Design and Research of Operating Repulsion Mechanism Suitable for 252kV High-Speed Breaking Circuit Breaker

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Abstract. This paper proposes a high-speed operating repulsive force mechanism suitable for 252kV high-voltage circuit breakers. The mechanism draws on the working principle of the electromagnetic repulsion operating mechanism of the medium voltage circuit breaker, and combines the new electromagnetic fast repulsion device with the traditional disc spring hydraulic mechanism to realize the fast action of the circuit breaker. This paper first introduces the working principle of the electromagnetic repulsion operating mechanism, and proposes the initial design scheme of the mechanism. Subsequently, the digital twin technology was used to establish the rigid-flexible coupling multi-body dynamics model of the mechanism, and the defects of the initial scheme were analyzed based on simulation. Finally, the paper optimized the design of the initial scheme and verified it by simulation. The test shows that the 252kV high-voltage circuit breaker with the improved scheme as the operating mechanism works normally and can complete the fault breaking within 20.1ms, which is twice as fast as the current products of the same type.

1. Introduction
As the protection equipment of the power system, the high-voltage circuit breaker needs to reliably cut off the fault area after the system fails to ensure the reliability of the entire system operation [1]. It controls the on and off of the current in the power system. It has a strict time limit in milliseconds from receiving the opening and closing action instructions to completing the work task. High-voltage circuit breakers are the most basic and important type of electrical appliances in high-voltage switchgear. As the core component of the high-voltage circuit breaker, the operating mechanism plays an extremely important role in the working speed, performance and reliability of the high-voltage circuit breaker [2-3].

At present, the power grids in some regions of the world (such as parts of China) are relatively weak, and the transient stability limit of high-voltage AC lines is far lower than the thermal stability limit. One of the key reasons is that the relatively long breaking time of the high-voltage AC switch accelerates the deterioration of the transient stability of the system after a fault, weakens the power transmission capacity of the line, and reduces the stability of the system [4]. In order to ensure the safe operation of the power system, electrical equipment in the power grid must be strengthened or replaced to solve the problems caused by excessive short-circuit current. However, this will lead to a substantial increase in the system's investment in electrical equipment and technical requirements. On the other hand, limited by the breaking capacity of the circuit breaker, there may be situations where no suitable circuit breaker can be selected. Therefore, it is important to study the high-speed action
operating mechanism to form a fast AC high-voltage circuit breaker to solve the above-mentioned problems.

At present, international scientific research institutions have carried out rapid breaking technology research. Mitsubishi Corporation of Japan improved the structure of the copper plate into a moving coil, and the breaking time of the hybrid circuit breaker made in this way is 1 millisecond [5]. The repulsion mechanism designed by ABB uses a combination of coil and permanent magnet mechanism in the closing part. Their opening coil adopts printed circuit board technology. The coil is very thin and concentrically wound to reduce inductance. The mechanical switching time is about 200 microseconds [6]. Shandong University and Huazhong University of Science and Technology have developed an AC high-voltage fast transfer switch by using a two-way electromagnetic thrust operating mechanism and a bistable disc spring mechanism. The opening and closing time is less than 5 milliseconds [7]. However, the above results are all researched for medium and low voltage products, and the rated voltage is relatively low, only tens of kilovolts, which is not suitable for line fault breaking. The State Grid Corporation of China and Chongqing University have conducted research on 363kV fast vacuum circuit breakers. The rated current capacity can reach 5000A and the opening time can reach 5 milliseconds [8]. However, its structure is complicated, its reliability still needs to be verified, and its cost is relatively high, so it has not yet been applied.

