Development of a Fast DC Switch Based on Electromagnetic Repulsion Mechanism

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Abstract. This paper introduces the overall structure design of a high-speed, medium-voltage compact fast DC switchgear. This device is driven by an electromagnetic repulsion disc, and uses a bistable spring as a holding device to maintain the opening and closing state. We calculated the steady-state heating of the switch under rated current for a long time, the results show that the steady-state heat generation of the through-flow part can meets the requirements of relevant standards. Then we calculated the breaking field strength of the isolation fracture, the breaking capacity of the switch at the rated distance meets the requirements of the rated voltage. The electromagnetic repulsion force on the repulsive disk and the stress distribution of the kinematic structure show that, the operating mechanism of the device can meet the requirements of opening distance greater than 5 mm within 1 ms. The closing time of this switch is less than 5 ms, the material and mechanical properties can meet the requirements. The above analysis shows that this device can meet the needs of medium-voltage DC systems for compact and fast DC switches.

Keywords: Fast transfer switch · Electromagnetic repulsion mechanism · DC switch

1 Introduction

With the development of science and technology in various countries, DC power systems have been applied in various fields, such as DC power transmission and distribution, and ship power [1, 2]. With the further increase in the power demand in the ship system, the medium voltage DC integrated power system has become the focus of current research. The structure of the medium-voltage DC system needs to have the ability to quickly disconnect and clear the fault, and at the same time, it can quickly isolate the faulty part of the system to ensure the stable operation of the rest of the system. Due to the short power lines, low equivalent impedance value and small time constant of the ship power system, when a short circuit fault occurs in the system, the current in the line will increase rapidly, so a DC circuit breaker that can quickly act to cut off the fault current is required. Device. At present, there are two main types of DC circuit breakers: hybrid DC circuit breakers and mechanical DC circuit breakers. In these two types of DC circuit

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breakers [3, 4], the fast mechanical switch is an important component, and its action speed is related to the breaking speed of the DC circuit breaker, so it is required to have fast action capability. The fast DC switch can also be used as the isolation switch of the DC system to quickly cut off the faulty part of the system to ensure the stable operation of the rest of the system.

This paper introduces the overall structural design of a compact ultra-fast medium-voltage DC switchgear. To meet the needs of fast action. This DC switch device is based on the principle of electromagnetic repulsion disc, uses electromagnetic repulsion to quickly start the moving contacts, reaches the rated opening distance within 1ms, and then maintains a sufficient separation distance between the moving and static contacts through the holding device to withstand the system voltage. In order to consider environmental protection requirements, nitrogen gas with several times atmospheric pressure is used as insulating medium inside the switch. The performance of the device is verified by the multi-physics finite element simulation software COMSOL to meet the design requirements.

2 Overall Structure of the Equipment

The 3D model of the switch (without the casing) is shown in Fig. 1. This is a DC switchgear with a rated voltage of 6 kV and a rated current of 2 kA. It consists of an internal flow part, an opening and closing operating mechanism and an external supporting structure. The overall height of the device is about 35 cm, and the outer radius is about 13 cm. The design of the through-flow part and the opening and closing operating mechanism will be verified in the following chapters.

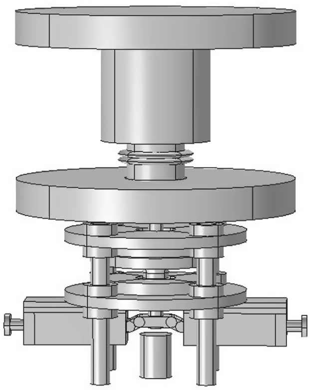

Fig. 1. 3D model of the quick switch.

3 Current-Carrying Part Design

Since the DC switch adopts a fully enclosed structure, that is, all moving parts are located inside the casing. In order to meet the electrical connection requirements, the strap contact finger structure is used as the electrical connection component between the movable contact and the external outgoing terminal. To sum up, the overall flow-through part includes four parts: the moving contact connected with the operating mechanism, the static contact and its external connection part, the transitional outgoing terminal connected with the outgoing terminal, the connecting moving contact and transitional outgoing wire The sliding finger structure of the terminal.

