Research on motion characteristics and stability of 500kV fast mechanical switch

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Abstract. The key component of fast mechanical switch (FMS) is electromagnetic repulsion mechanism (ERM), and the stability of ERM has an important influence on fault breaking time and breaking performance of hybrid DC circuit breaker (DCCB). In this paper, a FMS based on ERM is designed. In order to improve the stability of the FMS, the key factors affecting the stability of the excitation coil resistance, the inductance of the excitation coil, the capacitance of the energy storage capacitor, the charging voltage and the ambient temperature are analyzed. Then, 2D ERM simulation model is set up and study the above parameters deviation and the change of environmental temperature on the repulsive force driving characteristics. In order to ensure that the ERM moves to 10mm in 2ms, and the time dispersion is less than ±0.2ms. The reasonable variation range of each parameter required for the stable action of the ERM and the appropriate working environment temperature are determined. Finally, the developed FMS prototype was tested for opening, temperature rise and consistency, and the test results were consistent with the simulation results.

1. Introduction
Multi-terminal direct current (MTDC) based on flexible direct current, because of its flexible operation mode and higher system controllability, has become an important solution for the transformation of power grid transmission methods and the construction of future smart grid development [1]. However, the DC grid has low impedance, fast fault development and high fault current rise rate. DC current is difficult to break due to lack of natural zero-crossing power. Therefore, research on DCCB with simple structure, fast response and high stability, and the ability to quickly break large currents has become a key issue in the development of MTDC transmission [2].

The current research on high-voltage DCCB is mainly divided into mechanical and hybrid. DC transmission system requires FMS to meet the insulation distance within 2ms-3ms, the insulation distance can withstand the transient interruption voltage (TIV) during fault removal [3]. However, the traditional mechanical circuit breaker is difficult to complete the breaking task. ERM has many advantages over traditional operating mechanism [4], which based on the principle of inductive eddy current has the advantages of short mechanical delay time, quick switching speed and low loss in the on-state. Therefore, ERM can greatly improve the breaker's ability to break short circuit current, which
also meet the requirements of high voltage DCCB for quick switching. At present, the research on ERM mainly focuses on the parameter matching law, the optimization design of increasing the opening speed and the driving efficiency [5-7]. Literature [8] researched the influence of the structural parameters of metal plate and coil and the changing law of capacitance parameters on ERM. Literature [9] calculated and analyzed the effect of adding different magnetic material shells to the ERM on the motion characteristics and output efficiency. In summary, there are few researches on the influence of basic parameter deviation and operating temperature change of the ERM on the stability of the mechanism.

In this paper, a FMS applied to a single break unit of Zhangbei 500kV/3000A flexible DC engineering hybrid circuit breaker is designed. The time required for the ERM to move to the insulation distance of the TIV during the fault removal process is less than 2ms. Here the insulation distance is 10mm, and the dispersion of distance from movement to insulation is less than ±0.2ms. The influence of basic parameters of ERM and temperature under different working conditions on the motion characteristics is analyzed by electromagnetic field simulation software. The reasonable variation range of the parameters of the ERM is analyzed quantitatively. Through the planning of these parameters, the stability of the FMS is improved, and the breaking failure caused by the dispersion of each parameter is reduced. Finally, according to the parameters obtained by simulation, the FMS test platform is built and the FMS prototype is tested and verified.

2. Modeling of ERM

The design schematic diagram of the FMS based on the ERM designed in this paper is shown in Figure 1, which adopts a coil-plate structure. When the thyristor K1 is turned on, the energy storage capacitor C1 discharges to the opening coil to generate a pulse current. This current generates an alternating magnetic field around the coil. The metal plate generates a reverse induced eddy current due to the magnetic field. The magnetic field generated by the eddy current and the magnetic field generated by the opening coil generate a huge electromagnetic repulsive force, which promotes the movement of the metal plate. At the same time, it drives the contact of the transmission rod and the vacuum interrupter to realize fast breaking operation. The free-wheeling diode D1 plays the role of conduction and free-wheeling, and the principle of the closing process is similar.

The drive circuit diagram is shown in Figure 2. The parameters of the closing and opening coils are the same. Rc and Lc are the internal resistance and inductance of the energy storage capacitor, Ra and La are the lead internal resistance and inductance, R1 and L1 are the opening coil internal resistance and inductance.