Up to now, common operating mechanisms in high-voltage switches include pneumatic operating mechanisms, spring operating mechanisms, hydraulic operating mechanisms, permanent magnet operating mechanisms, and motor operating mechanisms [9]. However, due to many parts, heavy moving parts, slow response time and other reasons, the opening time of these mechanisms is generally tens of milliseconds or even hundreds of milliseconds. Since the action time of the fast mechanical switch in the high-voltage DC circuit breaker needs to be very short, which is a few milliseconds, none of the common operating mechanisms can meet its needs. In recent years, the electromagnetic repulsion operating mechanism has begun to be studied as a fast operating mechanism and used in vacuum switches and hybrid DC circuit breakers with lower voltage levels. However, in order to ensure reliable breaking current, high-voltage circuit breakers require greater mechanical force and faster breaking speed than medium and low-voltage circuit breakers. The circuit breaker needs to withstand an electromagnetic impact force of more than 70 kN within a few hundred microseconds, and the requirements for an electromagnetic repulsive force operating mechanism far exceed the existing mechanism [10]. Therefore, the current electromagnetic repulsion mechanism cannot be used for high-voltage fast circuit breakers.

All in all, the high-voltage circuit breaker has developed from a low-oil circuit breaker to SF₆ circuit breaker [11-12]. The full breaking time of the first generation circuit breaker is 100ms, and the second generation circuit breaker is about 50ms [13]. At present, fast high-voltage circuit breakers with large-capacity breaking capacity still need to be further studied. In particular, how to obtain a simple structure and high-reliability fast operating mechanism is an important challenge for fast breaking technology.

This paper proposes a high-speed operating repulsive force mechanism suitable for 252kV high-voltage circuit breakers. The mechanism draws on the working principle of electromagnetic repulsion operating mechanism of medium voltage circuit breaker, use virtual simulation and experiment to analyze the existing problems when it is applied to high voltage circuit breaker, and adopts structural improvement, material replacement and other methods to propose a high-speed operating repulsive force mechanism implementation scheme for 252kV high-voltage circuit breakers. Experiments show that the proposed scheme can realize the full opening time of 252kV high-speed circuit breaker is less than 25ms, and the opening time is less than 9ms.

2. The Principle of Operating Repulsion Mechanism
The full breaking time of the existing second-generation high-voltage circuit breaker is about 50ms, and the opening time of the operating structure is 20-40ms, which is difficult to meet the requirements of high-speed breaking [14-15]. This paper expects that the designed fast operating mechanism needs
to control the opening time to within 9ms when the full breaking time needs to be less than 25ms. Drawing lessons from the working principle of electromagnetic repulsion operating mechanism for medium voltage circuit breakers, this paper proposes an operating mechanism suitable for high-voltage circuit breakers for high-speed breaking. This mechanism combines a new electromagnetic rapid repulsion device with a traditional disc spring hydraulic mechanism. The structure and working principle of the electromagnetic repulsion operating mechanism are shown in figure 1 and figure 2.

![Figure 1. Structure diagram of electromagnetic repulsion operating mechanism.](image)

![Figure 2. Working principle diagram of electromagnetic repulsion operating mechanism.](image)

The mechanism has two opening and closing coils, the metal disc and the insulated pull rod are fixed and can move up and down, and the insulated pull rod is connected with the movable contact of the switch. When the switch is opened, the switch S is turned on, the energy storage capacitor C is discharged through the opening coil, and a pulse current with a duration of several milliseconds flows in the opening coil. The pulse current induces an eddy current in the metal disk that is opposite to the coil current, thereby generating repulsive force, driving the metal disk to drive the pull rod and the movable contact to move, and realize the opening operation. The closing process is similar to the opening process [10].

During the stamping process, the pressure of the hydraulic oil in the rear pipe of the repulsion device (connected to the disc spring hydraulic mechanism) is constantly changing with the high-speed opening and resetting process of the control valve in the repulsion device. And then the hydraulic oil in the disc spring hydraulic mechanism drives the moving contacts of the subsequent transmission mechanism to open, thereby realizing rapid switch action [15].

3. **Optimal Design of Operating Repulsion Mechanism**

Although the above-mentioned similar fast operating mechanism has been used in medium voltage circuit breakers, the breaking speed of the high voltage circuit breaker mechanism is faster and the impact force is greater. If the mechanism is directly applied without optimization, it will inevitably cause damage or even cause serious accidents. Therefore, in order to apply the fast operating mechanism to high-voltage circuit breakers, the material and structure of the operating mechanism must be optimized.