Since the sliding contact finger structure is sleeved on the periphery of the moving contact, there are certain requirements on the perimeter of the cross-sectional area of the moving contact. The radius of the moving contact of the designed plate electrode is 2.7 cm, the length is 5.3 cm, and the radius of the static contact is the same as that of the moving contact. The contact material is chrome bronze, the minimum flow area is 2290 mm^2, and the flow capacity can reach 4 kA, which meets the rated current requirements.

The 2D model of the current-carrying part is shown in Fig. 2. The middle diameter of the static contact holding spring is 47 mm, the wire diameter is 7.5 mm, the material is high-conductivity beryllium bronze C17500, the effective number of turns is 3, and the spring stiffness coefficient is about 1524 N/mm, the design closing retention force is 1500 N.

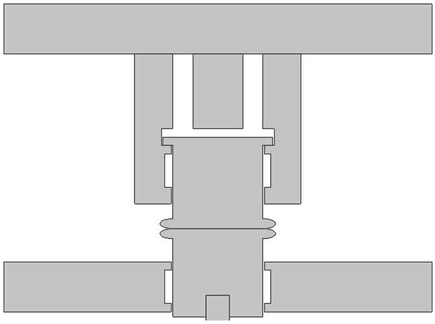

Fig. 2. 2D model of the current-carrying part.

According to relevant standards, the temperature rise of the electrical switch contact part at an ambient temperature of 40°C should not exceed 35 K, that is, the long-term operating temperature at an ambient temperature of 40°C should not exceed 75°C. The steady-state thermal calculation result of adding the rated current to the current-carrying part is shown in Fig. 3. When the external ambient temperature is 40°C, the maximum internal temperature rise is 30 K, which meets the standard requirements.

When the distance between the moving and static contacts is short, the electric field distribution between the contacts is relatively uniform. However, in order to improve the insulation breakdown level at the contact edge, the shape at the contact edge needs to be optimized.

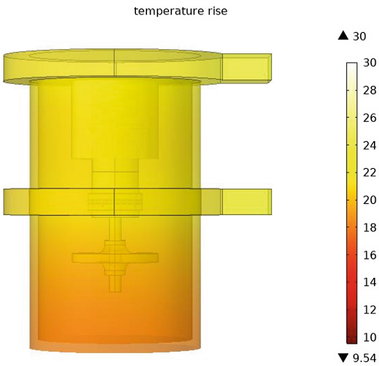

Fig. 3. Current-carrying part temperature rise distribution.

Using the scheme shown in Fig. 4 to carry out the optimization design, the electric field optimization results are shown in Fig. 5, *a* is 3 mm, the ratio of the long and short axes is 2.6, the field strength distribution between the poles is relatively uniform, and the maximum field strength is 1.24 kV/mm. When the pressure is 1.6 times the atmospheric pressure, the 5 mm withstand voltage level of nitrogen is already 20 kV which meets the withstand voltage requirement.

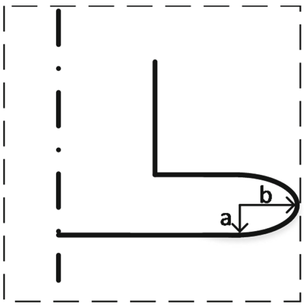

Fig. 4. Contact Edge Optimization Model.

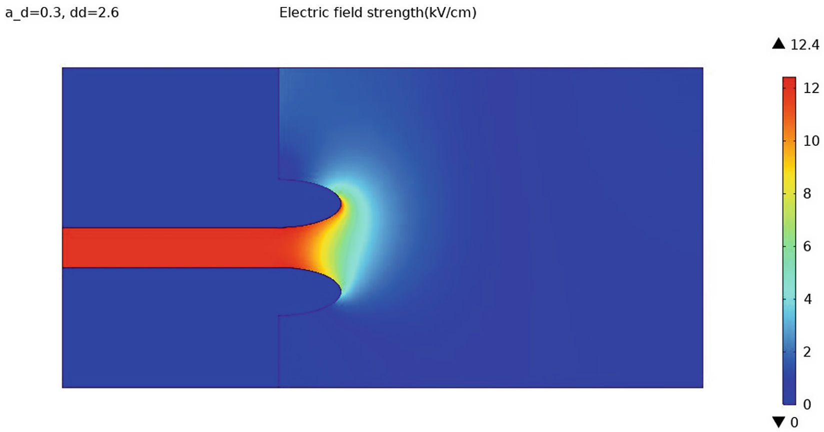

Fig. 5. Optimized electric field intensity distribution.

