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Characteristic analysis and design of a novel permanent magnetic actuator for a vacuum circuit breaker

Jong-Suk Ro[1], Seung-Ki Hong[2], Hyun-Kyo Jung[1]

[1]School of Electrical Engineering, Seoul National University, Kwanak-gu, Seoul, Korea
[2]LSIS. Co. Ltd, Chung-Ju, Choong-Buk, Korea
E-mail: jongsukro@naver.com

Abstract: In this study, a novel permanent magnetic actuator (PMA) termed a separated permanent magnetic actuator (SPMA) is proposed. The efficiency of the proposed SPMA is significantly higher than a conventional PMA because of its innovative structure, with which the magnetic flux path is efficient and the holding forces can be designed independently taking the unique values of each load into consideration. Hence, the SPMA is smaller in size and lower in cost than the conventional PMA. For the SPMA, a characteristic analysis and design method using a two-dimensional finite element method, an equivalent circuit, an equation of motion and a time difference method is suggested in this study to save time and reduce the costs incurred because of the experimental trial and error deign. The SPMA was designed and prototyped such that the usefulness of the SPMA for application to a vacuum circuit breaker and the reasonableness of the suggested characteristic analysis and design method were confirmed by the experimental data.

1 Introduction

The circuit breaker (CB) is used for the deliberate control of electrical power systems and for the fast and automatic disconnection of electrical power when a power system has problems such as overcurrent or short circuit. Therefore the CB is important in that it can prevent critical damage to the power system from unexpected fault current flows, which can burn and destroy connected machines.

According to the insulation material, CBs can be categorised as air CBs, oil CBs, SF6 gas CBs and vacuum CBs (VCBs). The most recently developed type is the VCB, which uses a vacuum for the fast extinguishment of the arc. VCBs are mostly used for medium/low voltage CBs (5–38 kV). The VCB has characteristics such as a long life time, a compact size, a low cost, excellent insulation and superior circuit breaking [1–3].

The actuator is an important component for the CB. Consequently, the hydraulic actuator, the pneumatic actuator, the motor spring actuator and the permanent magnetic actuator (PMA) have been utilised by many researchers. The motor spring actuator and the PMA are widely used in VCBs [4–8]. The motor spring actuator utilises mechanical elastic energy accumulated in the spring. The structure of the motor spring actuator is complex with many components such as the motor, the spring and the gear. Hence, the motor spring actuator is apt to breakdown and can incur high manufacturing/maintenance costs [5–11]. To solve these problems, the PMA has received a considerable amount of attention because of its many advantages, such as its short operation time, compact structure, high reliability, high repeatability and low maintenance costs [5–8, 12–15].

The PMA reported in [2, 5, 6, 12–14] is the typical type of PMA. This PMA has many merits compared to the motor spring actuator. However, the opening and closing holding forces, which require different values, have same value because of the symmetrical structure of PMA causing the degradation of the efficiency. This type of PMA could not be applied to a high voltage CB which requires the long stroke actuator. For the long stroke operation and the high voltage application of the PMA, Cai *et al.* added the auxiliary opening/closing coil to the typical type of PMA as presented in [16]. However, this type of PMA increases the volume of the coil and the actuator. The opening and closing holding forces of this PMA also could not be designed independently. We proposed the electromagnetic force driving actuator (EMFA) in the previous research as referred to [17, 18]. As the mover of EMFA is the coil and the Lorenz's force is used for the operation, the stroke of EMFA is not limited. On the other hand, the amount of the permanent magnet has to be increased proportional to the elongation of the stroke. To increase the driving force of EMFA, the bulk of coil, which is the mover, has to be grown up declining the efficiency of the actuator. Hitachi proposed the hybrid type, which combines the plunger type and the plate type, as presented in [19]. The plunger type is useful for the long stroke operation because of its lower magnetic resistance compared to the plate type. The plate type can generate a larger attractive force than the plunger type. The hybrid type of Hitachi has both merits of the plunger and the plate type. Moreover, the magnet of this type cannot be demagnetised by the electromagnetic flux of the coil because of its unique structure, although the demagnetisation could be occurred in the typical PMA. However, the hybrid type could be unstable and inefficient because the opening state is maintained only by the repulsive force of the spring. Hou *et al*. proposed the PMA that does not require the fault current sensor by using the low voltage coil as referred to [20], whereas, this PMA has to constantly consume the electrical power to maintain the closing state.