3.1. **Initial Scheme**

In order to achieve the optimal design of the operating mechanism, this thesis first gives the initial scheme of the electromagnetic repulsion mechanism, and its model is shown in figure 3 and figure 4.
Figure 3. Overall structure model diagram of electromagnetic repulsion operating mechanism.

Figure 4. The key structure diagram of the stamping part of the electromagnetic repulsion operating mechanism.

As shown in figure 5, the components related to the stamping process of the operating mechanism in the repulsion device model mainly include four parts:

- Repulsion mechanism: repulsion spindle, repulsion disc, backing plate, upper cover of the new mechanism;
- Main valve installation parts: short valve sleeve, long valve sleeve, valve stem;
- Repulsion device transmission installation parts: cam type (pressure relief wheel, retaining ring), self-made M20 nut, impact bolt, spool ejector rod, valve end cover;
- Large opening pressure relief valve and straight installation hole: screw sleeve, pressure relief valve mandrel, valve stem CYTA-13, valve sleeve CYTA-13.

Figure 5. Sectional view of related structure of operating mechanism stamping.

Table 1 shows the material selection of key components. In order to meet the requirements of rapidity and compression, light and hard materials are selected for the main stressed parts.

Table 1. Material selection for key components.

| Material                      | Component                                                                 |
|-------------------------------|---------------------------------------------------------------------------|
| Titanium alloy TC4             | Repulsion spindle                                                         |
| 40CrNi2Si2MoVA                 | Short valve sleeve, long valve sleeve, valve stem, impact bolt, spool ejector rod |
35CrMo | Pressure relief valve mandrel  
7075 Aluminum alloy | Repulsion disc  
40Cr steel | Retaining ring  
Steel 45 | Pressure relief wheel, self-made m20 nut  
PTFE | Backing plate

### 3.2. Characteristic Analysis of the Initial Scheme

Based on the proposed preliminary scheme, this paper first established the dynamic model of the mechanism in the multi-body dynamics simulation software ADAMS. Then, based on the three-dimensional finite element analysis software ANSYS, the high-stress components in the mechanism (such as repulsive disc, backing plate, spool ejector rod) are made flexible. Then the flexible parts are imported into the dynamic model in ADAMS, and the dynamic simulation of rigid-flexible coupling is performed on the mechanism. Figures 6 and 7 are the split diagrams of the backing plate and the spool ejector rod in ANSYS.

**Figure 6.** The flexible split diagrams of the backing plate in ANSYS.  
**Figure 7.** The flexible split diagrams of the spool ejector rod in ANSYS.

In the simulation process, the force load is applied to the spool ejector rod and valve stem (spool) of the key stamping components as shown in the figure 8 below. Under the action of the repulsion device, the change curve of the driving force load $F_q$ generated on the repulsion disc is shown in the figure 9.

**Figure 8.** The force load on the spool ejector rod and the valve stem.
The simulation analysis found that during the whole movement of the mechanism, the force on all parts of the structure is always lower than the yield strength. However, during the collision between the repulsion disc and the backing plate, that is, at about 1.35ms, the outer edge portion near the center hole of the repulsion disc exceeded the yield limit of the material of the repulsion disc. Figure 10 is a cloud diagram of the stress distribution when the repulsion disc is subjected to the maximum stress. Figure 11 shows the relative position of the entire mechanism under maximum stress. It can be seen from the figure that the maximum stress can reach 699.548MPa, while the material of the repulsion disc is 7075 aluminum, and the yield strength of the material is 455MPa, so the equivalent stress of the repulsion disc is greater than the yield limit of its material.

Based on the above analysis, although a relatively soft backing plate is added to reduce the collision between the repulsive disk and the baffle, the yield strength is still exceeded for a short time at the moment of collision. Although there are not many parts that exceed the yield strength, there is still a risk of deformation or even fracture after a long time and many experiments. And the initial point of fracture is most likely to appear at the outer edge of the center of the repulsion disc, and gradually spread out as the number of impacts increases.

