Comparative Analysis of Two Actuators for High Voltage Bypass Switch

Jinghua Jiang¹, Hongtie Zhang¹, Yingjie Sun¹, Jianlei Zhao¹, Yu Zhu², Liyan Zhang² and Enyuan Dong²*

¹ State Grid Pinggao Group Co., Ltd., Pingdingshan, Henan, 467001, China
² School of Electrical Engineering, Dalian University of Technology, Dalian, Liaoning, 116024, China
*Corresponding author’s e-mail: dey@dlut.edu.cn

Abstract. The bypass switch is required to complete the closing operation quickly and accurately protect the transmission line. Therefore, there is a high requirement for the actuator of the bypass switch. According to the characteristics of the bypass switch, the commonly used actuators are compared, and the magnetic force actuator and the motor actuator are initially selected to meet the requirements. Firstly, the characteristics of the magnetic and motor actuator are compared and analyzed in principle. Then, the optimization model of the two actuators is obtained through simulation optimization. Under the same working voltage, the action characteristics of the two actuators, including the action speed, the start time and the output force, are compared. Finally, a comprehensive reference for the selection of the bypass switch actuator is provided.

1. Introduction

The high voltage bypass switch is a key device in the series compensation device of the transmission line. It is usually connected in parallel with the series compensation capacitor. The capacitor is connected in series to reduce the line loss in the normal state. When a fault occurs, the bypass switch needs to be quickly closed to short the capacitor and protect the line. This puts higher requirements on the actuator of the switch, especially for the 1100 kV bypass switch. The bypass switch has a long contact travel and a short operating time, and has certain requirements for controlled closing. The actuator is a mechanical device that drives the switching contacts to perform the opening and closing motion. The performance of the actuator determines the overall performance of the switch. Therefore, it is of great significance to study the actuator of the bypass switch.

At present, the commonly used actuators in the power system include spring actuator, hydraulic actuator, permanent magnet actuator, repulsion actuator, magnetic force actuator and motor actuator. The characteristics of various types of actuators are shown in Table 1. It can be seen that the spring actuator, the permanent magnet actuator and the repulsion actuator all have short travel problems due to small output power [1-2]. So it is difficult to apply to the high voltage field. The hydraulic actuator is currently a commonly used actuator in the high voltage field [3]. However, its structure is complicated and the cost is high. Both the magnetic force actuator and the motor actuator can be applied to long travels. And intelligent control can be realized, which is more in line with the future development direction of the power grid.
Table 1. Characteristics of different actuators

| Actuator       | Advantage                                      | Disadvantage                                      |
|---------------|-----------------------------------------------|--------------------------------------------------|
| Spring        | Simple operation and low cost                 | Low output power, not suitable for long travels, high failure rate |
| Hydraulic     | High output power and stable operation        | Complex structure, high requirements on production process and high cost |
| Permanent magnet | Simple structure and good speed characteristics | Short travel and poor reliability                |
| Repulsion actuator | Fast action and simple structure               | Limited range of force, short travel              |
| Magnetic force | Simple structure, high output power and long travel | Higher power costs                                |
| Motor         | High reliability, and good intelligent foundation | Complicated control                              |

The magnetic force actuator was first proposed by Seoul National University of Korea. The dynamic performance of the magnetic force actuator was numerically analyzed and applied to the 72.5kV/20kA SF$_6$ circuit breaker and the 170 kV/20 kA vacuum circuit breaker [4-5]. Dalian University of Technology cooperated with Pinggao Group to carry out a lot of research on the magnetic actuator model, and developed 40.5 kV SF$_6$ circuit breaker and 126 kV vacuum circuit breaker respectively [6-7]. The motor actuator was first proposed by ABB for circuit breakers [8]. Shenyang University of Technology and Tsinghua University have carried out extensive research on the motor actuator for high voltage circuit breakers and successfully applied it to vacuum circuit breakers of 40.5 kV and 126 kV [9-10]. However, the application of these two actuators on the 1100 kV bypass switch has not been reported yet.

