The Application of NdFeB in the Magnetic Force Actuator

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Abstract
In this paper, NdFeB is used to design a new type of magnetic force actuator (MFA) with simple structure and high reliability. The permanent magnets are fixed on the static iron-core to generate a magnetic field, while the movable part locates within the magnetic field. It can drive the arc extinguishing unit powered by the Lorentz force, and this can be applied to the operation of the long-stroke high voltage circuit breaker (HVCB). At the open and closed position, the PMs generate holding force for the moving iron-core to keep the static state. Then, the finite element method (FEM) and prototype test are adopted to study the properties of PM and characteristics of the actuator. The simulation concludes that the material type and structure size of PM, end cap material and processing deviation of the actuator will impact the static characteristic of the actuator. The results of the test on prototype show that MFA using NdFeB can achieve the high power output, which is conductive for electronic control as well as the displacement tracking. Due to its stable performance, NdFeB is reliable in the running of the magnetic force actuator.

Keywords: NdFeB, permanent magnet material, magnetic force actuator, finite element method, reclosing experiment

1. Introduction
High voltage circuit breaker is an important switchgear and protection appliance in the power system, so its stability is extremely crucial. Besides, its reliable operation is based on the small dispersity of running and low failure rate of the actuator [1-2]. The typical mechanism of HVCB includes the pneumatic mechanism, hydraulic mechanism and spring mechanism, etc. [3]. The pneumatic mechanism applies the piston to drive the contact closed, uses mechanical blocking to ensure that the circuit breaker is firmly at the closed position and then adopts a storage solenoidal electromagnet to release the energy to achieve the mechanical unlocking as well as open[4]. The hydraulic mechanism can operate the circuit breaker using the characteristic that fluid cannot be compressed [4]. Similar to the spring mechanism, it also adopts the mechanical blocking device, which, coupled with many connected components, has increased the incidence of mechanical failure to some extent [5], so the frequent maintenance is required [6]. Moreover, the leakage of gas and liquid may bring down the reliability. In addition, the large number of mechanical links of pneumatic and hydraulic mechanism will lead to the increase in time dispersion, and the fast-adjust PWM control cannot be used to keep track of its real-time position and achieve the predetermined displacement curve.

In recent years, the PM material has been applied in HVCB, and a lot of related researches have been made [5-7]. This paper designs a novel type of magnetic force actuator. This actuator owns a simple structure, including five parts [8]: moving coil, moving iron core, static iron core, PMs and transmission rod, as shown in Figure 1. The static iron core, fixing the actuator’s model as its architecture, is always used to provide magnetic field for the magnetic field; while the transmission rod connected to the movable part drives the arc extinguishing unit.

In this actuator, PMs are embedded in the static iron core according to certain rules, as shown in Figure 2. The PMs with the same color own the same magnetic field direction. The main PMs locate at the central position, while the auxiliary PMs are at both ends. The golden yellow component is the moving coil, which is used to constitute the movable part with the moving iron core. The two end caps are all composed by aluminum-based material, and the auxiliary PMs, coupled with the main PMs at the same end, are placed at the negative direction of magnetic field according to the following principle: when the moving iron-core moves, the
auxiliary PM plays a role of buffering and slowing-down; when it is at the open and closed position, the auxiliary PM plays a role of maintaining the static state [9-10]. The main PMs are placed along the direction of magnetic field to provide the driving magnetic field. The excitation moving coil is powered by the Lorentz force to drive the movable part, thus boosting the connected transmission rod to drive the circuit breaker.

In addition to the small size, fewer mechanical parts and high reliability, this actuator also has another advantage compared with traditional permanent magnet ones [11-13], that is, the movable coil winding, which is the power source of the movable part. The characteristics of the moving coil determine its application in the long-stroke operating, which can better meet the requirement of HVCB [14-15]. Besides, the external sensor can be utilized to achieve the real-time tracking of movement displacement, and the controller is used to collect and analyze the dynamic data to issue the corresponding control command and adjust the running features, thus achieving the preset displacement curve [16]. It can ensure the accuracy and stability of the opening and closing time, thereby advance the phase-control switching technology of power system [3, 17], as well as provide a reliable guarantee to improve the intelligent proficiency of power switch in the smart grid.

