Research on a novel drive unit of fast mechanical switch with modular double capacitors

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Abstract: The fast mechanical switch is one of the key devices for high-voltage direct-current circuit breakers (DCCB), and the mechanical contacts separation time determines the operating time of hybrid mechanical circuit breakers. With the increasing of the voltage and power levels of DC system, numerous technical challenges begin to emerge. For high-voltage system, the new research and the series arrangements of very fast mechanical switches include designing new drive unit to satisfy larger load mass and longer travel stroke. Aimed to reducing the peak value of electric force, a novel drive unit by using modular double capacitors has been proposed here. Based on the equivalent circuit method (ECM), the mathematical model of Thomson coil (TC) actuators which is the key drive unit in fast mechanical switch is established. First, the time sequence of capacitance discharge is studied. Then, the electromagnetic force can be divided into five types in different time sequences, and the characteristics of the electromagnetic force are analysed. Finally, it is concluded that using a combination electromagnetic force with three approximate peaks can reduce the impact of the metal plate, which improve the reliability of the fast switch.

1 Introduction

The fast mechanical switches are the key equipment in HVDC circuit breakers, and its operating time determines the commutation time of hybrid mechanical circuit breakers [1, 2]. The ultra-fast electromechanical actuators are equipped with Thomson coil (TC) actuators (TCA), which have the advantages of simple structure and capability of attaining high accelerations. The driving processes of ultra-fast electromechanical actuators are the physical processes of circuit, electromagnetic field, and mechanical motion. Capacitor bank fully charged is used as an energising source that supplies pulse currents through the TC. The pulsed magnetic field in the metal plate will induce eddy currents and a large repulsive force will be generated between TC and the metal plate. The metal plate together with the moving contact will be driven away to the open position in a high speed.

There are mainly two methods, finite element method (FEM) and equivalent circuit method (ECM), to analyse and simulate the operating process of TCA. D.S. Vilchis-Rodriguez, Ara Bissal, and others have already done some very detailed work on the operating efficiency of the TCA and the practical accuracy considerations by using FEM [3, 4, 5]. However, FEM is quite time-consuming, which has been proven precise to solve the simulation of a 2D finite element (FE) transient axis-symmetric model of a TCA [6, 7]. More research and work about the influence of parameters on the performance of the actuator have been done by using ECM in [8, 9, 10].

In high-voltage DC applications, the fast mechanical switches are facing some difficulties including larger load mass and longer travel stroke. Since there is very few work to solve these problems, it is a good start to design and optimise the drive units of the fast mechanical switch.

2 Proposed solution

There are several key units that make up the HVDC CBs, such as control units, conducting electrodes, insulating mediums, and ultra-fast actuators.

For the basic requirements of HVDC CBs, two things are necessary:

(i) Interrupt the fault current.
(ii) Withstand the voltage response of the network after current interruption.

To improve the voltage level of HVDC CBs, there are several effective ways as follows.

(i) Increase travel stroke.
(ii) Inject an excellent gaseous dielectric medium such as sulphur hexafluoride (SF₆), carbon dioxide (CO₂), or nitrogen (N₂) into the arcing chamber.
(iii) Use multibreak interrupter, which is made up of several series-connected contacts, to share the transient interruption voltage (TIV) [11].

Therefore, HVDC CBs can be designed to consist of several contacts in a medium with a high dielectric strength (e.g. SF₆). However, the opening and closing of the conducting electrodes in the SF₆ is a complex physical process involving fluid mechanics, heat conduction, electrical contacts, and mechanical motion. Although this can minimise the travel stroke of contacts and improve the efficiency of actuators, it will also increase the complexity and cost of HVDC CBs.

Another way to withstand the higher TIV is to increase travel stroke. However, as the stroke increases, the efficiency of actuators will become less. In order to achieve a longer stroke within the specified time, a larger electromagnetic repulsive force must be generated. If the traditional single capacitance continues to be used, the waveform of electromagnetic force generated by the discharge of capacitor to the drive coil is similar to a half-wave shape with a peak value (as shown in the black solid line in Fig. 1). The larger the peak of the repulsive force, the greater the impact stress of the metal plate and the insulated pull rod, which makes the moving parts more susceptible to damage and deformation. Therefore, the ideal waveform of electromagnetic force should be a rectangular wave whose peak value is smaller but maintained for a longer time (as shown in the red dotted line in Fig. 1). In practice, the ideal rectangular waveform cannot be produced. Therefore, a combination of waveforms (as shown in the green solid line in...
The driving process of electromagnetic repulsion mechanism is modelled by ECM. Considering that the mechanism is an axisymmetric structure, the drive coil and metal plate are redrawn in the $r$-$z$ plane. Previous research has shown that the work frequency of circuit is generally <1 kHz, and skin effect in the metal plate was not significant [12].