In this paper, combined with the characteristics of long travel and high control precision of the bypass switch, the magnetic force actuator and the motor actuator are selected. And the two actuators are comprehensively compared and analyzed, which provides a reference for the actuator selection of the bypass switch.

2. Basic principles of two actuators

The basic structure of the magnetic force actuator is shown in Figure 1. The external control circuit of the magnetic force actuator is shown in Figure 2.

![Figure 1. Basic structure of magnetic force actuator](image1)

![Figure 2. External circuit of magnetic force actuator](image2)

It can be seen from Figure 1 that the magnetic force actuator is mainly composed of a coil, a moving iron core, a static iron core, a permanent magnet and a connecting rod. The coil is evenly wound on the moving iron core. The two together form the moving part. The static iron core constitutes the main frame of the magnetic force actuator, and is used to fix the permanent magnet and is responsible for establishing the magnetic field path. The permanent magnet is divided into the main permanent magnet and the auxiliary permanent. The main permanent magnet establishes a main magnetic field that causes the charged coil to move in the magnetic field. The auxiliary permanent...
magnet is used to maintain the actuator at the opening and closing position. External circuit is mainly composed of a charging capacitor, a SCR and a coil. The capacitor is discharged to the coil, and the coil in the magnetic field receives the ampere force and starts to move. The equation of state of the motion process is as follows:

\[
\begin{align*}
    i(t) &= -c \frac{dU_c(t)}{dt} \\
    \frac{d\psi(t)}{dt} &= U_c(t) - Ri(t) \\
    \frac{dv(t)}{dt} &= F(t) - F_i(t) \\
    \frac{dt}{dt} &= F(t) = 2nBli(t)
\end{align*}
\]

Where \(\psi(t)\) is the flux linkage, \(U_c(t)\) is the capacitance voltage, \(R\) is the internal resistance of the coil, and \(i(t)\) is the current flowing through the coil. It can be seen that the main external factor affecting the movement of the magnetic force actuator is the charging capacitor, which determines the magnitude of the current \(i(t)\).

The motor actuator uses a permanent magnet brushless DC motor, and its basic structure is shown in Figure 3. It is mainly composed of a stator, a rotor, a permanent magnet and windings. The winding is wrapped around the teeth of the stator. The permanent magnet is attached to the surface of the rotor. The external circuit of the motor actuator is shown in Figure 4. A three-phase full-bridge inverter circuit is used to invert the DC current on the capacitor to a three-phase ripple current. Three-phase currents are distributed on the windings in a certain order to form a rotating magnetic field. This magnetic field interacts with the magnetic field generated by the permanent magnet to drive the rotor to rotate. It can be seen that the working principle of the motor actuator is similar to that of the magnetic force actuator. They all rely on the permanent magnet to establish a static magnetic field. The actuator is moved by the action of the ampere force that the energized conductor receives in the magnetic field. The difference is that the coil is fixed in the motor actuator, the permanent magnet is moving, and the three-phase current is passed through the coil, thereby forming a rotating pulsating magnetic field, and the rotor is forced to rotate. In the magnetic force actuator, the coil passes through direct current, and the coil moves linearly in the magnetic field. In addition to the influence of its own mechanical parameters, the speed of the two actuators is affected by the voltage of the external circuit.

![Figure 3. Structure of motor actuator](image3.png)

![Figure 4. External circuit of motor actuator](image4.png)

### 3. Comparison of actuators characteristics

In order to meet the action requirements of the bypass switch, the two actuators are optimized respectively. And the optimized parameters obtained are shown in Table 2 and Table 3. The permanent magnets of the two actuators use the same NdFeB material. The external circuit voltage is 500 V. However, the coil of the magnetic force actuator has a larger coil diameter and a larger number of turns.
Table 2. Basic parameters of magnetic force actuator

| Parameter          | Value          |
|--------------------|----------------|
| Size               | 150*200*350 mm |
| Turns              | 120            |
| Capacitor          | 20 mF          |
| Voltage            | 500 V          |
| Moving mass        | 35 kg          |