2. Mathematical modeling and simulation analysis
2.1. The mathematical model
The solving region of finite element simulation of MFA is regarded as the entire model region, where the coil winding and the PM locate. And the current flows through the coil winding; therefore, to solve the magnetic field problems in this model [18-21], the magnetic potential vector $A$ should be introduced, that is

$$
\mathbf{B} = \nabla \times \mathbf{A}
$$

(1)

According to the Ampere’s Law, the following formula can be obtained

$$
\nabla \times \mathbf{H} = \mathbf{J}
$$

(2)

And there is a relational expression

$$
\mathbf{B} = \mu \mathbf{H}
$$

(3)

Combine (1) (2) (3) and the following relationship can be deduced:

$$
\nabla \times \left( \frac{1}{\mu} \nabla \times \mathbf{A} \right) = \mathbf{J}
$$

(4)
In the above formulas, B (Wb/m^2) is the magnetic induction, H (A/m) is the magnetic field intensity, J (A/m^2) is the current density, \( \mu (H/m) \) is the relative permeability.

For the solving of flux linkage \( \psi \), the following formula can be used:

\[
\psi = \int A dl
\]  

(5)

In this formula, \( \psi \) (Wb) is the flux linkage, \( l \) (m) is the length of the coil.

If the current density \( J \) is known, then the magnetic potential vector \( A \), magnetic flux density \( B \), magnetic linkage \( \psi \), and magnetic field strength \( H \) can be obtained according to the above formulas.

The movable part of the MFA is affected by a resultant force which contains three parts: static holding force, electromagnetic force and external force. The permanent magnet provides the holding force, shown as follows:

\[
F^{hold} = \int \left( \frac{1}{\mu_0} (B \cdot \hat{n}) B - \frac{1}{2\mu_0} B^2 \hat{n} \right) ds
\]  

(6)

In this formula, \( F^{hold} \) (N) is the holding force, \( S \) (m^2) is a closed surface surrounded by the coil, and \( \hat{n} \) is the unit vector along the normal direction of surface.

When the current flows through the coil winding, the conductive coil in the magnetic field is powered by the Lorentz force, shown as the following formula:

\[
F^{Lorentz} = q v \times B = J \times B
\]  

(7)

In this formula, \( F^{Lorentz} \) (N) is the electromagnetic force when the movable part moves, \( q \) (C) is the charge, and \( v \) (m/s) is the velocity vector.

The operating force, resultant force of the movable part, is shown as below:

\[
F^{operate} = F^{hold} + F^{Lorentz} + F^{external}
\]  

(8)

The above mathematical model formulas are the typical formulas of Ansoft kernel adopted in this paper.

2.2. Analysis on the properties of permanent magnet material in MFA

The low-frequency electromagnetic finite element software Ansoft Maxwell [19] is adopted to conduct simulation analysis on the application performance of the three different PM materials in this actuator. Figure 3 shows the curve of static magnetic force of MFA under the same structure and using different PM materials. The holding force of permanent magnet AlNiCo40/17 and Y25 is relative small at the open and closed position, which cannot achieve the static state maintaining of the non-blocking device.

![Figure 3. the static magnetic force of different PM materials](image1)

![Figure 4. the impact of PM with different thickness on the static magnetic force](image2)
The working principle of this actuator is that the moving coil is powered by the Lorentz force to drive the movable part, which requires large remanence to generate sufficient Lorentz force. The remanence of the ferrite PM is generally less than 0.4T, and the coercivity of these two materials is small, so the demagnetization is apt to emerge, thus it is not appropriate to be applied in this actuator. The NdFeB PM owns the characteristics of large remanence and high magnetic energy product. The calculation results of NdFeB (N30) indicate that the holding force at the open and closed position is sufficient enough to achieve the non-blocking static state maintenance in 40.5kV-class gas circuit breakers.

2.3. The impact of the permanent magnet’s thickness on static magnetic force
The PM provides the main magnetic field for MFA, which is conductive for the actuator to obtain sufficient driving force. Meanwhile, to save the PM, this paper conducts simulation analysis on the influence of the PM’s thickness on its static magnetic force characteristics.
As shown in Figure 4, the variation of the PM’s thickness within a certain range has slight impact on static magnetic force. Therefore, if the requirement of the holding force at the open and closed position is satisfied, the factors such as economy and volume should be taken into account to select the PM with appropriate thickness.

2.4. The selection of end cap material
Figure 5 shows the static magnetic force curves of permeability material electrical pure iron and non-permeability material aluminum. Therefore, the end caps of the permeability material generate little holding force with the opposite direction to the required one at the open and closed position, which cannot meet the requirement. The main reason lies in that the magnetic short circuit caused by the end cap of the permeability material reduces the flux flowing through the moving iron core, thus making the movable part fail to obtain enough holding force. Obviously, the aluminum end caps can meet the requirement for holding force. Therefore, the end cap composed by non-permeability material aluminum has been adopted in this design.