![Figure 1. Schematic diagram of ERM.](image1)

![Figure 2. Equivalent circuit model of ERM.](image2)
2.1. Mathematical model

According to the energy conservation principle, the energy stored in the capacitor should be equal to the sum of the mechanical work \(dW\), the change of magnetic field energy \(d\mathcal{W}\) and the heat loss \(dQ\), as shown in Equation (1). The energy conversion process of the ERM can be expressed as

\[
dE_m = dW + d\mathcal{W} + dQ \tag{1}\]

According to the equivalent external circuit diagram 2 and the coupling relationship between the excitation coil and the metal plate, the above equation can be expressed as

\[
u_1i_1dt + \nu_2i_2dt = dW + d\mathcal{W} + i_2^2R_1dt + i_2^2R_2dt \tag{2}\]

Here: \(\nu_1\) and \(\nu_2\), \(i_1\) and \(i_2\), \(R_1\) and \(R_2\) are respectively the voltage, current and resistance of the excitation coil and the metal plate.

The metal plate can be equivalent to a series of coils. The excitation coil and metal plate of the changing magnetic field are considered as a whole. Therefore, the magnetic energy is determined by the following equivalent.

\[
E_m = \frac{1}{2}i_1^2L_1 + \frac{1}{2}i_2^2L_2 + i_1i_2M \tag{3}\]

The self-inductance \(L_1\) of the excitation coil and the self-inductance \(L_2\) of the metal plate can be regarded as constant. From (2) to (4), the electromagnetic repulsion force (ERF) can be expressed as

\[
F = i_2\frac{dM}{dx} \tag{4}\]

According to Equation (5), \(F\) is related to the current of the excitation coil \(i_1\), the induced eddy current of the repulsion plate \(i_2\), and the change rate of mutual inductance \(M\) with the open distance \(dM/dx\).

According to [10], the mechanical kinematics equation of the ERM can be expressed as

\[
\begin{align*}
F - F_r - F_s &= ma \\
\nu &= \int v dt \\
s &= \int \nu dt
\end{align*} \tag{5}\]

Here: \(F\) is the ERF received by the repulsion plate in the direction of motion, \(F_r\) is the reaction force received by the ERM, \(F_s\) is the component of the spring force in the vertical direction, \(M\) is the mass of the moving part, \(a\) is the switch acceleration, \(\nu\) is the speed of motion, \(s\) is the motion displacement.

2.2. Simulation model

The movement process of the ERM is a complex process involving circuit discharge, electromagnetic induction coupling, mechanical movement and other interactions. As is shown in Figure 3, in order to design a highly stable FMS, this paper uses the electromagnetic field finite element (FE) simulation software Ansoft Maxwell to establish a 2D axisymmetric model of the ERM of 500kV FMS. The magnetic field intensity distribution chart when ERM moves for 1ms is shown in Figure 4. The simulation parameter settings of the ERM are shown in Table 1. The data in Table 1 are the dimensions of coil of each turn.

According to the simulation model, the deviation of coil resistance, coil inductance and energy storage capacitor are important factors affecting the stability of ERM. The motion characteristics and stability of ERM are quantitatively analyzed by calculating and solving the deviations of the above parameters. Through calculating the value of the equivalent resistance and the conductivity of the aluminum plate changing with the temperature, ignoring other factors that have less influence with the temperature change, the corresponding parameters change value are imported into the simulation software. Finally, suggestions are made for the corresponding parameter deviations and the ambient temperature range for stable operation.
3. ERM’s parameter deviation impact analysis

The mechanical switch of hybrid DCCB is mainly in the form of multi-break series. The stability of single break will affect the synchronicity of multi-break. Therefore, it is necessary to effectively predict and evaluate the time deviation that caused by the above factors to ensure the stability of ERM and reduce the dispersion of action time. The time dispersion of the ERM's opening movement to the insulation distance is less than 0.2ms, the deviation caused by the design and processing of various parameters will cause the time dispersion of the ERM's opening movement to the insulation distance to be less than 0.05ms. The effect of environmental temperature changes will be less than 0.15ms. Therefore, different parameter deviations are analyzed by simulation to obtain corresponding parameter constraint range.