$I_1$ is the self-inductance of the drive coil. $R_1$ is the equivalent resistance of the drive coil. $L_2$ is the self-inductance of the metal plate. $R_2$ is the equivalent resistance of the metal plate. $U_{C1}$ and $U_{C2}$ are the voltage of the capacitor $C_{d1}$ and $C_{d2}$, respectively. $M$ is the mutual inductance between the drive coil and the metal plate. $I_{ed1}$ and $I_{ed2}$ are the corresponding drive current. $I_e$ stands for the eddy current in the metal plate (Figs. 2 and 3).

The electromagnetic force is determined by the drive current, the eddy current, and the derivative of the mutual inductance between the drive coil and the metal plate.

The parameters having influences on the discharge drive characteristics of the modular double capacitors include the drive capacitances ($C_{d1}$, $C_{d2}$), the capacitor bank charging voltages ($U_{C1}$, $U_{C2}$), and the discharge time of each capacitor. The impact of the interval time between the discharge of capacitors on the drive characteristics is the main aspect which will be focused on.

4 Discussion

To do deeper research on the relationship between the parameters of the modular double capacitors, the following work is taken (Fig. 4).

First, the schematic diagram of five different types of drive current from the modular double capacitors is listed to reveal the relationship between the discharge time of the drive capacitance ($t_0$) and the interval time between the starting discharge of capacitors ($t_1$).

As can be seen in cases (a) and (b), the discharge time of the drive capacitance ($t_0$) not <1 ms. If $t_0$ is <1 ms, no matter how to adjust $t_1$, the drive current will be zero for a certain period of [0, 2 ms], as in case (a). If $t_1$ appears before the time of peak current ($t_p/2$), as shown in case (e), the two drive current added together will make eddy current in metal plate too large. To avoid this kind of current waveform, the interval time between the starting discharge of capacitors ($t_1$) should appear after the time of peak current ($t_p/2$). To sum up, the conditions that the interval time

\[ F = \frac{dM}{dx} i_e \]  

The motional equations of metal plate are shown as follows in (9) and (10):

\[ \frac{dx}{dt} = v \]  

\[ \frac{dv}{dt} = \frac{F}{m_{load}} \]

The electromagnetic force is generated by the drive current, the interval between the starting discharge of capacitors on the drive characteristics is the main aspect which will be focused on.
between the starting discharge of capacitors \( t_1 \) and the discharge time of the drive capacitance \( t_0 \) are as follows:

\[
t_1 < t_0 \\
t_0 \geq 1 \\
t_1 > \frac{1}{2} t_0 \\
t_0 = 2 - t_1
\]

The value range of \( t_0 \) and \( t_1 \) is obtained by solving the above inequality group, as follows:

\[
1 \leq t_0 < \frac{4}{3} \\
\frac{2}{3} < t_1 \leq 1
\]

To analyse the influence of the starting discharge of capacitors \( t_1 \) on the electromagnetic force, the electromagnetic force is divided into five cases shown in the schematic diagram. In case (a), the electromagnetic force with only a high peak is generated by the original drive unit. In case (b), the peak value in the middle is much larger than the peak of the first crest. The electromagnetic force can be seen as a variation of the original waveform, but a wave crest is added to the rising place, which makes the electromagnetic force increase faster. In case (c), the peak value in the middle is slightly higher than the peak on both sides. The three peaks grouped together are similar to the plane waveform, which is closer to the rectangular wave. In case (d), the first crest peak is higher than the peaks of the next two peaks. In case (e), there are only two peaks remaining on the both sides, and there is a gap in the middle part (Fig. 5).

Based on the preliminary design, there are two different research directions [12]:

(i) Keep the capacitor bank charging voltages constant and change the drive capacitances.

(ii) Keep the drive capacitances constant and change the capacitor bank charging voltages (Table 1) (Figs. 6 and 7).

5 Conclusion

Although there are some differences between the combination electromagnetic force and the ideal force, the presented drive unit provides the possibility of generating electromagnetic force with
different shapes. So far few literature is from the point of electromagnetic force to design and optimise the fast mechanical switches. However, with the increase of travel stroke and load mass, the high efficiency of driving technology and the impact resistance of the transmission system must be considered.

Future theories and experimental work will include optimising the control parameters of drive units and analysing the factors that affect the operation efficiency. To get more details about the process of operation, the FEM simulations will be adopted. One of the interesting research directions is the control of speed change, such as secondary acceleration and deceleration buffering.

6 Acknowledgments

The authors would like to thank Prof Yulong Huang and Dr Weijie Wen for the frequent discussions. Here, the research was sponsored by the National Natural Science Foundation of China under the reference number 51677095, National key R & D plan (2017YFB0902404) and Henan Pinggao Electric Co., Ltd, Pingdingshan, Henan Province, China.

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