4 Operating Mechanism Design

4.1 Simulation Model Establishment

The isolation switch action mechanism based on the coil-disc electromagnetic repulsion mechanism mainly includes three parts: a driving device, a holding device and a buffer device. The principle of the driving device is as follows: the pre-charged capacitor C is discharged to the closing or opening coil to generate a pulse current, and the repulsive disc is subjected to electromagnetic thrust due to the induced eddy current, thereby driving the connecting rod to move to realize the closing or opening of the switch.

Based on the composition and driving principle of the electromagnetic repulsion mechanism, the force characteristics of the mechanism are further discussed. The electromagnetic repulsion borne by the repulsion disc is the driving force for the action of the mechanism, and the electromagnetic repulsion can be expressed as:

$$F = \frac{\mathrm{d}W}{\mathrm{d}z} = \frac{i_1 i_2 \mathrm{d}M}{\mathrm{d}z} \tag{1}$$

It can be seen from the above formula that the electromagnetic repulsion force F is related to the current i_1 in the excitation coil, the eddy current i_2 in the repulsion disk, and the derivative of the mutual M inductance to the displacement z, and it is difficult to directly obtain the analytical results. In the finite element analysis, the Lorentz force on the repulsive disk can be obtained by field calculation.

In addition to the electromagnetic driving force, the mechanism is also affected by other reaction forces during the operation, including: the opening and closing holding force provided by the holding device, the buffer force, the friction force, the gravity, etc.

The bistable spring retaining device has the advantages of convenient output adjustment, simple structure and compact installation space, and is currently widely used in electromagnetic repulsion mechanisms. Its output characteristics can be described by the following formula [5]:

$$F_h = 2k \frac{\left(x_0 - l_0 + \sqrt{l_0^2 - (z - z_0)^2}\right)(z - z_0)}{\sqrt{l_0^2 - (z - z_0)^2}} \quad (2)$$

In the formula, k is the elastic coefficient of the coil spring, z is the displacement of the mechanism, l_0 is the length of the connecting plate, and x_0 is the spring compression amount of the holding device when z is equal to z_0. The holding force F_h can be changed by changing the spring rate, the amount of pre-compression and the length of the connecting plate.

The drive coil dimensions are as follows (Table 1):

Table 1. Drive coil dimensions.

part	outer diameter	inside diameter	number of turns	single turn width	single turn height
value	100 mm	40mm	20	1 mm	7 mm

The size parameters of the repulsion disc are as follows (Table 2):

Table 2. Repulsion disc size.

part	outer diameter	width	Circumference width	Circumference height	Bevel chamfer radius
value	10 cm	1 cm	5 mm	1 cm	1 cm

The cross-sectional model of the repulsive disc and coil is shown below (Fig. 6):

The height of the repulsion disc fixing nut is 5mm, and the radius of the pull rod is 7mm. The material of the repulsion disc is 7075 aluminum alloy, and the material of the tie rod and nut is TC4 titanium alloy. Its material parameters are shown in Table 3:

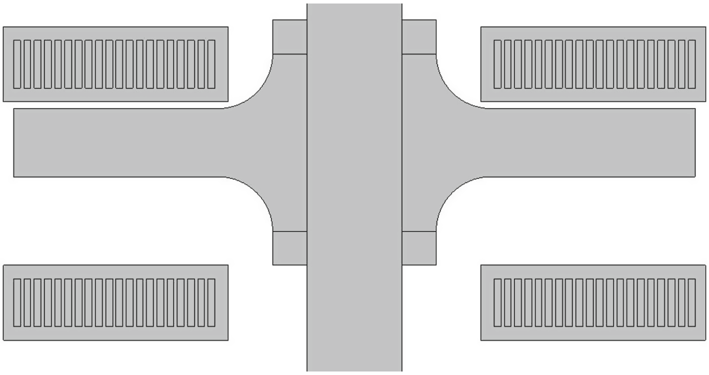

Fig. 6. Repulsion disk and coil section model.

