Analysis of Operating Characteristics of PM-Type Magnetic Circuit Breaker

Hee-Deuk Jun,* Kyung-Il Woo and Byung-Il Kwon*****

Abstract - This paper describes the operating characteristic analysis of the PM-type linear oscillatory actuator used as a magnetic circuit breaker for the electromagnetic field, electric circuit, and mechanical motion problems. Transient calculations are based upon a 2D finite element magnetic field solution including non-linearity of materials. Changes of the dynamic characteristics from the eddy current in the plunger are quantified from finite element analysis. A new laminated model is proposed to decrease the eddy current effect.

Keywords: Eddy current, laminated model, PM-type linear oscillatory actuator

1. Introduction

The purpose of using a circuit breaker is to protect an electric power system in case of an accident. The traditional circuit breaker is composed of springs, gears, and so forth. But, it has a defect that requires periodic repair and part replacement after a great number of actions. The PM-type magnetic circuit breaker overcomes its shortcomings and has high performance reliability, and its advantages has recently drawn great attention.

The PM-type magnetic circuit breaker's action is interaction of the mechanical exercise, magnetic circuit and an electric circuit. So, a combined analysis with those parts is needed to analyze the characteristics of the circuit breaker [1-3]. The circuit breaker's plunger of circuit breaker is generally of single construction, (i.e., it is not laminated), because the transformation of the plunger occurs in a large mechanical impact. If an accident occurs in the electric power system, the eddy current by the fast change of flux may occur greatly in the plunger's interior when voltage is approved [4], affecting the characteristics of the circuit breaker.

This paper describes the operating characteristics of the PM-type magnetic circuit breaker, using commercial software to consider the eddy current caused in the plunger. The electromagnetic field, electric circuit, and mechanical motion are combined for the analysis. As a result, the change of electric and mechanical characteristics with the variation of the conductivity of the plunger is investigated. To minimize the delay time of the plunger reaction by the eddy current, a new laminated model is proposed with a lamination part in the plunger and the characteristics comparison of the laminated non-laminated models is carried out via the finite element method.

* Small Business Corporation, Office of Motor Design, Korea (jhdeuk@hanmail.net)
** Division of Electrical, Control and Instrument of Electrical Engineering, Pukyong National University, Korea (cogging@pkun.ac.kr)
*** Dept. of Electrical Engineering, Hanyang University, Korea (bikwon@hanyang.ac.kr)
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2. Characteristic Analysis

2.1 Analysis Model

Linear actuators can be classified into moving coil type, moving magnet type, and moving core type [5]. The analysis model is the moving core type with permanent magnet, shown in Fig. 1.

A motion of the plunger is controlled by alternate switching of the excitation coils, as shown in Fig. 1. If the current flows across Coil A, the plunger is attracted upward by the excited magnetic flux. When the coils are opened, the plunger is held at its moved position by the permanent magnet. Table 1 shows the designed specification of the PM-type magnetic circuit breaker.

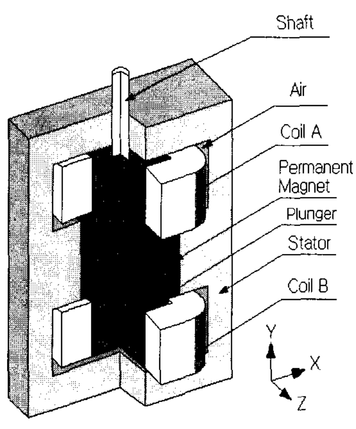


Fig. 1 The designed model of the PM-type magnetic circuit breaker.

Table 1 Specifications of Designed Model.

Turn number of coil	1500 [turn]
Diameter of coil	1 [mm]
Input voltage	200 [V]
Material of core	s23
Residual flux density of PM	1.05 [T]
Height of plunger	232 [mm]
Width of plunger	77 [mm]
Moving distance of plunger	20 [mm]
Force in the plunger by the PM	3300 [N]

2.2 Finite Element Analysis

Analysis is used in 2D nonlinear magnetic field problems using the magnetic vector potential as the field variable. The Maxwell and assistance equations are used to draw the governing equation for analysis [6-8].

$$\nabla \times H = J_0 + J_e \tag{1}$$

$$B = \mu_0 (H + M_r) \tag{2}$$

$$H = \frac{1}{\mu_0}(\nabla \times A) - \frac{1}{\mu_r} M_r \tag{3}$$

where J_0 is the winding current density, J_e is the eddy current density, and A and M_r are the magnetic vector potential and residual magnetization, respectively.

