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Design and Analysis Method for A DC Magnetic Contactor with a Permanent Magnet

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Abstract – **The demand for a DC power distributed system is increasing as renewable energy sources and DC electrical load are proliferating. For the automation of a power system, a magnetic contactor for the DC power system is required. The conventional magnetic contactors are mostly equipped with a solenoid magnetic actuator. However, the conventional magnetic contactor has problems with continuous power consumption, and heat generation. To address these problems, a permanent magnet type DC magnetic contactor is proposed in this paper.**

Keywords: **Magnetic contactor, Electromagnetic actuator, Finite element method, Time difference method**

1. Introduction

In recent years, most electric devices such as information technology (IT) devices, television (TV), Audio/Video (AV) devices, personal computer (PC) and facsimile (fax) are operated by direct current (DC) electrical power. Furthermore, renewable energy which generates DC power is increasing rapidly. Hence, the DC power distributed system has been attracting attention. DC magnetic contactors (DCMC) are essential devices to operate the DC power distributed system.

A magnetic contactor (MC) is a device which controls the load such as motors and heaters by means of an electromagnetic force. For the conventional MC mechanism, a solenoid actuator is widely used. The solenoid type magnetic contactor has relatively simple structure and low cost advantages. However, to maintain the closed state, continuous power consumption is required to excite the solenoid coil. Therefore, the solenoid type MC has critical problems of high energy consumption, noise, and high possibility of burning coil. For these reasons, Conventional magnetic contactors have a low level of stability and short life cycle.

To solve these problems, a novel structure for a Permanent Magnet (PM) - type DCMC is proposed to generate enough holding force to maintain the closed state without exciting the coil.

The operating characteristics of the proposed PM-type DCMC are calculated by a three dimensional (3D) Finite Element Method (FEM) with the combination of a circuit equation, motion equation, and the Time Differential Method (TDM).

2. The Structure and Operating Principle of DCMC

2.1 The Structure of PM-Type DCMC

Fig. 1 shows the structure of the PM-type DCMC. The PM-type DCMC consists of five parts: movable core, fixed core, mover, solenoid actuator, and contacts.

The contacts are composed of two parts: fixed contact and the movable contact. The movable contact moves along the motion of the actuator.

When the mover is placed at the top, the movable contact comes into contact with the fixed contact and the load circuits are closed. This state is the closed state. When the movable contact moves in a downward direction where the contacts are separated, the load circuits are opened. This state is the opened state. The movable contact moves in the closing and opening directions along the motion of the mover. The mover is made of nonmagnetic material.

The solenoid coil of the actuator generates magnetic flux and electromagnetic forces if the current is excited. When the current is excited, the movable core and fixed core becomes a path of the flux. Then, the movable core moves either in the closing or opening direction, according to the direction of the magnetic flux produced by the current.

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The directions of the magnetic flux generated by excited closing coil and the permanent magnet are identical during the closing operation. In the opening operation, the directions of magnetic flux produced by the opening coil and the permanent magnet are opposite.

The role of the permanent magnet of DCMC is to maintain the closed state with the holding force, which is the electromagnetic force from the permanent magnet. The electromagnetic energy generated by the permanent magnet should be greater than the total of the spring and the gravitational energy applied to the movable part for the permanent magnet to maintain the closed state.

The PM-type DCMC has a saving energy benefit due to the permanent magnet maintains a closed state without consuming energy.

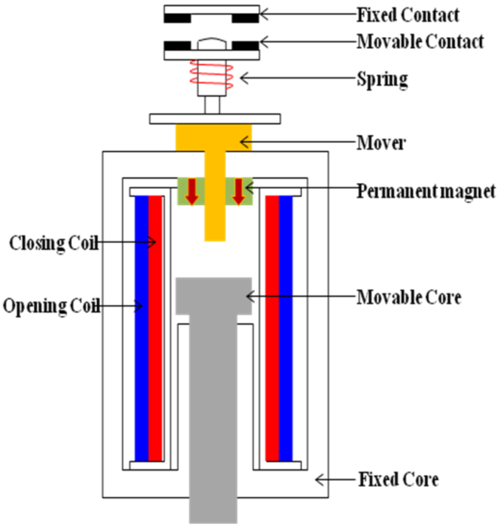


Fig. 1. The structure of PM-type DCMC

2.2 Operating Principle of the PM-type DCMC

The closing operation can be explained as follows. If the current is applied to the closing coil, the movable core and the mover move in the closing direction. Then, the movable contact moves with the mover and the spring becomes compressed. If the movable contact comes into a contact with a fixed contact, the movable contact positions in the closed state. Because the movable contacts touch the fixed contacts in the closed state, the main circuit is connected. Fig. 2 (a) shows the closing operation. In the closing operation, the permanent magnet aids in the operation by adding a magnetic force as the direction of the flux of magnet and closing coil are identical. When the closing coil is activated by a power source, a capacitor is charged. After the closing operation, a permanent magnet maintains the closed state with a mere holding force without current excitation.