The PMA has to use a rare earth permanent magnet for high efficiency with a large output power. The cost of these rare earth permanent magnets, which are an essential component in a PMA, is steadily increasing at present, inspiring research with the aim of mitigating the use of permanent magnets in PMAs [8]. The permanent magnet accounts for a considerable part of the total cost for a PMA. Hence, a novel PMA is proposed in this research. Specifically, the electromagnetic force is increased compared to the conventional PMA by the efficient magnetic flux path. Furthermore, the holding forces at the opening state and the closing state can be independently controlled and designed so as to satisfy unique load conditions. This makes it possible to increase the efficiency of the actuator while reducing the size and the cost of the actuator. The proposed actuator is referred to as the SPMA based on the shape of the structure in this research.

We proposed a characteristic analysis and design method using two-dimensional finite-element method (2D FEM), an equivalent circuit, an equation of motion and a time-difference method (TDM) for the separated permanent magnetic actuator (SPMA). Concretely, the 2D FEM was introduced in this paper for the analysis of the magneto-static field. The characteristic analysis method for the calculation of the exciting current of the coil, the velocity of a mover and the voltage drop of the capacitor was suggested in this research using the equivalent circuit, the equation of the motion, a TDM and the calculated data from 2D FEM.

The SPMA for a 17.5 kV/40 kA VCB was designed and prototyped in this research. In addition, the usefulness of the suggested SPMA for a medium/low voltage VCB was confirmed by meeting all of the required characteristics for the 17.5 kV/40 kA VCB through the experiment. Furthermore, the reasonableness of the proposed characteristic analysis method for the SPMA was testified by comparing the calculated data with the experimental results.

2 Working principle of SPMA

2.1 Working principle of the VCB

The motor spring actuator has a large number of mechanical components: typically around 160. The magnetic operating mechanism, in contrast, is significantly simpler, as shown in