The governing equation for the 2D finite element analysis of the PM-type magnetic circuit breaker is expressed as

$$\nabla \times (\frac{1}{\mu} \nabla \times A) = J_0 + J_e + \nabla \times \frac{1}{\mu_r} M_r . \tag{4}$$

The problem analysis entails determining the electrical current in the coil and mechanical displacement of the plunger for a given electric voltage when solving the following equation system.

$$V = R_m I_m + L_m \frac{dI_m}{dt} + E_m \tag{5}$$

$$m \frac{d^2 x}{dt^2} = F_{mag} - F_0 \tag{6}$$

where V is the supply voltage, R_m is the resistance of coil, I_m is the total external current, E_m is the back EMF, m is the mass of the plunger, x is the displacement, F_{mag} is the magnetic force, and F_0 is the fractional force.

2.3 Skin Depth of the Magnetic Field

When the time variable field transits the conductor, the equation regarding the frequency, conductivity and magnetic permeability is [9].

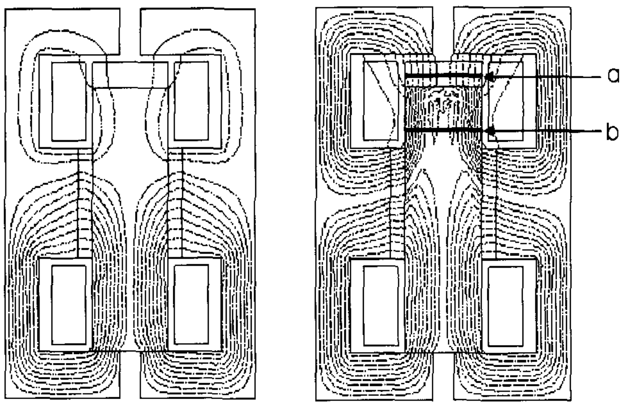
$$\delta = \sqrt{\frac{2}{\omega \sigma \mu_0 \mu_r}} \tag{7}$$

where ω is angular frequency of the induced field, σ is the conductivity of the conductor, and $\mu_0 \mu_r$ is the magnetic permeability. As the time varying flux passes through the conductor, the skin depth is changed.

3. Simulation Results

3.1 Characteristic Analysis by the Plunger's Conductivity

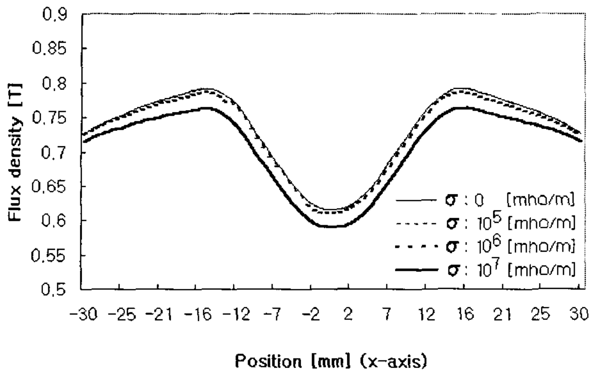
Fig. 2(a) shows the flux plot of the PM-type magnetic circuit breaker when the coils are not excited. The plunger is kept by the permanent magnet. After Coil A is excited with DC 200V, the flux plot at 0.05 [sec] is shown in Fig. 2(b). At this time, the magnetic field changes with the current, and so does the force exerted on the plunger.



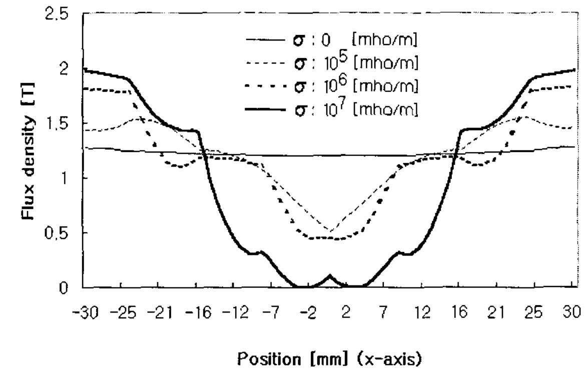
(a) The coils are not excited. (b) Coil A is excited.

Fig. 2 The flux plot of the actuator.

A simulation is performed when the conductivities of the plunger are 0, 1e5, 1e6, and 1e7 [mho/m]. Figs. 3(a) and 3(b) show the distribution of flux density in the air gap_(the region a of Fig. 2(b)) and the plunger_(region b of Fig. 2(b)) at 0.05 [sec], respectively. The gap flux density decreases accordingly as the conductivity of the plunger increases. When the conductivity of the plunger is not considered, the flux density is almost constant at the region. But the flux of the plunger is concentrated on the surface of the plunger by the skin effect.



(a) The flux density in the air gap.



(b) The flux density in the plunger.

Fig. 3 The flux densities in the air gap and the plunger by the conductivity variation.