Table 3. Kinematic structure material parameters.

Material	part	tensile strength/MPa	Yield Strength/MPa	Elastic Modulus	Poisson's ratio
7075-T651	repulsion disc	560	540	7.0e10	0.33
TC4	drive rod、connector	895	860	1.1e11	0.34

The bistable spring retaining device is designed as follows:

The middle diameter of the spring is 20 mm, the wire diameter is 5 mm, the effective number of turns is 7, the axial intercept is 10 mm, the material is SWPB, the stiffness coefficient is about 150 N/mm, and the pre-compression is 10 mm, which can be adjusted by the rear screw. The central opening of the connecting plate on the upper part of the device is a part of the tie rod positioning device.

Figure 8 shows the overall structure of the plate electrode isolation switch after installing the motion mechanism fixing frame and the bistable spring holding device. The mass of the moving part of the switch is about 1.34 kg (Fig. 7).

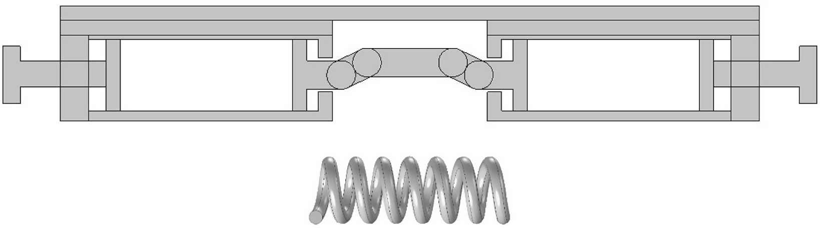

Fig. 7. Bistable spring structure diagram.

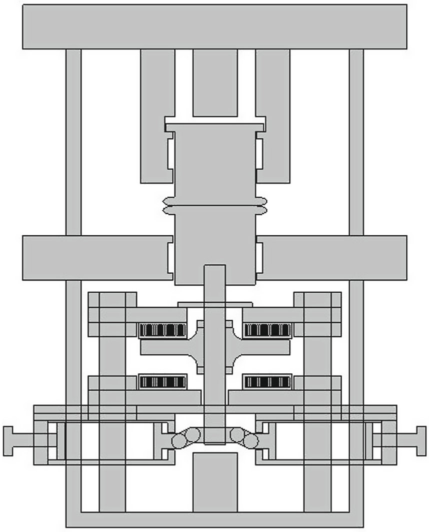

Fig. 8. DC Switch Section Model.

The designed opening capacitor capacity is 1200 μF, the charging voltage is 1.2 kV, and the simplified opening model is established as shown in Fig. 9:

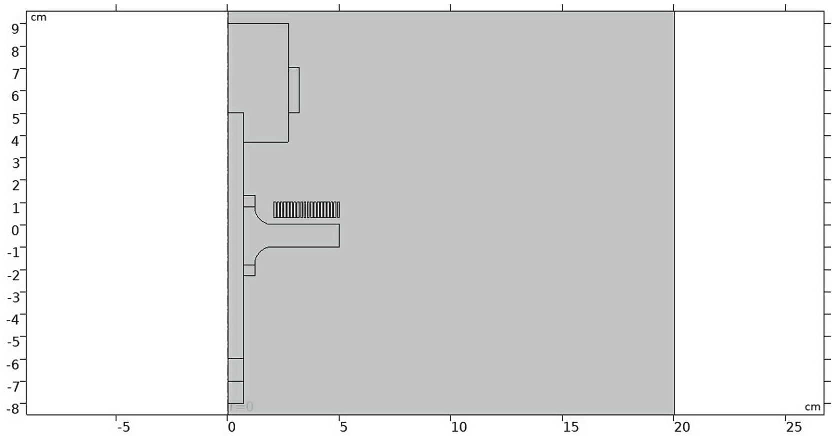

Fig. 9. 2D Axisymmetric Model of Plate Electrode Repulsion Disk.