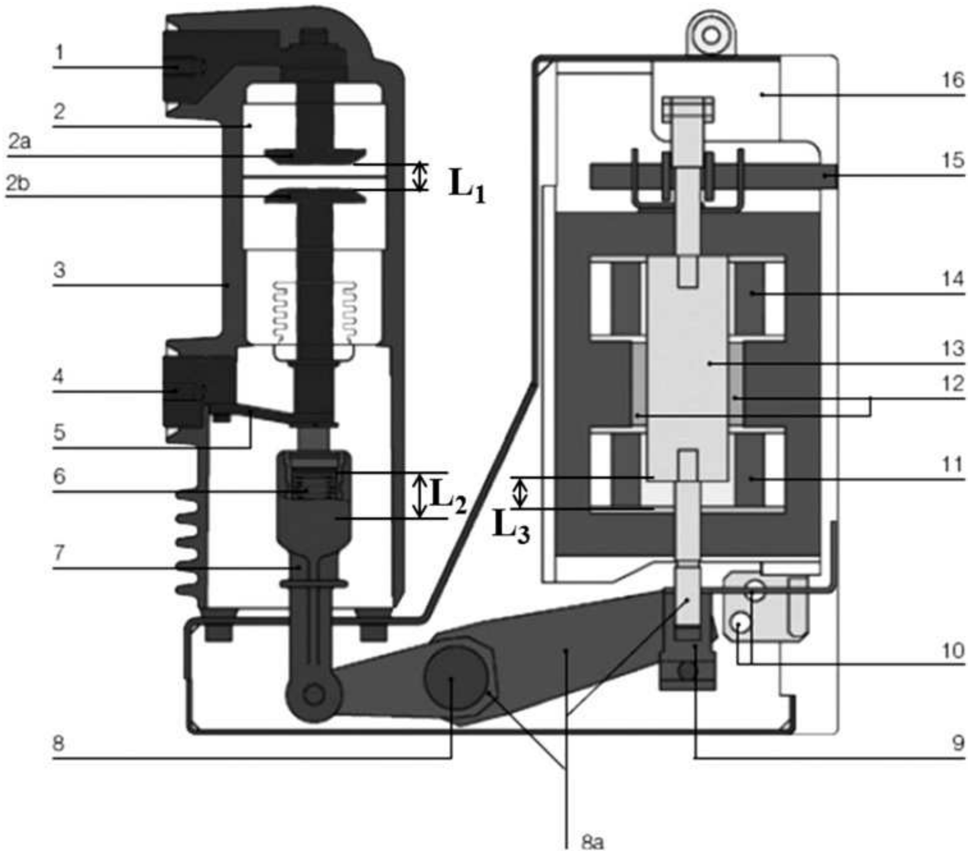

Fig. 1 *Mechanical structure of the VCB*

1. Top terminal, 2. Vacuum interrupter, 2a. Fixed contactor, 2b. Moving contactor, 3. Pole, 4. Bottom terminal, 5. Flexible connection, 6. Compressive spring, 7. Insulating rod, 8. Pin, 8a. Lever and shaft, 9. Regulator, 10. Position sensors, 11. Closing coil, 12. Permanent magnets, 13. Moving armature, 14. Opening coil, 15. Manual emergency opening device, 16. Supporting structure

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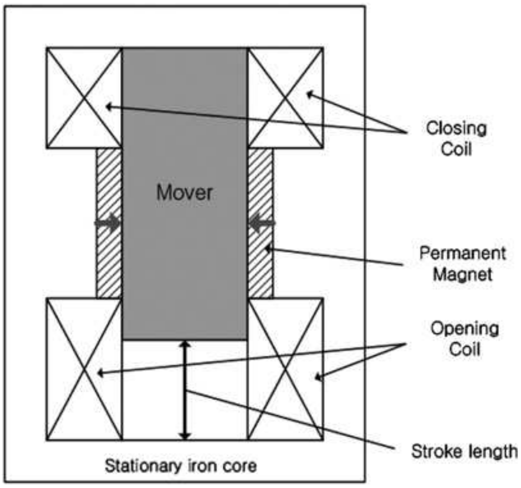

Fig. 2 *Conventional PMA*

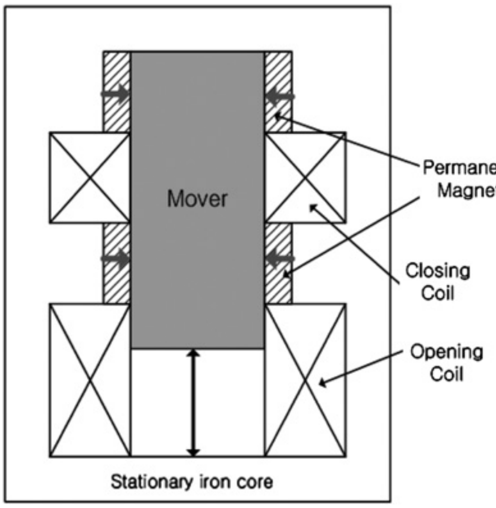

Fig. 3 *Proposed SPMA*

Fig. 1. The number of parts has been reduced to less than 40% compared to the motor spring actuator [2, 5, 6].

As shown in Fig. 1, the moving contactor is operated by the transmission of the mechanical energy of the actuator via the shaft, the lever and the compressive spring [2, 5, 6, 15]. The moving contactor moves in the vacuum chamber for the extinguishment of the arc. While the actuator operates within L_3, the force and the displacement of the actuator are converted by the lever and acted on the moving contactor. L_1 and L_2 indicate the stroke of the moving contactor and the compressible length of the spring, respectively.

2.2 Working principle of the SPMA

Figs. 2 and 3 show the conventional PMA and the proposed SPMA. When the mover is at the top position, it is the closed state. When the mover is at the bottom position, it is the open state. The PMA and the SPMA can maintain a closed or open state using only a permanent magnet without any power consumption. When the closing or opening coil is excited by current, a movable electrode connected to the mover by a shaft can move and the circuit can be opened or closed.

Minimal holding force is required because the holding force acts as a load on the actuator. The holding force must carry out the subsequent role with the minimal holding force. In the closed state, a large amount of closing holding force is needed to hold the mover and to overcome the large repulsive force of the compressed spring. The fixed electrode and the movable electrode of the interrupter have to be in surface-contact with each other for a smooth current flow with a high current density. Hence, a compressive spring is used for the compression of the electrode. This spring is also a great help to the opening operation of the interrupter because it delivers the mechanical elastic energy of the spring to an actuator in a short time. In an open state, less holding force is needed compared to a closed state, eliminating the bounce which occurs because of the fast opening operation of the mover and preventing an unintended return from an open state to a closed state by unexpected external forces such as a shock or an earthquake. Hence, a different value of the holding force is required for the open state and the closed state.