Fig. 4 presents the exciting current according to the change of the conductivity (abbreviated as cond in Figs. 4 and 5) when the voltage is applied. While the back EMF by the fast motion of the plunger increases, the current decreases. But the current increases again after the plunger reaches in the yoke. At this time, the eddy current occurs differently according to the plunger's conductivity. This changes the electricity and mechanical time constants. If the plunger's conductivity is higher, the current passes greatly and the convergence speed of current is delayed because of the electro-mechanical time constant.

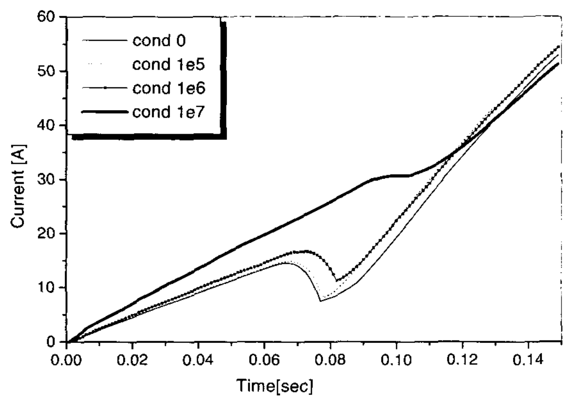
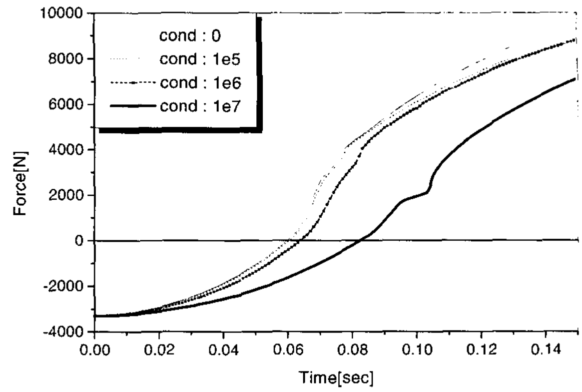
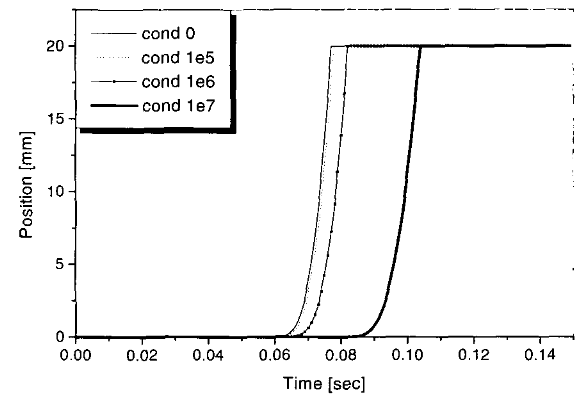


Fig. 4 Exciting current of coil A.



(a) Thrust of the plunger.



(b) Displacement of the plunger.

Fig. 5 Thrust and displacement of the plunger.

Fig. 5 shows the thrust and the moving displacement of the plunger for various conductivities. When Coil A is excited, the thrust increases continuously, and when the thrust becomes more than the holding force 3000 [N] by the permanent magnet, the plunger begins to move. As conductivity in the plunger becomes higher, the operation of the plunger is slower, and these phenomena become significant when the conductivity is beyond 1e6 [mho/m].

3.2 A Proposed New Model

The circuit breaker's plunger is generally of non-laminated single construction because the transformation of the plunger occurs in a large mechanical impact. If an accident occurs in the electric power system, the fast change of flux may cause eddy current to occur greatly in the plunger's interior when voltage is approved. This, of course, affects the characteristics of the circuit breaker.

Fig. 6 shows a new proposed model with a lamination part in the plunger to decrease the eddy current effects and to consider the stiffness of the plunger. Fig. 7 show the flux plots of the non-laminated model and the proposed laminated model at 0.06_[sec]. The penetration depth of the flux of the proposed laminated model is larger than that of the non-laminated model around Coil A. because the eddy current effect is reduced by the laminated part.

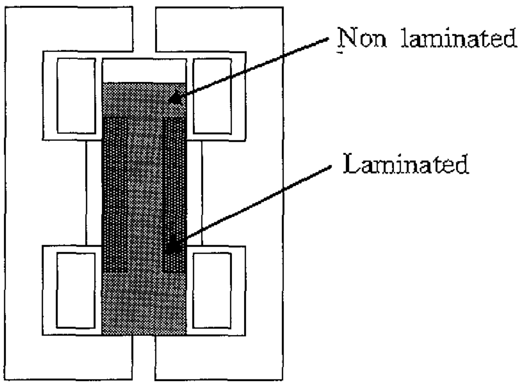


Fig. 6 Proposed model.