4.2 Analysis of Simulation Results

The results obtained from the flexible body transient simulation are shown in the figure below:

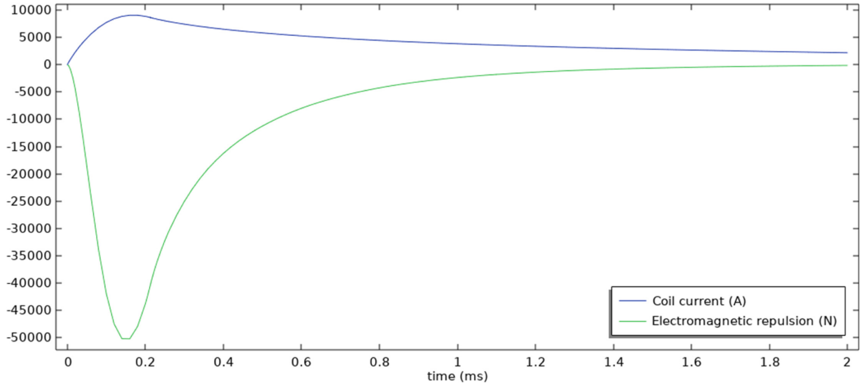

Fig. 10. Coil Current and Electromagnetic Repulsion.

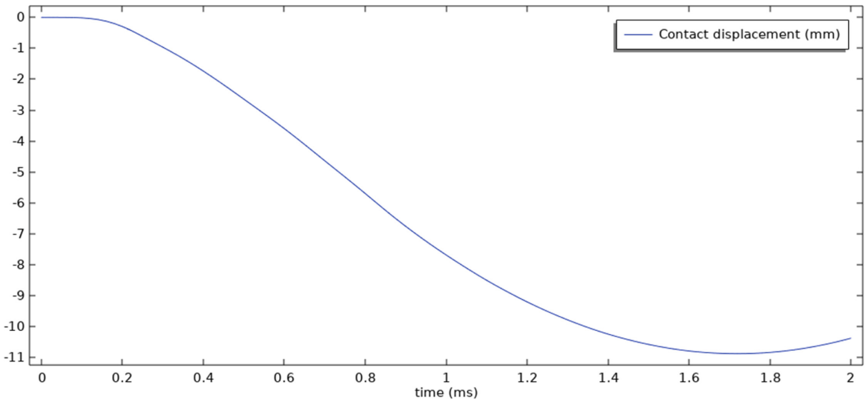

Fig. 11. Displacement vs Time Plot.

It can be seen from Fig. 10 that the peak value of the electromagnetic repulsion is about 50 kN, compared with which the frictional resistance and gravity are negligible. It can be seen from Fig. 11 that the moving contact reaches the rated opening distance of 5mm at 0.8 ms, reaches the opening position at 1.7 ms, and the opening distance is 10 mm.

The maximum stress on the repulsion disc during the movement is 404 MPa, which is reached at 0.18 ms. At this time, the stress distribution of the repulsion disc is as follows (Fig. 12):

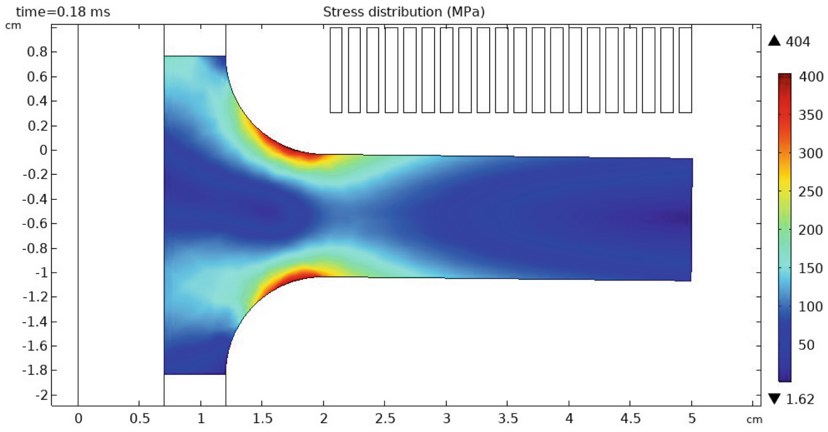

Fig. 12. Repulsive disk stress distribution at 0.18 ms.