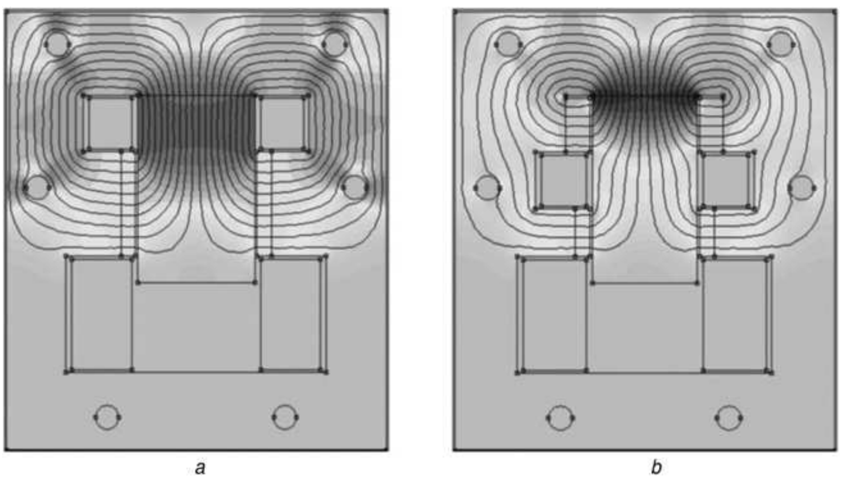

Fig. 4 *Comparison of the calculated magnetic flux density of the closed state between the PMA and the proposed SPMA using the same amount of the permanent magnet*

a PMA
b SPMA

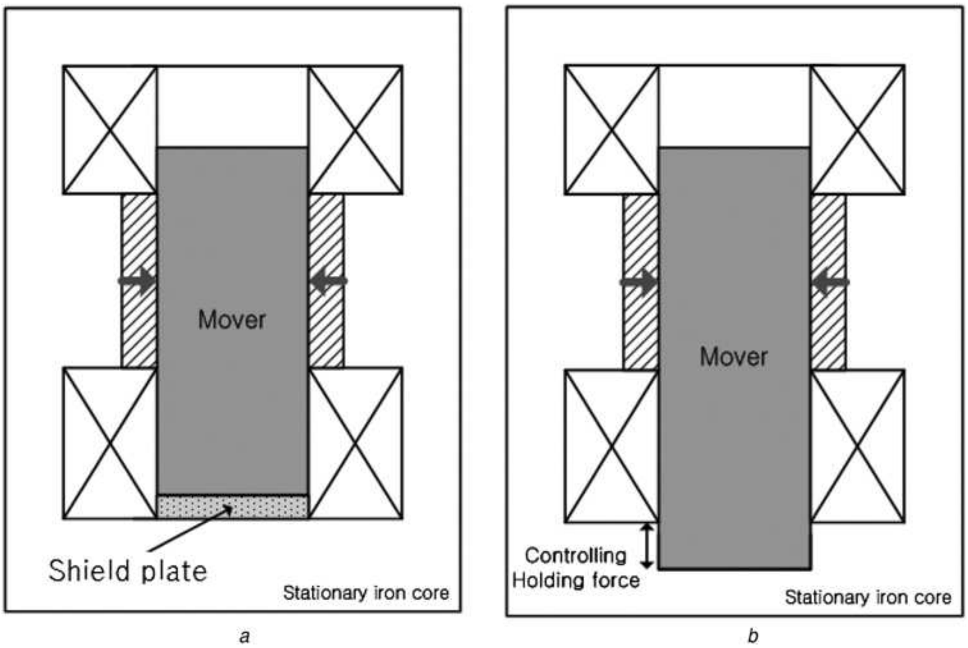

Fig. 5 *Structures that reduce the opening holding force of the PMA*
a Shield plate structure
b Basin shape

However, the conventional PMA cannot generate a different value of the holding force for the open state and the closed state, and the efficiency for the generation of the holding force is low because permanent magnets are located only in the middle of the actuator symmetrically. In order to address these problems with the conventional PMA, a novel structure is suggested in this research, as shown in Fig. 3. It involves the use of separated permanent magnets.