2.5. Processing deviation of air-gap
In order to prevent the friction between the movable part and the permanent magnet, the air-gap is a necessity when processing. In theory, the air-gap should be as small as possible, but deviation in varying degrees is prone to emerge due to the impact of machining accuracy, which will affect the magnetic force to a large extent. Figure 6 shows the static magnetic force of different air gaps with the width of 0.5mm, 1mm and 2mm. The results indicate that different air gaps have a great impact on the holding force at the open and closed position. If the processing of the air gap is set as 0.5mm, as shown in the figure, when the air gap is 1mm caused by the processing deviation, the holding force at the open and closed position is still able to meet the design requirements. While when the air gap increases to 2mm due to the processing deviation, the holding force decreases by 45% at the open position and by 42% at the closed position, which cannot satisfy the requirement. Therefore, in the process
of actuator manufacture, the machining accuracy of workpieces should be ensured and errors should be reduced.

2.6. Dynamic characteristic analysis

Based on the previous studies about the factors of static characteristic, this paper carries out a simulation analysis on the dynamic characteristic of MFA\[18,25\]. The Ansoft transient solver is used to calculate parameter changes of the circuit breaker in the opening process, thus obtaining the relationship that the coil current and output power vary versus time.

![Figure 7. the dynamic characteristics of MFA in the opening process](image1)

![Figure 8. the comparison between the MFA and the spring mechanism](image2)

In Figure 7, the 60,000 $\mu$F capacitor charged to 300V is adopted to discharge to the moving coil, thus achieving the opening dynamic characteristics of MFA for 40.5kV-class gas circuit breaker. The contact distance of this actuator is 60mm and the overtravel is 20mm. As shown in Figure 7, the peak of coil current is 80A which is relatively low and the drop-out time is 38ms, which reflects better opening characteristics of circuit breaker.

As shown in Figure 8, the operating characteristics of the spring mechanism have been qualified by the State Experiment Station. The comparison shows that the displacement curves of MFA at the opening and closing process can contain the curves of the spring mechanism, coupled with a certain redundancy, which has provided a design basis for the realization of closed speed regulation loop by using programming PWM chopper. The tracking control for the running of MFA can be achieved by the displacement sensor in order to realize the performance which is completely consistent with the spring mechanism.

3. Experiment

3.1. The experimental methods

The model obtained in the above simulation analysis, that is, the prototype as shown in the Figure 9, is an actuator of 40.5KV SF6 circuit breaker. The length of this actuator is 0.3m, the width is 0.19m, the height is 0.18m and the stroke length is 80mm. Besides, the iron core is made by the electrical pure iron (DT4), the main permanent magnet and auxiliary permanent magnet are all composed by NdFeB (N30), and the end cap material is aluminum. The 60,000 $\mu$F capacitor with the initial voltage of 300V and controlled by IGBT is adopted to open or close the discharge circuit, and its equivalent schematic diagram is as shown in Figure 10.

The DTM-8X portable mechanical properties tester is used to collect the dynamic parameters. The reclosing experiment in closed-loop control refers to the Open-Close-Open experiment of MFA tracking the real-time displacement changes by displacement sensor, which will be fed back to the DSP controller [22-24]. Then the controller will analyze these data and send out the corresponding chopper instructions to achieve speed governing and finally complete the closed-loop control for MFA’s path to achieve the predetermined displacement curve.

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3.2. The results of reclosing experiment in closed-loop control

Combined with the advanced electronic control unit, the new type magnetic force actuator composed by the NdFeB magnetic material can achieve the tracking of the preset displacement curve and decrease the time dispersion.

Table 1. fast reclosing controlled by closed-loop

<table>
<thead>
<tr>
<th>No.</th>
<th>Operate</th>
<th>Pre-Voltage (V)</th>
<th>Post-Voltage (V)</th>
<th>Time (ms)</th>
<th>Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Open</td>
<td>310</td>
<td>286</td>
<td>32.26</td>
<td>2.82</td>
</tr>
<tr>
<td></td>
<td>Close</td>
<td>286</td>
<td>262</td>
<td>46.80</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>262</td>
<td>237</td>
<td>32.52</td>
<td>2.74</td>
</tr>
<tr>
<td>2</td>
<td>Open</td>
<td>320</td>
<td>296</td>
<td>32.40</td>
<td>2.86</td>
</tr>
<tr>
<td></td>
<td>Close</td>
<td>296</td>
<td>272</td>
<td>46.65</td>
<td>2.30</td>
</tr>
<tr>
<td></td>
<td>Open</td>
<td>272</td>
<td>247</td>
<td>32.48</td>
<td>2.76</td>
</tr>
<tr>
<td>3</td>
<td>Open</td>
<td>320</td>
<td>296</td>
<td>32.82</td>
<td>2.96</td>
</tr>
<tr>
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<td>Close</td>
<td>296</td>
<td>272</td>
<td>46.58</td>
<td>2.32</td>
</tr>
<tr>
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<td>Open</td>
<td>272</td>
<td>247</td>
<td>32.43</td>
<td>2.74</td>
</tr>
<tr>
<td>4</td>
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<td>2.88</td>
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<td>46.78</td>
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<tr>
<td></td>
<td>Open</td>
<td>263</td>
<td>237</td>
<td>32.42</td>
<td>2.74</td>
</tr>
</tbody>
</table>