At 0.18 ms, the tension rod stress also reaches the maximum value, which is 575 MPa. At this time, the tension rod stress distribution is as follows (Fig. 13):

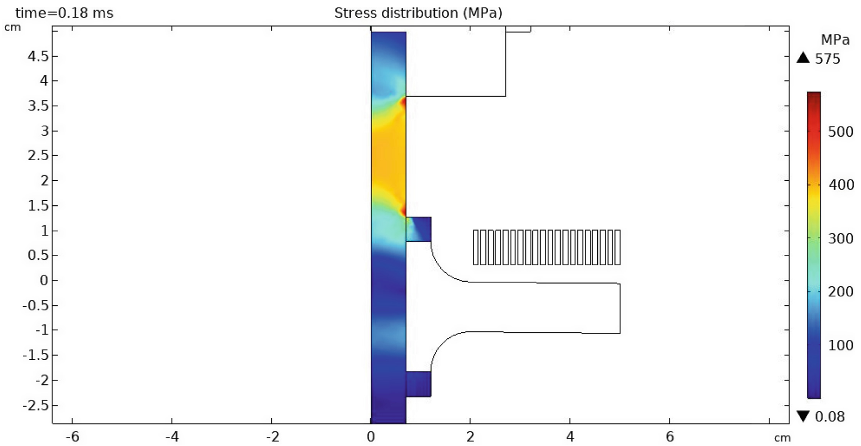

Fig. 13. Tie rod stress distribution at 0.18 ms.

The maximum stress during the entire movement is as follows (Fig. 14):

From the mechanical properties of the material, it can be known that the disk and the tie rod can meet the requirements in the whole process.

Set the closing capacitor capacity to 1100 μF and the charging voltage to 1.2 kV. The flexible body simulation results are shown in the following figure:

It can be seen from Fig. 15 that the peak value of the electromagnetic repulsion is about 36 kN when the gate is opened. It can be seen from Fig. 16 that the moving contact can reach the closing position within 5 ms.

The maximum stress during the entire movement is as follows (Fig. 17):

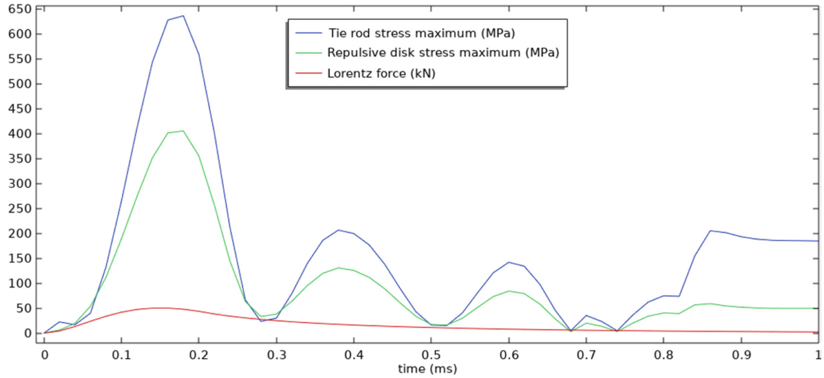

Fig. 14. Electromagnetic force and component stress curve.

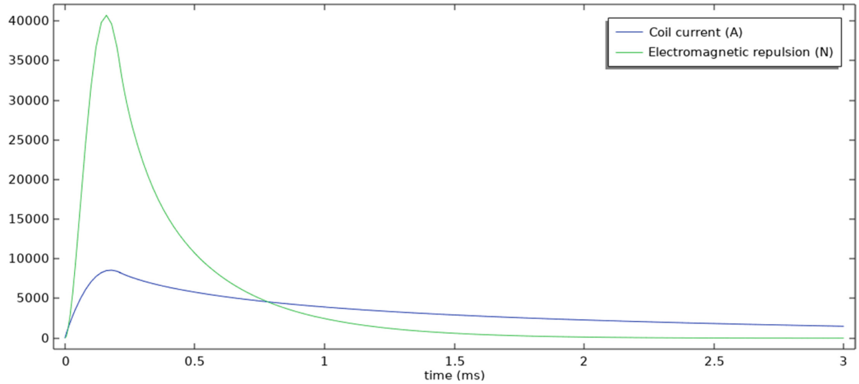

Fig. 15. Coil Current and Electromagnetic Repulsion (closing).

