ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 25(4), 491-495 (2020) https://doi.org/10.4283/JMAG.2020.25.4.491

Characteristics of a Mechanical Circuit Breaker with New Induction Needle and Magnets Type to Extinguish a DC Arc

Sang-Yong Park[1], Dong-Chul Chung[2], and Hyo-Sang Choi[1]*

[1]*Dept. of Electrical Engineering, Chosun University, Gwangju 61452, Republic of Korea*
[2]*Carbon Fiber Convergence Technology Research Center, Jeonbuk National University, Jeonju 54896, Republic of Korea*

(Received 30 September 2019, Received in final form 4 December 2020, Accepted 5 December 2020)

Permanent magnets are currently attracting much attention as they are used in various application devices requiring high magnetic force. There are many types of permanent magnets with different properties, and they need to be tested for suitability for the applied devices. Sintered NdFeB permanent magnets have a large coercive force and are used in a variety of application systems. In particular, they are being used in circuit breakers to protect the DC transmission and distribution systems, which are actively being developed now. DC maintains a constant current value because it does not have a frequency. Thus, it is very difficult to interrupt large transient currents when an accident occurs. Therefore, a new type of induction needle and a permanent magnet near a mechanical break contact were combined. This induction needle is serially connected to a ground wire. This new breaking technique extinguishes the arch that occurs between the contacts by pushing it to the ground using an induction needle. The permanent magnet applied here, however, must be strong against a high-temperature arc that occurs quickly, and must generate a high magnetic force. Simulations were conducted with FEM (finite element method) and TDM (time difference method) using Maxwell, an electronic analysis program, and a permanent magnet that is appropriate for use as a component of a circuit breaker was selected. Consequently, it was found that the use conditions of permanent magnets varied by the arch generated in the mechanical circuit breaker.

Keywords : neodymium, arc-induction type, direct current, circuit breaker, induction needle, lorentz's force

1. Introduction

The utilization of renewable energy sources is increasing globally to reduce carbon emissions, and the application scopes of distributed power supplies and microgrids are expanding. As the scope of the grid is expanding, the line impedance is decreasing. Consequently, protection coordination in the grid has to be considered. In particular, unlike the overcurrent of the AC system, that of the DC system does not have a frequency, and the overcurrent must be blocked at a high voltage. There is therefore an urgent need to develop a circuit breaker that addresses this condition. In the DC transmission system, system protection coordination is being conducted by combining a semiconductor, a mechanical circuit breaker, and the control systems. For the DC distribution system, the economic aspects should be considered as well as the breaking technology. Therefore, rather than applying the semiconductor and control systems, the combination of a mechanical circuit breaker and a simple application technology is actively being researched on [1, 2]. One of the most important breaking technologies involves effectively extinguishing the arc generated at the break contact. This research team proposed a technology for extinguishing the arc using the magnet and induction needle developed by the team. This technology directs the arc path to the induction needle using Lorentz force, and flows the arc through a ground wire serially connected to the induction needle, thus extinguishing it. To achieve this, however, the magnet must have the appropriate properties. The magnetic force of the magnet must be strong and resistant to heat, and must have high mechanical strength.

In this study, the $Nd_2Fe_{14}B$ magnet was applied. The NdFeB magnet has twice as high coercive force as the other permanent magnets, such as $SmCo_5$, Alnico and Sr-ferrite. It is weak to heat, however, because its Curie temperature is about twice as low [3]. Therefore, a method

*Corresponding author: Tel: +82-62-230-7025
Fax: +82-62-230-7684, e-mail: hyosang@chosun.ac.kr

for preparing for arc heat while using the strong magnetic force was developed. A simulation model applying the NdFeB magnet to the arc-induced DC breaking technology was designed using Maxwell 3D, an electronic system analysis program, and the characteristics of the electronic system were analyzed by performing breaking operations.

2. The Principle and Mechanism of Arc-induced DC Circuit Breaker

Figure 1 shows the arc-induced DC circuit breaker, graphically representing the structure of each component and breaking action. Figure 1(a) is an anode and Figure 1(b) is a cathode, both of which are designed with a cylinder shape, and the material is copper (Cu). Figure 1(c) is an induction needle made of Cu. The induction needle was designed in the shape of a lightning rod. Figure 1(d) is a neodymium magnet. The neodymium magnet is a molded sintered product whose main components are rare-earth elements, iron oxide (Fe), and boron (B). Its magnetic energy is approximately 200-400 kJ/m^3, the highest among the commercialized magnets. It is highly dependent on the temperature, however, and a magnet with appropriate properties in the temperature range of 80-200 °C should be used.