3.1. Analysis of coil resistance deviation

In this paper, the excitation coil of ERM is a plate-type coil with copper flat winding. The deviation of the coil resistance will have a great influence on the peak current and the time of the mechanism's

Table 1. Parameter table of ERM.

| Parameter     | Value  | Parameter     | Value  | Parameter     | Value  |
|---------------|--------|---------------|--------|---------------|--------|
| Copper turns  | 32     | Distance      | 22mm   | R₁            | 10mΩ   |
| Coil height   | 9mm    | Coil gap      | 2mm    | Lₜ           | 150μH  |
| Coil width    | 2mm    | Rₐ            | 2.6mΩ  | L₁           | 90μH   |
| Plate thickness | 15mm | Al Conductivity | 3.8×10⁻⁸S·m⁻¹ | Lₐ | 3μH   |
| C             | 3700μF | Cu Resistivity | 1.7×10⁻⁸Ω·m | Mass | 5.84kg |
| U₁            | 1400V  | Al Resistivity | 2.6×10⁻⁸Ω·m | Holding force | 3kN   |
opening. Based on the processing of the measured standard coil plate resistance of 10mΩ. Actual production errors and high-frequency drive circuits will cause deviation in resistance values. Ensuring other conditions unchanged, simulation analysis was carried out on the ±5mΩ resistance deviation, the simulation results are shown in Figure 5.

As shown in Figure 5(a)-5(c), when the coil resistance of the ERM changes from 5-15mΩ, the peak current decreases with the increase of the coil resistance R. The peak of the ERF decreases by 4.7% and 9.1% respectively and break-brake time gradually increased. Figure 5(d) shows that the designed gate opening action of the ERM meets the requirement of 2ms motion insulation distance. In order to meet the dispersion of the movement to insulation distance time t0 within 0.05ms during the opening, the coil plate resistance deviation should be controlled within the range of 4mΩ during processing and minimize the influence of the line stray resistance on the ERM.

![Figure 5](image)

**Figure 5.** (a) Current of the ERM; (b) ERF of the ERM; (c) Displacement of the 10mm; (d) Change of 10mm displacement time with resistance.

### 3.2. Analysis of coil inductance deviation

Excitation coil is made of flat copper wire. Epoxy resin is injected between each turn of the coil for insulation and fixing. The coil winding technology of the same specification has different inductance due to different clearance size of each coil. Inductance deviation will directly affect the excitation time and action characteristics of ERM. The measured inductance value of the standard coil designed and processed is 90μH, and the line parasitic inductance is 3μH. Ensuring other conditions unchanged, the inductance deviation of the ERM coil is ±5μH for simulation analysis, and the simulation results are shown in Figure 6.

![Figure 6](image)

**Figure 6.** (a) Current of the ERM; (b) ERF of the ERM; (c) Displacement of the 10mm; (d) Change of 10mm displacement time with resistance.

As shown in Figure 6(a)-6(c), as the coil inductance L1 increases from 85μH to 95μH, the excitation time gradually increases. Excitation time is delayed 80μs and 150μs respectively and the peak ERF decrease by 6.5% and 11.8% respectively, which is not conducive to the fast lifting gate speed of the ERM at the initial stage of movement. Therefore, in the process of designing the drive circuit and making the coil, the inductance of the coil itself should be reduced as far as possible. According to Figure 6(d), when the inductance changes within the range of this deviation, the designed ERM can meet the requirement that ERM movement to insulation distance in 2ms. However, in order to meet the requirement that the time dispersion between movement and insulation distance is within 0.05ms, it is required that the coil inductance deviation in the manufacturing process should be controlled within 4μH and the influence of line inductance on the mechanism should be minimized.
3.3. Analysis of energy storage capacitor deviation

ERM mostly uses energy storage capacitor as power supply. However, it is difficult to guarantee the absolute consistency of capacitance of the same specification in the actual production process. This paper takes the designed standard capacitor of 3700μF as the benchmark and performs a simulation analysis on the capacity error within 0 to ±6%. The simulation results are shown in Figure 7.

As can be seen from Figures 7(a)-7(c), when the capacity of the energy storage capacitor changes within ± 6%, as the capacitance capacity increases, the peak value of the coil current increases and the ERF increases. As shown in Figure 7(d), the time of the ERM move to insulation distance gradually decreases. Within this capacitance capacity deviation range, the designed ERM can meet the requirement that ERM movement to insulation distance in 2ms. However, in order to meet the requirement that the time dispersion between movement and insulation distance is within 0.05ms, it is required to select the capacitor capacity deviation within the range of 0± 5%.