2.3 Closed state of the SPMA

The proposed SPMA uses separated permanent magnets located in the upper and middle parts to efficiently generate a large amount of closing holding force. As shown in Fig. 4, the calculated closing holding force of the PMA and the SPMA was 6430 and 7188 N, respectively. The PMA requires an increase of the magnet of more than 20%, or 11% with growth of the mover volume of 14%, to generate the same holding force as the SPMA. This shows that the proposed SPMA is more efficient than the PMA because of the following reasons. The magnetic flux of the PMA is concentrated not in the air gap between the mover and the stationary iron core but in the mover. Furthermore, the magnetic flux path of the SPMA is shorter than that of the PMA.

2.4 Open state of the SPMA

For the generation of less opening holding force than the closing holding force, a shielding plate structure and a basin shape were proposed to reduce the opening holding force for the PMA, as shown in the earlier work Fig. 5 [21, 22]. The shield plate structure can reduce the holding force through the use of a shield plate inserted between the mover and the stationary iron core. However, the shield plate structure can be damaged by the impact of a mover after several operations, and the performance of the actuator will be degraded with an increase in the size and the cost.

On the other hand, the basin shape is less effective for reducing the holding force. However, the opening holding force of the proposed SPMA can be reduced and controlled effectively while maintaining the same closing holding force by controlling only the ratio between the upper magnet and the middle magnet. Hence, the size and the cost of the closing coil and the mover can be reduced significantly as well as the capacitor that supplies the energy for the closing operation.

3 Analysis and design of the SPMA

3.1 Analysis of the magneto-static field

The magnetic vector potential, $\vec{A}$ (Wb/m^2), can be calculated by solving (1) by the FEM while applying the boundary condition [20–23]

$$\nabla \times \nu\left(\nabla \times \vec{A}\right) = \vec{J_0} + \nabla \times \left(\nu\mu_0\vec{M}\right) \tag{1}$$

which is subject to

$$\nu = (\mu_0\mu_r)^{-1} = \{\mu_0(1+\chi_m)\}^{-1} \tag{2}$$

where ν(m/H) is the reluctivity, $\vec{J_0}$(A/m^2) is the external current density vector, μ_0 (H/m) is the permeability of the free space, $\vec{M}$(A/m) is the residual magnetisation vector, and χ_m is the magnetic susceptibility.

The magnetic flux, Φ(Wb), can be calculated by [24]

$$\Phi = \int \vec{B}\cdot \mathrm{d}s = \int \nabla \times \vec{A}\cdot \mathrm{d}s = \oint \vec{A}\cdot \mathrm{d}l \tag{3}$$

where $\vec{B}$(Wb/m^2) is the magnetic flux density, s(m^2) is the area and l(m) is the length of the coil.

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The magnetic force vector, $\vec{F}_{mag}$(N), can be calculated by the Maxwell stress tensor method [25] as (4)

$$\vec{F}_{mag} = \iint_s \left(\frac{1}{\mu_0}\left(\vec{B}\cdot\vec{n}\right)\vec{B} - \frac{1}{2\mu_0}B^2\vec{n} \right) \mathrm{d}s \tag{4}$$

where s(m^2) is the area of the outer surface of the mover and $\vec{n}$ is the unit vector in the direction normal to the surface of the mover.

3.2 Analysis of the SPMA using an equivalent circuit and the TDM

Fig. 6 shows the equivalent circuit of the SPMA, where C is the capacitance of the capacitor, V_c is the charged voltage at the capacitor, T_r is the switching controller, I is the current of the coil, R_{coil} is the resistance of the coil, L is the inductance of the coil and Diode denotes the fly-wheel diode [26].