Figure 1(A) shows the shape in a normal state, with the anode and cathode in contact with each other. The magnet and induction needle are fixed at a certain distance from the break contact. The induction needle is serially connected to the ground wire. Figure 1(B) shows the transient state, with an opening action occurring as the cathode moves. At this moment, a strong arc is generated between the contacts. At the same time, Lorentz force is generated due to the magnetic force and arch of the magnet. This force changes the arc movement direction to the vertical direction so that the arc will be directed towards the induction needle. Consequently, the arc induced by the induction needle flows through the ground wire and is extinguished [4].

3. Design of the Simulation for the Arc-induced DC Circuit Breaker Applying the Magnets

Figure 2 shows a simulation model that applies a magnet to the arc-induced DC circuit breaker. Figure 2(a) is an anode, (b) is a cathode, and (c) is an induction needle. The anode and cathode are designed with a cylinder shape and with a 12 mm diameter and a 150 mm height. The induction needle has a conical shape with a 4 mm base diameter and a 70 mm height. The material of these components was Cu. The applied voltage is +750 [Vdc] for the anode and –750 [Vdc] for the cathode. The simulated accident operation is as follows. The anode is a fixed electrode and thus does not move while the cathode is a moving electrode that moves from 0 to 9.9 mm in 0.1 mm intervals in the direction opposite the anode. Then the electric field distribution characteristics were analyzed. Figure 2(d) shows the magnets. Table 1 lists the parameters of the magnets used as a simulation model.

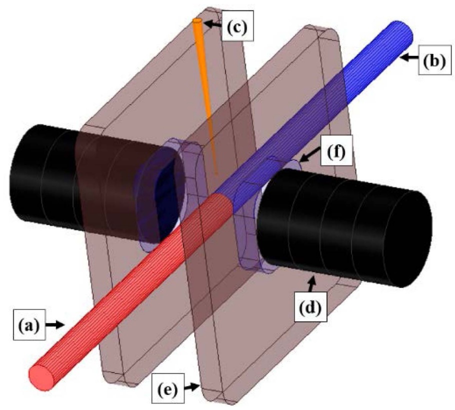

Fig. 2. (Color online) Simulation model.

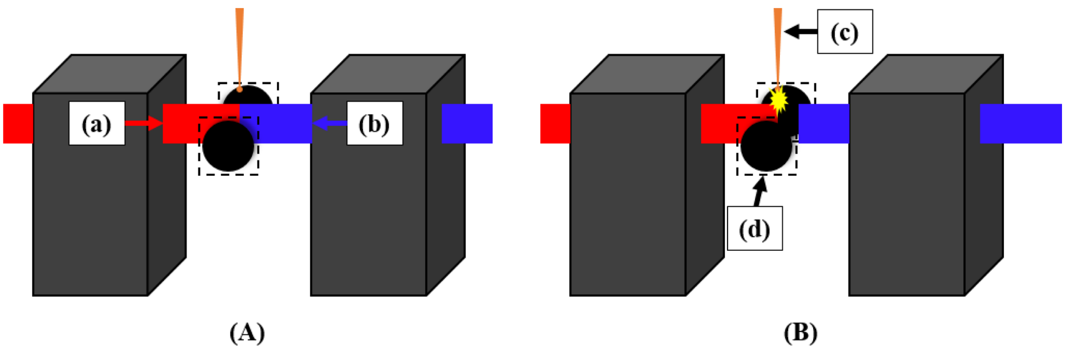

Fig. 1. (Color online) Arc-induced DC circuit breaker structure and DC breaking operation.

Table 1. The parameter of the magnet

Material	Neodymium (Nd)
Type	N35AH
Residual induction Br [mT]	1,170-1,250
Coercive force BHc [KA/m]	876
Intrinsic coercive force Hcj [KA/m]	2,786
Energy product BH max [KJ/m^3]	2,630-2,950
Max. operating temp. [ºC]	220

The magnet has a 40 mm diameter and a 15 mm height. Each of the two magnets is positioned at approximately 42 mm from the break contact. The angle between the two magnets is 180°. Four magnets were combined to increase the intensity of the magnetic force [5]. Figure 2(e) shows an insulation plate made of the Bakelite. It protects the magnet from the heat generated by the arc between the break contacts. Figure 2(f) shows an acrylic plate that blocks the heat of the arc while passing the magnetic force of the magnet. We proposed the arc-induced DC circuit breaker has a maximum breaking time of about 30 ms. To reduce the damage from arc heat, we designed the gap between the mechanical contact and the acrylic to be about 12.5 mm. In addition, the distance between the mechanical contact and the Bakelight was designed to be about 20 mm.