![Figure 7](image)

**Figure 7.** (a) Current of the ERM; (b) ERF of the ERM; (c) Displacement of the 10mm; (d) Change of 10mm displacement time with resistance.

3.4. Analysis of energy storage capacitor deviation

The ambient temperature in the circuit breaker operating condition is variable. When the ambient temperature changes, the resistance loss of ERM and the eddy current loss of the metal plate will be caused, which will affect the performance of ERM quick closing. Since not greatly affected by temperature changes, coil temperature rise is not considered. The main consideration is the influence caused, which is an important factor affecting the output efficiency of ERM.

The conversion method of the coil resistance with temperature is can be expressed as

$$R_T = R_0 \left(1 + \alpha (T - T_0)\right)$$

Here: $\alpha$ is the temperature coefficient of resistance of the conductor, which is taken 0.00393/°C^{-1} for the copper conductor. $R_0$ is the resistance value of the coil plate when the temperature is $T_0$, $R_T$ is the resistance value of the coil plate when the temperature is $T$. $T$ is the measured ambient temperature, $T_0$ is room temperature, which is taken as 20°C.

The resistivity of the metal plate material directly determines the value of the induced eddy current in the core, which is an important factor affecting the output efficiency of ERM. The conversion of the conductivity of aluminum plate with temperature is can be expressed as

$$\sigma_T = \frac{1}{\rho_0 (1 + \lambda T)}$$

Here: $\sigma_T$ is the electrical conductivity at a temperature of $T$, $\rho_0$ is the resistivity at a temperature of 0°C, and $\lambda$ is the conductivity temperature coefficient of the aluminum plate, which is taken 0.004/°C^{-1}.

Taking into account the actual working environment temperature of the FMS, the temperature range is 10°C-80°C. The calculated values of the coil resistance and aluminum plate conductivity with temperature are shown in Table 2. The corresponding variation values are imported into the simulation software. The simulation characteristic curve is shown in Figure 8.

According to Figure 8(a)-8(c), as the temperature increases, ERF and the peak value of current gradually decreases. As shown in Figure 8(d), when the ERF is opened at an ambient temperature of
10°C-70°C, it meets that ERM movement to insulation distance in 2ms. When the temperature is higher than 70°C, the requirements are no longer met. And the opening distance of motion varies discretely with temperature rise. It can be determined that the ambient temperature range in which the ERM works stably is 10°C-70°C. When the temperature exceeds 80°C, the high temperature will cause damage to the power electronic components of the control circuit. At the same time, it will lead to the accelerated aging of the material of the insulation layer of the excitation coil, which will easily cause interturn breakdown and affect the mechanism break and the overall mechanical life.

Table 2. Relation between resistance and conductivity of aluminum plate with temperature.

| T/°C | -10 | 0 | 10 | 20 | 30 | 40 | 50 | 60 | 70 | 80 |
|------|-----|---|----|----|----|----|----|----|----|----|
| R/mΩ | 10.71 | 11.15 | 11.6 | 12.1 | 12.57 | 13.05 | 13.53 | 14.06 | 14.48 | 14.95 |
| σ/S·m⁻¹ | 4.32×10⁷ | 4.13×10⁷ | 3.96×10⁷ | 3.8×10⁷ | 3.65×10⁷ | 3.5×10⁷ | 3.39×10⁷ | 3.27×10⁷ | 3.17×10⁷ | 3.06×10⁷ |

Figure 8. (a) Current of the ERM; (b) ERF of the ERM; (c) Displacement of the 10mm; (d) Change of 10mm displacement time with resistance.

Figure 9. (a) FMS in ambient temperature test; (b) Test the consistency of nine FMSs in series.

4. Design of repulsive mechanism and analysis of test results

4.1. Establishment of experimental test platform

As shown in Figure 9(a), in order to study the time-dispersion of FMS and verify the validity of the conclusion, a prototype of FMS was designed and manufactured according to the simulation results. The laser displacement sensor is used to measure the displacement data of the switch contact, and the displacement curve is converted to an oscilloscope. As shown in Figure 9(a), a temperature rise test platform was built. The temperature control box was used to conduct long-term high and low temperature tests on the whole mechanism, which testing the tripping speed, peak current and tripping time and the tripping characteristic curves of multiple groups at different temperatures. Based on the test results of multi-component gate at different temperatures, the average time difference of the gate was calculated to verify the high stability of the FMS. As shown in Figure 9(b), established experimental platforms for nine fast switches opening consistency test.