Table 3. Basic parameters of motor actuator

| Parameter                  | Value          |
|----------------------------|----------------|
| Stator outer diameter      | 200 mm         |
| Winding diameter           | 1.085 mm       |
| Stator inner diameter      | 120 mm         |
| Air gap                    | 1 mm           |
| Voltage                    | 500 V          |
| Moment of inertia          | 0.1168 kg*m²   |
| Permanent magnet           | NdFeB          |

3.1. Displacement curve

The displacement curves of the two actuators are shown in Figure 5. The black solid line is the displacement curve of the motor actuator, and the red dashed line is the displacement curve of the magnetic force actuator. Since the motor is a rotary motion, its actual angle of rotation is 180°. For the convenience of comparison between the two actuators, the angle is converted into a displacement according to the size of the rotating shaft. It can be seen that under the same operating voltage, the operating time of the motor actuator is 1 ms shorter than that of the magnetic force actuator. At the same time, the motor actuator starts to move at the 5 ms, and the magnetic force actuator starts to move at the 2.5 ms. This is because the motor actuator is a rotational motion. In the initial rotation angle, although the motor has rotated a certain angle, it is actually only shifted by a small length after being converted into a linear motion. Therefore, the starting time of the motor actuator is longer than that of the magnetic force actuator, but the operating time is shorter than that of the magnetic actuator.

3.2. Speed curve

Figure 6 is a speed comparison curve for the two actuators. Similarly, the angular velocity of the motor is converted to the displacement velocity. It can be seen that although the speed of the motor actuator is smaller than the magnetic force actuator at the beginning, its acceleration is larger than that of the magnetic force actuator. So the speed quickly exceeds the magnetic actuator. Moreover, the speed of the motor actuator reaches a maximum value at the 17 ms, which is about 8 m/s, and then begins to slowly decrease. The magnetic actuator reaches its maximum speed at the 23 ms, which is about 7 m/s. The speed of the magnetic actuator then begins to decrease rapidly. This shows that the
movement of the magnetic actuator is not buffered. And a large impact will occur when the switch is to be closed, which is disadvantageous to the switch itself. And the motor actuator has a deceleration process in the latter half of the displacement due to the rotational motion. Therefore, there is a buffer for the closing action. In this respect, the motor actuator is superior to the magnetic actuator.

3.3. Force curve

Figure 7 shows the force curves of the two actuators. For the sake of comparison, the force of the magnetic actuator is converted into a torque. It can be seen that the torque of the motor actuator is much larger than that of the magnetic actuator. And after reaching the maximum value at the 5 ms, it starts to slowly become smaller, which is also consistent with the trend of the speed curve in Figure 6. The torque curve of the magnetic actuator is relatively stable and the fluctuation is small, so that the magnetic actuator is always in an accelerated state during the movement. This is not good for the actuator.

![Torkus.png](attachment:Torkus.png)

Figure 7. Comparison of the output of the two actuators. Since the magnetic actuator outputs the force, the motor actuator outputs the torque. For comparison purposes, the force is converted to a moment, where the length of the arm is 0.04 m.

4. Conclusion

In this paper, the existing actuator is compared and analyzed for the requirements of the high-voltage bypass switch. And it is determined that the magnetic force actuator and the motor actuator are more suitable for long travel. The two actuators are similar in basic principle, except that the form of motion is different. The magnetic force actuator is a linear motion, and the motor actuator is a rotary motion. The motion characteristics of the two actuators were compared at the same voltage. Although the starting time of the motor actuator is slower than that of the magnetic force actuator, the average moving speed of motor actuator is faster than that of the magnetic force actuator. And in the latter half of the travel, the speed of the motor actuator will gradually slow down, which is very important for reducing the closing bounce of the actuator. In the case of substantially the same volume, the output of the motor actuator is much larger than that of the magnetic force actuator. Considering comprehensively, the motor actuator is more suitable for high-voltage bypass switches.

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