The opening operation is illustrated as follows. The capacitor energy charged in the closing operation is used for the opening operation without extra power sources. If the opening coil is excited by the capacitor, magnetic flux is generated in the opposite direction to the magnetic flux of a permanent magnet. Thus, an electromagnetic force is generated in the opening direction. If electromagnetic energy produced by the opening coil overcomes the energy of the PM, the movable part moves in the opening direction (Fig. 2b). At this time, the repulsive force of the spring assists with the closing operation with the energy of the compressed springs.

When the movable contacts move with the mover in the opening direction, the compressed spring returns to its initial length. As the movable contact and fixed contact are separated, the main circuit is disconnected. After the opening operation, the current stops flowing through the coil

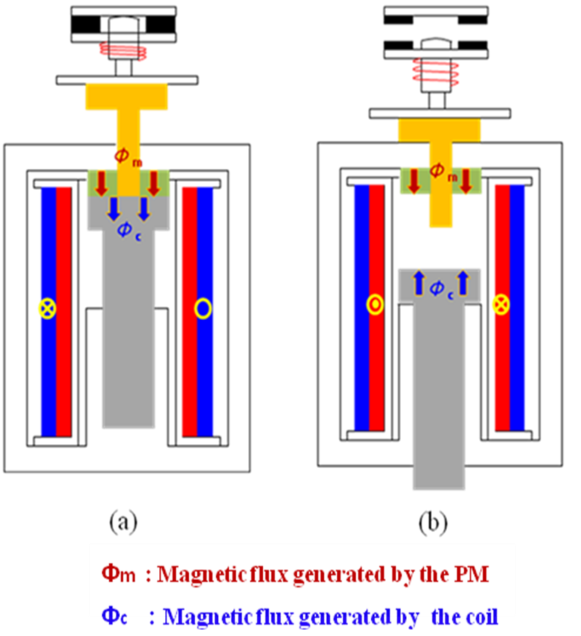


Fig. 2. The operating principle of PM-type DCMC: (a) Closing operation and (b) Opening operation.

3. Analysis and Design for DCMC

3.1 Design Method for DCMC

The design and analysis for the static state and dynamic states should be conducted in the iterative manner after the analysis of the system.

The restrictions and objectives such as the actuator size, operation time limit and peak current limit have to be considered for the analysis of the system.

The DCMC operates by the forces applied to the movable parts which are the electromagnetic, frictional, gravitational and spring forces. Among these forces, the electromagnetic force and spring force are dominant. The friction force is negligible due to small value compared to the other forces.

The design of the DCMC is conducted by two separated steps: the static and the dynamic states [1].

In the process of analysis and design for the static state, the main magnet, fixed core, movable core and stroke are designed for the adequate amount of the holding force to maintain the closed state. The holding force is mainly decided by the size of the permanent magnet and the steel core. The increasing size of the permanent magnet and the movable core leads to the increment of the holding force. However, the increase of the size of the movable core results in greater gravitational forces. As the direction of the gravitational force is opposite to the holding force, the greater amount of holding force should be required. For these reasons, simultaneous consideration of the holding and gravitational forces is needed for the design of the movable core.

The larger volume of the permanent magnet produces the greater holding force. Especially, the diameter of the magnet has greater effect on the magnetic flux compared to the height of the magnet. However, when the opening coil is excited and generates the magnetic flux, the permanent magnet is demagnetized if the height of permanent magnet is not sufficient. In this case, the opening operation cannot be conducted (Fig. 3 and Fig. 4). The height of permanent magnet should be greater than 3.5mm when considering the demagnetization effect on the permanent magnet. Fig. 3 shows the DCMC equipped with a 4mm height permanent magnet. If the opening coil of the actuator in Fig. 3(a) is excited, the opening operation is conveyed as shown in Fig. 3(b). In contrast, in the case of the DCMC with a 2mm height permanent magnet in Fig. 4(a), if the opening coil of the actuator is activated, the magnetic flux of the permanent magnet becomes weakened and the opening operation is not carried (Fig. 5b).