4.2. Analysis of test results

The comparison between the experimental displacement waveform and the simulation results under the FMS at room temperature is shown in Figure 10(a). Since the ERM will be affected by friction and
self-closing force of the vacuum interrupter during the actual movement, the closing time will be slightly longer than the simulation time. As is shown in Figure 10(a), the test waveform meets the actual situation and has high consistency with the simulated waveform. The waveform diagram of insulation distance to TIV is shown in Figure 10(b), and coil current waveform is shown in Figure 10(c). As is shown in Figure 10(b) and 10(c), the time of ERM motion to 10mm is 1.8ms, coil current peak is 8kA. The results show that the test waveform and simulation waveform have good consistency, which verifies that the FMS designed in this paper meet the design requirements.

![Figure 10](image_url)

Figure 10. (a) Opening displacement curve; (b) Time test waveform of ERM motion to 10mm; (c) Coil current waveform.

![Figure 11](image_url)

Figure 11. Time compliance test waveforms of nine FMS that are opened to 10mm.

As shown in Figure 11, the time of nine fast switches moving to 10 mm is less than 0.2 ms. Therefore, it meets the design requirements. The five FMS prototypes were tested for multiple opening tests, and the average value of the test data are shown in Table 3. The time from the FMS contact opening to insulation distance opening distance is less than 2ms and the time dispersion is less than 0.2ms, which meets the requirement of contact opening distance of 10mm within 2ms. The opening distance of the FMS contact at 2ms is greater than 12mm, which ensures that the DC CB has a strong breaking ability. The opening speed of the FMS is controlled, which avoids the large opening rebound at the end of the opening and causes the opening failure and reduces the serious impact on the mechanical life of the ERM.

| No | 1   | 2   | 3   | 4   | 5   |
|----|-----|-----|-----|-----|-----|
| TIV Time/ms | 1.80 | 1.78 | 1.82 | 1.76 | 1.86 |
| 2ms Displace/mm | 12.5 | 12.7 | 12.58 | 12.85 | 12.2 |

Table 3. Test data for the opening of FMS.

The five FMS prototypes were placed in the high-low temperature test box for a long time, and the temperature rise test of 10°C-80°C was conducted for the FMS at every 10°C stage. The multi-component brake test data were tested. Take the average value of the 10mm movement time when the FMS is broken, and the results are shown in Table 4. When the FMS is at 10°C-70°C, the time
dispersion of the opening motion of 10mm is less than 0.15ms, which verifies that the designed FMS has high stability and meets the engineering technical requirements. At the same time, it also proves the effectiveness of simulation and provides effective reference and accurate guidance for actual operation of circuit breaker.

In order to meet the requirement of quick action, the mechanical switch of hybrid HVDC circuit breaker usually adopts the form of multi-break series. Test the consistency of nine FMS in series, and the test result is shown in Figure 1. According to the test waveform, the time dispersion of each FMS is less than 0.2ms, which has good consistency.

| Table 4. FMS opening test data at different temperatures. |
|------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| Temperature/°C   |  -10 |  0  |  10  |  20  |  30  |  40  |  50  |  60  |  70  |  80  |
| Time/ms          |  1.7  |  1.72  |  1.73  |  1.76  |  1.78  |  1.8  |  1.83  |  1.85  |  1.89  |  1.95  |

5. Conclusions
In this paper, the important parameters deviation that affect the stability of ERM are simulated and analyzed. Suggestions on the reasonable range of parameters needed for stable operation of FMS are put forward. At the same time, the determination of temperature is an important factor affecting the stability of the FMS. Finally, a prototype of the FMS is made through the simulation results, and the characteristics of breaking, temperature rise and consistency are tested. The results show that the FMS designed in this paper has high stability and can meet the requirements of design technology and engineering practice. It will be applied to the 500kV/3000A hybrid DCCB of Zhangbei flexible project. The research method of this paper can be applied to FMS of other voltage levels. This study provides theoretical guidance and reference value for high stability FMS processing design and operating temperature.

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