3.3. Scheme Improvement and Analysis
In order to improve the problems of the initial scheme, this paper made the separate components of the repulsion disc and the repulsion spindle in the original mechanism into an integrated 7075 aluminum alloy component, thereby reducing the force on the connection between the center of the original repulsion disc and the repulsion spindle. Figure 12 and figure 13 are the improved component and overall model structure diagram.
Figure 12. Structure of the tie rod (integrated repulsion disc and repulsion spindle).

Figure 13. Improved overall model diagram of stamping structure.

The multi-body dynamics simulation analysis of rigid-flexible coupling is carried out on the improved scheme. The simulation result found that the force on the surface of the repulsion disc is always lower than the yield strength during the entire movement of the improved mechanism. And there is no significant difference between the stress on the connecting part of the repulsion disc and the repulsion spindle of the repulsion disc and the disc surface. Figure 14 is a cloud diagram of the stress distribution when the tie rod (integrated repulsion disc and repulsion spindle) is subjected to maximum stress. Figure 15 shows the relative position of the entire mechanism under maximum stress.

Figure 14. The cloud diagram of the stress distribution when the tie rod is subjected to the maximum stress.

Figure 15. The relative position of the entire mechanism under maximum stress.

From the above analysis, the problem of the fracture risk of the repulsion disc is solved after optimization. At the same time, it can be seen from the simulation analysis that the time for a complete stamping process of the repulsion device is about 3ms, and the rapidity is good, which lays the foundation for the control of the total breaking time within 9ms.

4. Experimental Verification

In order to verify the correctness of the simulation results, this paper first made a prototype based on the initial scheme, and carried out the breaking experiment. Experiments had shown that the repulsion disc did break after multiple fault opening action. Figure 16 is a physical picture of a broken repulsion disc. It can be seen from the figure that the fracture is a straight crack penetrating the center, which conforms to the inference of this paper and verifies the correctness and effectiveness of the simulation model.
In order to verify the actual effect of the optimization scheme, we made a 252kV high-speed breaking circuit breaker prototype based on the optimization scheme of the operating mechanism and the specific design of other components. The prototype was used for a three-day test and inspection at the 500kV Tianyi test base in Ningbo, Zhejiang, China. The experimental results show that the operating mechanism of the first 252kV high-speed breaking circuit breaker that uses a combination of repulsive force device and disc spring hydraulic mechanism as the operating mechanism works well, and the whole machine can achieve fault breaking within 20.1ms. Figure 17 is a field diagram of the 252kV high-speed breaking circuit breaker undergoing manual short-circuit test at the site of Zhejiang Tianyi Substation. The above experiment verifies the effectiveness of the optimized scheme and shows that with the help of the scheme, the 252kV high-speed breaking circuit breaker is twice as fast as the current full breaking time (about 50ms) of other switches of the same type. It can greatly shorten the control and guarantee time of the power system and improve the transmission capacity.

5. Conclusion

This paper proposes a high-speed operating repulsive force mechanism suitable for 252kV high-voltage circuit breakers. This mechanism combines a new electromagnetic rapid repulsion device with a traditional disc spring hydraulic mechanism, which can realize the rapid breaking of the circuit breaker. The conclusions of the paper are as follows:

- Based on the simulation analysis of the initial design scheme of the mechanism, using the repulsion disc and the repulsion spindle as separate components will cause the connection between the two to be excessively stressed for a short time, exceeding the yield strength. This phenomenon is likely to cause the repulsion disc to deform or even break after many experiments, and the initial point of fracture is most likely to appear at the outer edge of the center of the repulsion disc, and gradually spread out as the number of impacts increases. In the actual test, the repulsion disc did indeed experience a penetrating fracture, which verified the above analysis results.

- The repulsion disc and the repulsion spindle are made into an integrated 7075 aluminum alloy component, which can effectively reduce the force on the connection between the center of the original repulsion disc and the spindle. The test shows that the 252kV high-voltage circuit breaker with the improved scheme as the operating mechanism works normally and can complete the fault breaking operation within 20.1ms, which is twice as fast as the current products of the same type.
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