The diameter and number of turns of the coil should be determined for the analysis and design of the dynamic state. The diameter and number of turns of the closing and opening coils have a main influence on the performance (e.g., completion time and the peak current) of the DCMC.

If the diameter of the coil increases in a fixed size slot, the number of turns of the coil decreases. Generally, the amount of increase in the current surpasses the decrease in the coil turns. Thus, if the diameter of the coil increases, the total magneto-motive force NI increases, where N is the number of turns in the coil and I is the electric current through the coil. Then, performance characteristics of the DCMC improve. However, if the diameter of the coil exceeds some value, the decrement of the turns of coil could be greater than the increment of current. Fig. 5 shows the completion time according to the diameter of the coil. Additionally, the design for the coil should be conducted adequately due to the restriction of the peak current.

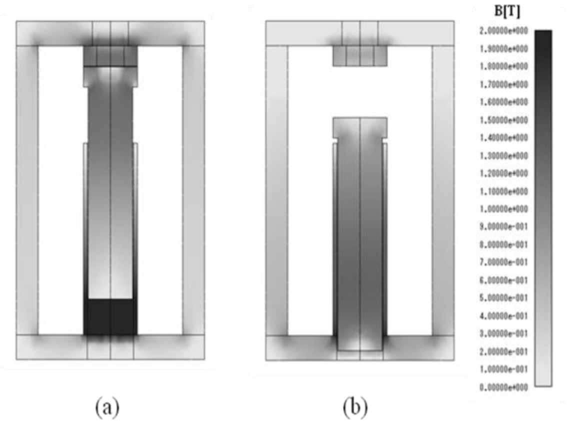


Fig. 3. DCMC with 4mm height permanent magnet: (a) The opening coil is not excited and (b) The opening coil is excited

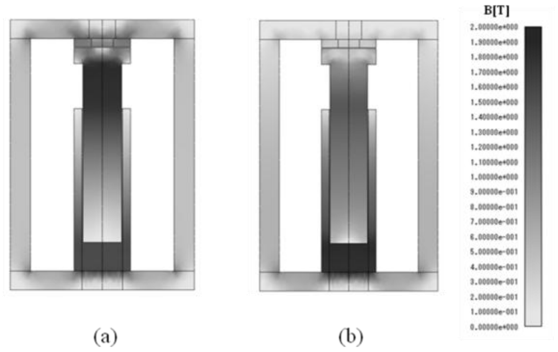


Fig. 4. DCMC with 2mm height permanent magnet: (a) The opening coil is not excited and (b) The opening coil is excited

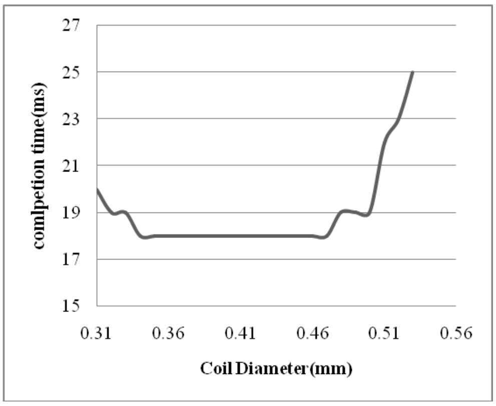


Fig. 5. Completion time according to the coil diameters

In the opening operation, the capacitor is utilized to excite the coil without an external power supplier. The current should be sufficient as the electromagnetic force from opening coil should surpass the holding force of the permanent magnet.

Hence, the capacitance of the capacitor should be decided so that the opening coil produces adequate amount of electromagnetic energy.

Fig. 6 shows the design process for the PM-type DCMC.