The electromotive force (EMF) of the coil must be analysed precisely while taking the motion of the mover into account for the analysis of the PMA [27, 28]. In this research, the inductance is used in the expression of the induced EMF. A transformer EMF is defined as the change of the magnetic flux about the unit value of the exciting current by (5), in which the script n expresses the nth time step. The motional EMF (MEMF) generated by the motion of the mover is formulated by (6). The unique values of the inductance have to be calculated at every time step because the mover and the iron core of the PMA consist of a nonlinear material and because the value of the inductance varies greatly according to the motion of the mover

$$L_i^n = N\frac{\mathrm{d}\Phi^n(I)}{\mathrm{d}I^n} = N\frac{\Phi^n(I) - \Phi^{n-1}(I)}{\mathrm{d}I^n} \tag{5}$$

$$L_x^n = N\frac{\mathrm{d}\Phi^n(x)}{\mathrm{d}x^n} = N\frac{\Phi^n(x) - \Phi^{n-1}(x)}{\mathrm{d}x^n} \tag{6}$$

We suggested the governing equations for the analysis of the SPMA according to the operating stage, as follow.

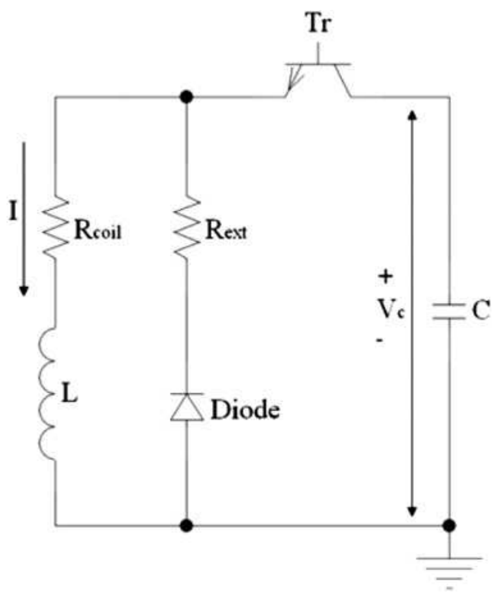

Fig. 6 *Equivalent circuit of the SPMA*

3.2.1 Initial stage of the closing operation while the mover is at a standstill:

Early in the closing stage, the mover is located at the end of the open position and is not in motion. Hence, the MEMF is not generated during this stage. For this reason, the voltage equation was derived as (7) by the equivalent circuit and according to the Kirchhoff's law. The change of the current at the nth time step, $\mathrm{d}I^n$, was induced from (7) as (8)

$$V_c^n = \left(I^{n-1} + \mathrm{d}I^n\right)R_{coil} + L_i^{n-1}\frac{\mathrm{d}I^n}{\mathrm{d}t} \tag{7}$$

$$\mathrm{d}I^n = \frac{\mathrm{d}t\left(V_c^n - I^{n-1}R_{coil}\right)}{R_{coil}\mathrm{d}t + L_i^{n-1}} \tag{8}$$

At the first time step, the calculation of the change of the current using (8) is impossible because the inductance, L_i^0, and the voltage, V_c^1, cannot be calculated. Hence, the inductance L_i^1 and the small time step dt were calculated by applying a small amount of current to the governing equations. The governing equation for the analysis of the time step, dt, was derived from (7) to (9), where it was assumed that $L_i^0 \simeq L_i^1$ and $V_c^0 \simeq V_c^1$ (V_c^0 is a given value) because the increase in the current is small

$$\mathrm{d}t = \frac{L_i^0\mathrm{d}I^1}{V_c^1 - \left(I^0 + \mathrm{d}I^1\right)R_{coil}} \simeq \frac{L_i^1\mathrm{d}I^1}{V_c^0 - \left(I^0 + \mathrm{d}I^1\right)R_{coil}} \tag{9}$$

3.2.2 Closing operation accompanying the motion of the mover:

If the exciting current exceeds a specific value, a mover starts moving. The MEMF has to be added in (7) and (8), as shown in (10) and (11) while the mover is moving. Normally, the change in the current, dI^n, has a negative value because of the large MEMF, inducing a decrease in the current

$$V_c^n = \left(I^{n-1} + \mathrm{d}I^n\right)R_{coil} + L_i^{n-1}\frac{\mathrm{d}I^n}{\mathrm{d}t} + L_x^{n-1}\frac{\mathrm{d}x^n}{\mathrm{d}t} \tag{10}$$

$$\mathrm{d}I^n = \frac{\mathrm{d}t\left(V_c^n - I^{n-1}R_{coil}\right) - L_x^{n-1}\mathrm{d}x^n}{R_{coil}\mathrm{d}t + L_i^{n-1}} \tag{11}$$

