5 times. Figure 16 shows the characteristic curve of mechanism opening. The average opening speed can reach 10m / s, and the minimum opening time is about 8ms. Figure 17 shows the closing characteristic curve of the mechanism. The average closing speed can reach 3.3m/s, and the minimum closing time is 66ms.

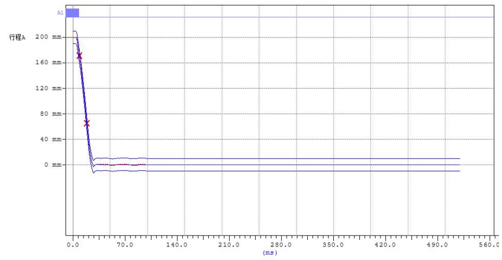


Fig.16 Opening waveform under rated operating voltage / rated oil pressure

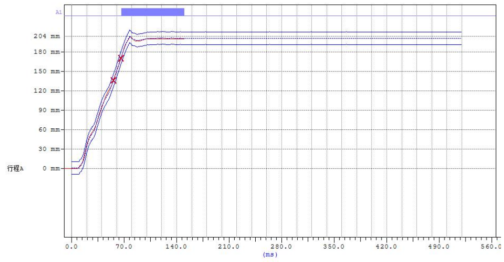


Fig.17 Closing waveform under rated operating voltage / rated oil pressure

The test results are shown in Table 1. Through the mechanism modification, the operation time of 550kV fast circuit breaker mechanism can be reduced by 65%, and the precompression time can be reduced by 30%; the arc extinguishing chamber and the long arc burning time can not be changed, and the full breaking time under rated conditions can be reduced by 10ms.

TABLE I. TEST RESULTS OF MECHANICAL PROPERTIES

Inspection items		**Technical Requirement**			**Test Result**
		Operating Voltage	*Operating oil pressure*	*Parameter requirements*	
Opening characteristics	*Opening time(ms)*	Rated Value	Rated Value	8.3±0.5	8.2
	Average opening speed（m/s）	Rated Value	Rated Value	10.2-11.5	10.54
Closing characteristics	*Closing time(ms)*	Rated Value	Rated Value	65±6	66.1
	Average closing speed（m/s）	Rated Value	Rated Value	2.5-4	3.30

Remarks	1) The hydraulic mechanism of quick circuit breaker is equipped with repulsion mechanism, and the variable gauge is used to open and close the coil. The control voltage is not distinguished from rated, maximum and minimum voltage. 2) Closing power supply voltage: DC990V. 3) Opening power supply voltage: DC990V. 4) Oil pressure (rated): 45-49Mpa. 5) During the test, the SF_6 gas pressure in the sample gas chamber is 0.65Mpa (20 ℃ gauge pressure).

V. CONCLUSION

Based on the traditional AC circuit breaker, this paper optimizes the design of high-power hydraulic spring operating mechanism for 550kV fast circuit breaker. The conclusions are as follows:

1) By comparison, it is found that the difference between the simulation results and the experimental results is within the analyzable range. Firstly, the actual drive circuit contains part of the line stray inductance and resistance, which leads to the difference of the current size and period between the drive coil and the ideal state simulation results; secondly, the fluid structure coupling calculation is not included in the simulation calculation, which leads to the failure of thermal convection heat dissipation mode and the decrease of accuracy.

2) The simulation results show that the change of the vertical electromagnetic force is very sensitive to the capacitor voltage, which leads to the obvious increase of speed by changing the smaller capacitor voltage value. Therefore, it is recommended to adjust the capacitor voltage in a small range, generally in the range of 10-20V.

3) According to the simulation curve of opening curve, the mechanism can meet the requirement of 13mm stroke in 4ms when opening, and the vertical electromagnetic force is 0 when the stroke reaches 8.3mm during closing It can be seen that the current pulse time of the driving coil of the electromagnetic repulsion mechanism is very short, so the maintenance time of the electromagnetic force is relatively short. If it still needs to hold a large electromagnetic force at the end of the stroke, it is not recommended to use this structure.

4) Through the mechanism modification, the operation time of 550kV fast circuit breaker mechanism can be reduced by 65%, and the precompression time can be reduced by 30%; the arc extinguishing chamber and the long arc burning time can not be changed, and the full breaking time under rated conditions can be reduced by 10ms.

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