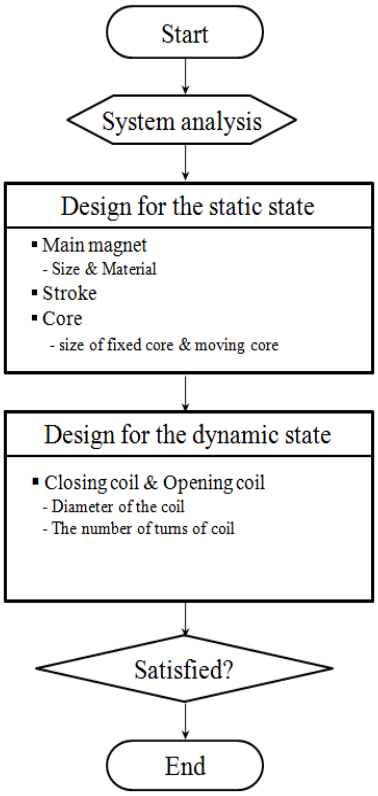


Fig. 6. Design process for the PM-type DCMC

3.2 Static Magnetic Field Analysis

From the Maxwell stress tensor (MST) method, the electromagnetic force can be obtained by (1):

$$\vec{F}_{mag} = \iint_s \left(\frac{1}{\mu_0}(\vec{B}\cdot\vec{n})\vec{B} - \frac{1}{2\mu_0}B^2\vec{n}\right)dS \tag{1}$$

The magnetic flux is generated by the permanent magnet and the magneto motive force of coil. The magnetic flux can be expressed by (2) [2].

$$\vec{B} = \mu_0\{(1+\chi_m)\vec{H} + \vec{M}\} \tag{2}$$

where μ_0 is the permeability of free space, χ_m is magnetization, H is the magnetic field intensity, and B is the magnetic flux density.

From the Maxwell equation, Ampere's circuital law and charge conservation can be expressed by (3) and (4).

$$\nabla \times \vec{H} = \vec{J}_0 \tag{3}$$

$$\nabla \cdot \vec{B} = 0 \tag{4}$$

where J_0 is the current density.

The governing equations (5) and (6) are induced by substituting equation (3) to (2) and using the vector's null identity [3].

$$\vec{B} = \nabla \times \vec{A} \tag{5}$$

$$\nabla \times \nu(\nabla \times \vec{A}) = \vec{J}_0 + \nabla \times (\nu\mu_0\vec{M}) \tag{6}$$

where A is the magnetic vector potential, and ν is the reluctivity.

$$\nu = \frac{1}{\mu_0(1+\chi_m)} \tag{7}$$

The magnetic vector potential $\vec{A}$ can be calculated by using the FEM [4].

The magnetic flux is obtained by (8).

$$\Phi = \int B \cdot dS = \int A \cdot dl \tag{8}$$

3.3 Circuit Equations and Motion Equations

TDM and 3D-FEM can be used to analyze the circuit equations and motion equation. The correctness of this method is verified through our previous research in [1]. For the analysis with TDM, the total operation duration time should be divided by the specified number of steps. In each steps, the magnetic flux and electromagnetic forces are obtained by static field analysis and used for the circuit and motion equations.

Fig. 7 shows the equivalent circuits of the closing and opening coil. *Vs* is an external voltage source, *C* is a capacitor, *Vc* is the voltage of the capacitor. *Lcc* is the inductance, *Rcc* is the resistance components of the closing coil, Loc is the inductance and *Roc* is the resistance of the opening coil. *S1* and *S2* are the switches in the closing and opening circuit, respectively.

During the closing operation, the *S1* switch is turned on and the *S2* switch is turned off. Then, the electrical power source is supplied to the capacitor and the capacitor is charged. The charged electrical energy of the capacitor is used for the opening operation. If the magneto motive force in the closing coil is sufficient, the closing operation is executed.

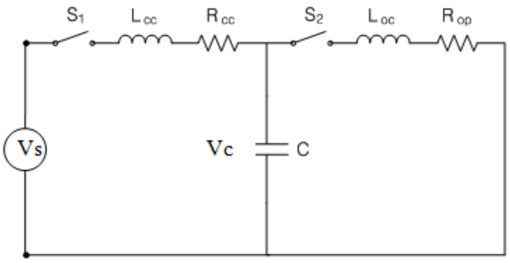


Fig. 7. The circuit of closing and opening coil

The closing circuit equation can be derived by (9), where di^n is the change of the current at the nth time step, Li^n is the inductance for the transformer electro-motive force (TEMF), and Lx^n is the inductance for the motional electro-motive force (MEMF).

$$V_s^n = R_{close}(i^{n-1} + di^n) + L_i^{n-1}\frac{di^n}{dt} + L_x^{n-1}\frac{dx^n}{dt} + V_c^n \qquad (9)$$

The *S1* switch should be off, and the *S2* should be on so that the opening coil can be activated for the opening operation. The capacitor energy is used for the excitation of the opening coil.