4. Results of the Simulation for the Arc-induced DC Circuit Breaker without the Magnets

Figure 3(a) shows the electric field distribution that appeared when the break contacts of the arc-induced DC circuit breaker opened 0.1 mm. An electric field was formed between the anode and the cathode. A high electric field was partially generated at the edge of each conductor. The highest electric field was approximately 1.5E+07 V/m. Furthermore, the current was directed from the anode to the cathode even after the break contacts opened.

Figure 3(b) shows a graph of the electric field generated when the break contacts were opened from 0 to 9.9 mm in 0.1 mm intervals. When the electrode gap was 0 mm, the anode and cathode were in contact with each other. The highest electric field strength occurred when the electrode gap was 0.1 mm.

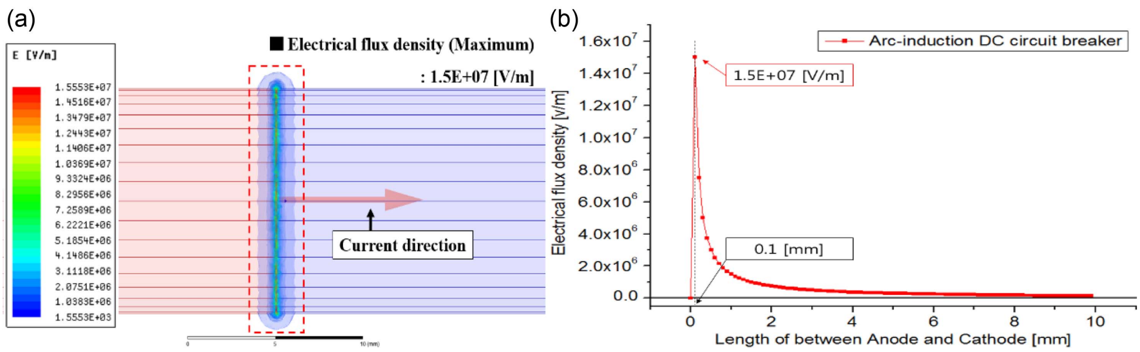

Fig. 3. (Color online) Graph of the electric field distribution generated when the electrode gap of the arc-induced DC circuit breaker was 0.1 mm.

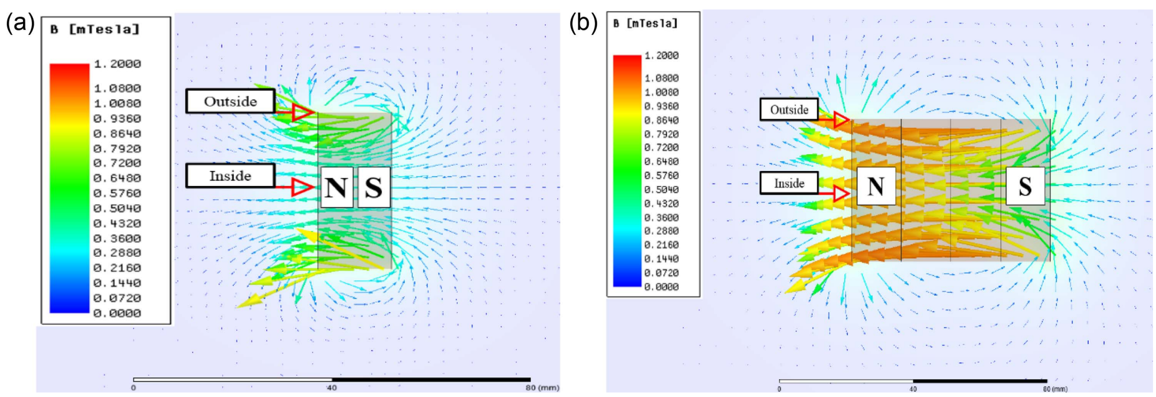

Fig. 4. (Color online) Magnetic field distribution by the number of magnets.