As shown in Table 1, the data of the reclosing closed-loop control experiment of 40.5KV SF6 circuit breaker indicates that when the D-value of the capacitor voltage is up to 10V in the closing, the D-value of the closing time is 0.22ms; when conducting the reclosing, the difference of the opening time is 0.26ms when the D-value between the first-opening and second-opening capacitor voltage reaches its maximum value 48V. The measured displacement curve is as shown in Figure 11. Therefore, controlled by the closed loop, the stability of this kind of MFA has been largely improved, which is conductive for phase-control accurately.

4. Discussion

Environmental temperature may impact the application of NdFeB to some extent. The temperature rise may lead to the decrease in the coercivity of the PM; while the low temperature may lead to its increase. The temperature coefficient of NdFeB is relatively high. Generally, the temperature coefficient of Br is -0.123% / °C and its ferromagnetic Curie point is low, usually 312 °C [26]. The maximum range of outdoor temperature of HVCB ruled by the IEC is -40 °C ~40 °C [3], which is smaller than the Curie temperature of NdFeB, so it cannot change the order of magnetic domain of permanent magnetic material. Therefore, the impact of temperature on the permanent magnet material can be ignored in MFA.
In addition, the permanent magnet material work in the magnetic field of the moving coil, so it is necessary to take into account the influence of the magnetic field on the demagnetization of PMs. The premise for the demagnetization of PM is that first the magnetic field amplitude should be high enough to overcome the material coercivity, which is an indicator of the demagnetization degree [27]. So only in this way, the remanence can be decreased. However, the peak current in the excitation coil is around 80A with the constant direction and short operating time; besides, the direction of its magnetic field is perpendicular to that of the permanent magnet magnetic field, which, coupled with the characteristic of high coercivity of the NdFeB, endows it good resistance to demagnetization and stable performance. The NdFeB materials have been widely applied in the permanent magnet actuator(PMA) for more than 10 years. Besides, the direction of magnetic field generated by the moving coil in PMA is parallel to the direction of permanent magnetic field, so its demagnetization effect is even more serious than that in MFA. Meanwhile, the permanent magnet will never receive a frontal attack, so NdFeB permanent magnetic materials will fail to work due to the demagnetization factors.

5. Conclusion

This paper introduces the application of NdFeB permanent magnet material in the new type magnetic force actuator, and then analyzes their driving characteristics in the new system of the circuit breaker by large number of simulation and experiments. Conclusions are shown as follows:

1. Apply the NdFeB PMs in MFA to achieve the function of driving and positions holding of a circuit breaker by a certain seriation, which endows the actuator small size, simple structure and good application for long stroke driving, thus providing greater holding force and driving power. Besides, its reliability is higher and failure rate is lower than that of the traditional mechanism.

2. Carry out the simulation analysis on the structure parameters of NdFeB permanent magnets in MFA. The analysis results show that the NdFeB can generate holding force, which is great enough for MFA compared with the traditional permanent magnet; its thickness has a poor impact on the characteristics of the new actuator within a certain range; to obtain larger holding force, non-permeability material should be adopted for the end caps of MFA; in addition, the processing deviation of the air gap between the movable part and the permanent magnet should never be too large.

3. The simulation on its dynamic characteristic indicates that it can meet the design requirements of the 40.5kV-class gas circuit breaker; then utilize the design parameters obtained by the simulation to make prototype and carry out the test. The test results show that it can get the job done great.

4. Combine the electrical control to carry out the real-time tracking of the MFA’s displacement and the optimal contact trajectory of the programmable circuit breaker, which has provided a guarantee for the realization of phase-control technology of circuit breakers.

5. The NdFeB permanent magnet material applied in MFA has stable performance and good resistance to demagnetization; the 10-year maintenance-free operation experience of PMA indicates that the magnetic field generated by the moving coil has a slight impact on the magnetic properties of the NdFeB; besides, the demagnetization phenomenon never emerges obviously when it contacts with the ferromagnetic materials.

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References


The Application of NdFeB in the Magnetic Force Actuator (DONG Enyuan)


[16] CHEN Ming-fan. Study on Intelligent Adaptive Control for Operating of Vacuum Switch, Dalian University of Technology. 2010


[26] Li Yan-fei. The Study of Electromagnetic Force driving Actuator of Circuit Breaker, Dalian University of Technology. 2009