The opening circuit equation can be derived by (10)

$$V_c^n = R_{open}(i^{n-1} + di^n) + L_i^{n-1}\frac{di^n}{dt} + L_x^{n-1}\frac{dx^n}{dt} \qquad (10)$$

The equation of the motion for the DCMC can be represented by (11), where x^n is the displacement, *m* is the mass of the movable parts, *m* is the mass of a mover, *g* is the acceleration of gravity, F_{mag} is the magnetic force acting on the movable parts, F_{spring} is the spring load, and $F_{friction}$ is the frictional force. FEM is used to obtain the value of F_{mag}.

$$\vec{F}_{mag}^{\,n} + \vec{F}_{spring}^{\,n} + \vec{F}_{friction}^{\,n} = m\left(\frac{d^2\vec{x}^{\,n}}{dt^2} + \vec{g}\right) \qquad (11)$$

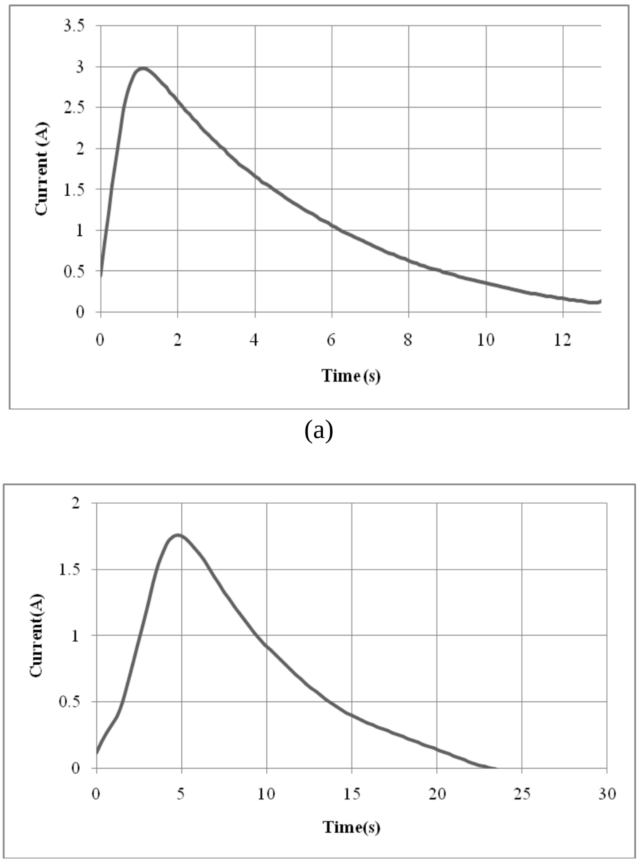
In the circuit equation, the values of the resistance and the capacitance are constant. On the other hand, the value of inductance varies with time because of the variation of the linked flux according to the current and the displacement of the movable core during the operation. Accordingly, this should be calculated for each step. Furthermore, if the magnetic materials are saturated, inductance could vary according to the current of the coil because of the nonlinear BH magnetic characteristics of the materials.

4. Analysis Results

The proposed PM-type actuator for a DCMC is analyzed and designed by 3D FEM with TDM.

The dimension of the actuator is 40.8*48.5*63.8 mm, the stroke is 10.9 mm and the diameters of the closing and opening coils are 0.4 mm and 0.29mm, respectively.

Fig. 8 displays the current of the closing and opening coils when a 70(V) voltage source is applied. In Fig. 8 and Fig. 9, the designed DCMC satisfies the 3A current restriction. Hence, we can confirm that the proposed DCMC is designed adequately.



(a)

(b)

Fig.8. The current of the coil according to time: (a) Current of the closing coil during the closing operation, and (b) Current of the opening coil during the opening operation.

5. Conclusion

The novel PM-type DCMC is proposed in this paper.

Additionally, design and analysis methods for the PM-type DCMC are illustrated. For the analysis of the PM-type DCMC, FEM combined with circuit equation, a motion equation and TDM is used.

The proposed PM-type DCMC can consume significantly lower power compared to the conventional MC. This research contributes to the commercialization of a proposed PM-type DCMC through the decrease of power consumption and increase in stability.

Acknowledgements

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