5. Results of the Simulation for the Magnets

Figure 4 shows the magnetic field density when there is one magnet and when there are four magnets in the simulation model of the N35AH magnet. This sets the N pole and S pole of the magnetic field in the Maxwell program, and can express the vector of the magnetic field by using the field overlays function. Figure 4(a) shows the magnetic field distribution when there is only one magnet. The magnetic field density is approximately 9,788.1 [gauss] in the outer part and approximately 3,355.7 [gauss] in the inner part. Figure 4(b) shows the magnetic field distribution when there are four magnets. The magnetic field density is approximately 8,540.2 [gauss] in the outer part and approximately 5,472.6 [gauss] in the inner part. This confirms that increasing the number of magnets can form a high magnetic field by gathering the magnetic field towards the center of the magnets. The magnetic field strength increased by approximately 61 % when there were four magnets compared to when there was only one magnet.

6. Results of the Simulation for the Arc-induced DC Circuit Breaker with the Magnets

Figure 5 analyzes the magnetic field at the contact of the arc-induced DC circuit breaker according to the structure of each magnet. This sets the N pole and S pole of the magnetic field in the Maxwell program, and expresses the scalar of the magnetic field using the Field Overlays function. Figure 5(a) shows the single structure where a magnet is at one side. The magnetic field applied to the electron at the center of the anode and cathode was measured. Accordingly, the magnetic field of the check-point was approximately 861.2 [gauss]. Figure 5(b) shows a double structure in which magnets are positioned at both sides. The magnetic field value at the center of the anode and cathode was measured, and it was approximately 1,765.8 [gauss]. Furthermore, when Bakelite was applied as shown in Figure 2, it did not affect the magnetic field of the magnet.

7. Numerical Analysis

The graph was interpreted based on the force applied to the electron. The direction of the electrons determines the flow of the current. Furthermore, the electrons are moved by an electric or magnetic field. Therefore, Lorentz force, which is generated by the coexistence of the electric and magnetic fields, influences the moving velocity and direction of the electrons. Therefore, the states of the arc-induced DC circuit breaker with and without a magnet were compared by referring to the simulation results in Figure 3. Equation (1) can be used to calculate the Lorentz force of the electrons generated between the anode and the cathode according to the changing electrode gap. $\vec{f}$ is the Lorentz force and is a vector value. $\vec{E}$ is the electric field, v_t is the electron movement speed, and $\vec{B}$ is the magnetic field. θ represents the angle of generation of current and magnetic field. Furthermore, equations (2) and (3) can be used to calculate the force affecting the electrons depending on the existence or absence of a magnet. $\vec{F_E}$ represents the force exerted on the total amount of charge according to the electric field, and $\vec{F_e}$ is the force exerted on the electron, which can be calculated through the vector sum of force of the electric field and Lorentz force.

Figure 6 shows a graph of the intensity and directions of the electric field and Lorentz force with and without a magnet. For a detailed description, with a magnet, the movement of the electrons is determined only by the force of the electric field. Without a magnet, the forces of the electric field and magnet overlap and generate Lorentz

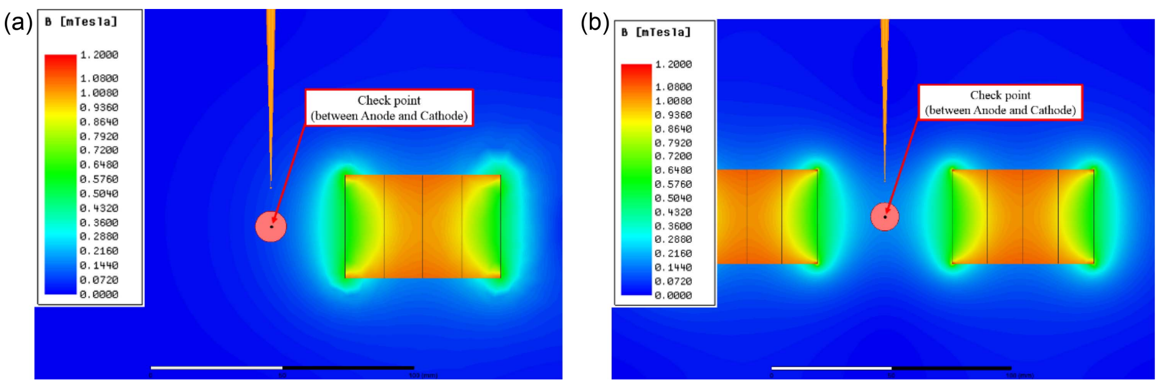

Fig. 5. (Color online) Magnetic field distribution according to the magnet structure.