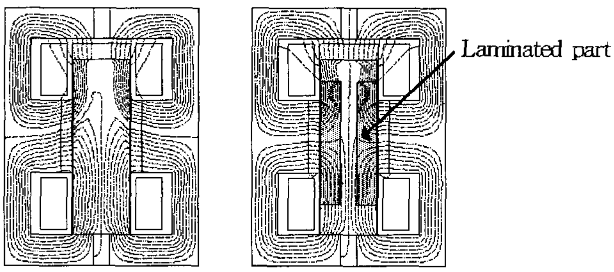
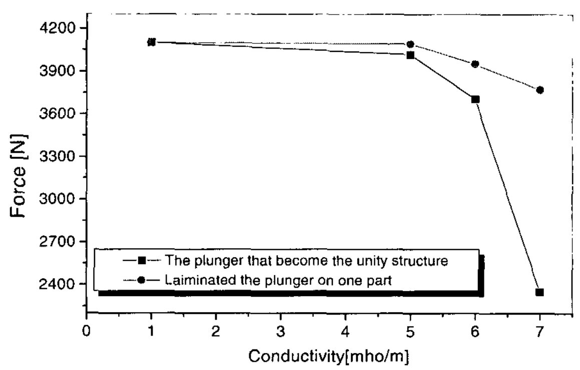
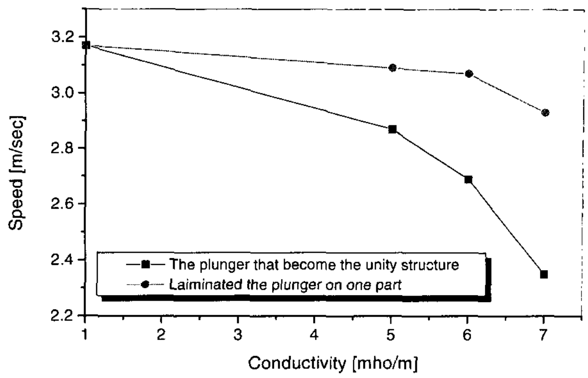


Fig. 7 The flux plots at 0.06_[sec].

Figs. 8(a) and 8(b) show the characteristics comparison of the laminated and the non-laminated models. We know that the differences of the characteristics are large when the conductivity of the plunger is 1e7_[mho/m] from these figures. Fig. 8(a) shows that the force of the laminated model is larger than that of the non-laminated model about 1745_[N]. As a result, the speed characteristic of the laminated model is better than that of the non-laminated model by about 0.82_[m/sec] (Fig. 8(b)). From these figures, the characteristics of the laminated model are shown to be better than those of the non-laminated model.



(a) Force characteristic.



(b) Speed characteristic.

Fig. 8 Characteristics comparison of the laminated and non-laminated models.

4. Conclusion

This paper presents the operating characteristics of the PM-type linear oscillatory actuator used as a magnetic circuit breaker considering the eddy current caused in the plunger. The electromagnetic field, electric circuit, and mechanical motion are combined for the analysis. As a result, the change in electric and mechanical characteristics with the variation of the conductivity of the plunger is investigated. To minimize the eddy current effect in the plunger, a new laminated model with a lamination part in the plunger is proposed and its characteristics are analyzed via the finite element method. From the characteristics comparison of the laminated and the non-laminated models, the characteristic of the laminated model is shown to be better than those of the non-laminated model.

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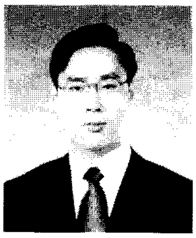
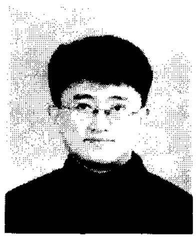


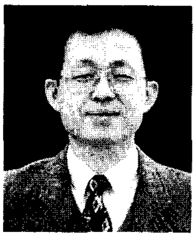
Hee-Deuk Jun

He received the B.S degree in Electrical Engineering from Hanyang University. He is with the Office of Motor Design of the Small Business Corporation. His research interests are motor design, analysis, and testing.



Kyung-il Woo

He received the B.S., M.S., and Ph.D. degrees in Electrical Engineering from Hanyang University. He is currently a full-time instructor in the Division of Electrical, Control and Instrument Engineering of Pukyong National University. His research interests are numerical analysis of electrical machine and control.



Byung-il Kwon

He received the B.S and M.S degrees in Electrical Engineering from Hanyang University, Korea, and the Ph.D. degree in Electrical Engineering from Tokyo University, Japan. He is working as a professor at Hanyang University. His research interests are linear drive systems, numerical analysis of electric machines, and control.