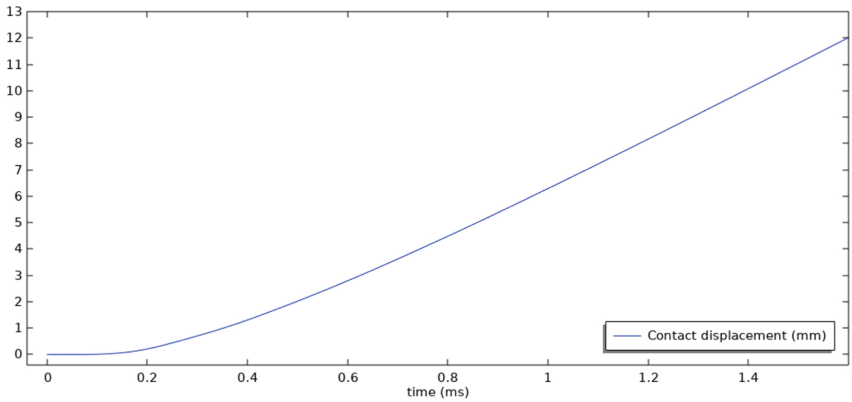

Fig. 16. Displacement vs Time Plot (closing).

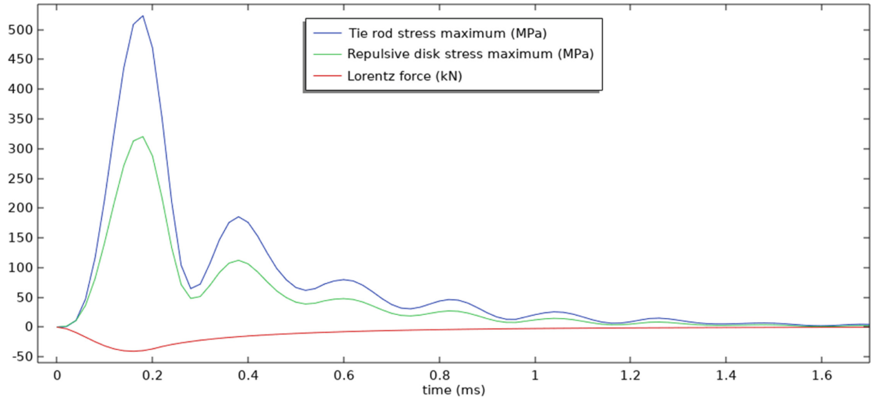

Fig. 17. Electromagnetic force and component stress curve (closing).

The requirement for material strength in the closing process is smaller than that in the opening process.

5 Conclusion

This paper introduces the overall structural design of a compact ultra-fast medium-voltage DC switchgear using an electromagnetic repulsion mechanism. The performance of the device is verified by the multiphysics finite element simulation software COMSOL:

(1) The steady-state heat generation of the switch for long-term current flow was calculated, and the results showed that the steady-state temperature rise of the switch for long-term current flow was 30K, which met the requirements of relevant standards.
(2) Calculated the electric field intensity distribution, and verified that the rated breaking capacity of the switch at the rated distance of 5 mm meets the design requirements of the rated withstand voltage of 6 kV, the electric field distribution of the isolation fracture is relatively uniform, and the maximum electric field strength is far less than the withstand voltage level of the insulating medium.
(3) The dynamic mass of the switch is 1.34 kg, the electromagnetic repulsion force on the repulsion disc and the stress distribution of the moving structure are calculated, the opening time is less than 1 ms, the closing time is less than 5 ms, and the material properties meet the requirements.
(4) The outer height of the switch is about 35 cm and the outer radius is about 13 cm. The overall structure is compact and the volume is small.

The simulation results show that the device can meet the demand of high-speed DC switches in medium-voltage DC systems.

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