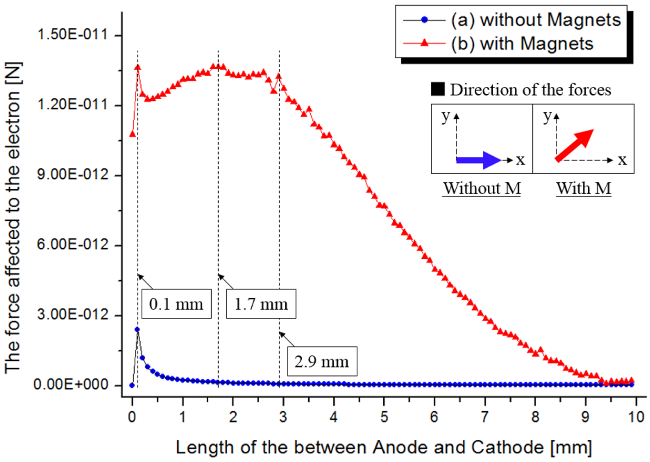

Fig. 6. (Color online) Graph of the changes in the force applied to the electron: (a) electric field without a magnet; and (b) Lorentz force with a magnet.

force. Thus, the force applied to the electrons determines the movement of the electrons. Figure 6 shows the forces with and without a magnet.

$$\vec{f} = q(\vec{E} + |v_t||\vec{B}|\sin\theta) \text{ [N]} \quad (1)$$

$$\vec{F_E} = \vec{E}Q \text{ [N]} \quad (2)$$

$$\vec{F_e} = \vec{F_E} + \vec{f} \text{ [N]} \quad (3)$$

Figure 6(a) shows the state when no magnet was applied to the arc-induced DC circuit breaker. The force applied to the electron was 2.403E-12 [N] when the electrode gap was 0.1, and the direction of the force was from the anode to the cathode.

Figure 6(b) shows a model applying magnets to the arc-induced DC circuit breaker. When the electrode gap was 0.1 mm, a high force of 1.363E-11 [N] was generated by the effect of the electric field. Furthermore, a high force was also generated in the 1.7 mm electrode gap, and its value was approximately 1.364E-11 [N]. The direction of force was 45° towards the induction needle. Therefore, this force is higher approximately 5.6-fold than that without a magnet. As it is directed towards the induction needle, it can be determined that the plasma electrons of the arc will move towards the induction needle.

The graph increased between the 0.1-1.7 mm electrode gap, but it decreased again from the 2.9 mm electrode gap. Thus, the area between the electrode gaps increased due to the movement of the cathode, a moving electrode. This seems to be the reason for the temporary increase of the magnetic field force.

8. Conclusions

Arc extinguishment can be an important element of the circuit breaking technology for DC system protection. A technology for extinguishing an arc quickly and safely by applying magnets to the arc-induced DC circuit breaker was proposed.

An arc is a form of energy that forms a plasma pillar through the uncertain movement of the electrons. The arc generation phenomenon can be analyzed by identifying the source of the force applied to the electron. The electric and magnetic fields can overlap with each other due to the magnets, and Lorentz force is generated as a result. As such, the electric and magnetic field distributions by the number of magnets in this study were interpreted according to the breaking operation of the arc-induced DC circuit breaker. In addition, the phenomenon that appears when magnets are applied to the arc-induced DC circuit breaker was analyzed through simulations. Lorentz force is generated by the overlapping of the electric field between the break contacts and the magnetic field generated in the magnets. It was numerically analyzed, and the results verified how much Lorentz force helps in the arc induction of the induction needle. In conclusion, Lorentz force is sufficiently involved in the arc phenomenon between the break contacts.

Continuous research on the breaking operations of the arc-induced DC circuit breaker can pave the way for its application to the actual DC grid system.

Acknowledgment

This research was supported by Korea Electric Power corporation [grant number: R16XA01], This study was supported by research fund from Chosun University, 2020.

References

[1] S. H. Fang, H. Y. Lin, S. L. Ho, X. B. Wang, P. Jin, and H. C. Liu, IEEE Trans. Magn. **45**, 10 (2009).
[2] B. J. Bae and M. H. Kim, J. Magn. **21**, 3 (2016).
[3] N. J. Yu, M. X. Pan, P. Y. Zhang, and H. L. Ge, J. Magn. **18**, 3 (2013).
[4] S. Y. Park, I. S. Jeong, H. W. Choi, H. S. Gu, and H. S. Choi, J. Supercond. Nov. Magn. **32**, 5 (2019).
[5] V. C. Žežulka and P. V. Straka, J. Magn. **21**, 3 (2016).