3.2.3 Closing operation immediately after the mover arrives at the closing position:

If the mover arrives at the closing position, the switching controller turns the capacitor voltage off. Directly after the capacitor voltage is turned off, the capacitor voltage takes the previous step value, via (12). The voltage equation is suggested by the Kirchhoff's law is (13), in which the voltage V is the external input voltage with a zero value because the controller cuts off the power. The equation for the analysis of the change of the current can be derived from (13) by (14)

$$V_c^n = V_c^{n-1} \tag{12}$$

$$V = \left(I^{n-1} + \mathrm{d}I^n\right)\left(R_{coil} + R_{ext}\right) + L_i^{n-1}\frac{\mathrm{d}I^n}{\mathrm{d}t} \tag{13}$$

$$\mathrm{d}I^n = \frac{\mathrm{d}t\left\{V - I^{n-1}\left(R_{coil} + R_{ext}\right)\right\}}{\mathrm{d}t\left(R_{coil} + R_{ext}\right) + L_i^{n-1}} \tag{14}$$

3.2.4 Time step and the capacitor voltage: The current and the time can be calculated by (15) and (16)

$$I^n = I^{n-1} + \mathrm{d}I^n \tag{15}$$

$$\mathrm{time}^n = \mathrm{time}^{n-1} + \mathrm{d}t \tag{16}$$

The capacitor voltage will drop, as shown in (17). Directly after the power of the capacitor is turned off, the capacitor voltage will be maintained as (12)

$$V_c^n = V_c^{n-1} - \frac{1}{C} I^n \mathrm{d}t \tag{17}$$

3.3 Analysis of the SPMA using the equation of motion and the TDM

The velocity and the displacement of the mover can be calculated by analysing the equation of motion and the TDM [28, 29]. The equation of motion for the SPMA is determined by (18). The velocity of the mover, $\vec{v}^n$, and the displacement of the mover, $\vec{x}^n$, are derived by (19) and (20), respectively, where m is the mass of a mover, $\vec{g}$ is the acceleration of the gravity, $\vec{F}_{\mathrm{mag}}$ is the magnetic force acting on a mover, $\vec{F}_{\mathrm{spring}}$ is the spring load and $\vec{F}_{\mathrm{fric}}$ is the frictional force.

$$m\left(\frac{\mathrm{d}^2\vec{x}^n}{\mathrm{d}^2 t} + \vec{g}\right) = m\left(\frac{\mathrm{d}\vec{v}^n}{\mathrm{d}t} + \vec{g}\right) = \vec{F}^n_{\mathrm{mag}} + \vec{F}^n_{\mathrm{spring}} + \vec{F}^n_{\mathrm{fric}} \tag{18}$$

$$\vec{v}^n = \vec{v}^{n-1} + \mathrm{d}\vec{v}^n = \vec{v}^{n-1} + \left(\frac{\vec{F}^n_{\mathrm{mag}} + \vec{F}^n_{\mathrm{spring}} + \vec{F}^n_{\mathrm{fric}} - m\vec{g}}{m}\right)\mathrm{d}t \tag{19}$$

$$\vec{x}^n = \vec{x}^{n-1} + \mathrm{d}\vec{x}^n = \vec{x}^{n-1} + \vec{v}^n \mathrm{d}t = \vec{x}^{n-1} + \vec{v}^{n-1}\mathrm{d}t + \frac{1}{2}\left(\frac{\vec{F}^n_{\mathrm{mag}} + \vec{F}^n_{\mathrm{spring}} + \vec{F}^n_{\mathrm{fric}} - m\vec{g}}{m}\right)\mathrm{d}t^2 \tag{20}$$

3.4 Design of the SPMA

Initially, the permanent magnet, the stationary iron core and the movable iron core (mover) have to be designed for the generation of a sufficient amount of closing holding force. The coil then has to be designed for the required characteristics. The important design points are as follows:

3.4.1 Holding force: The suggested SPMA was applied to the 17.5 kV/40 kA VCB. The maximum reactive force generated by the compressed spring per phase is about 400 kgf. The total reactive force for three-phase operation will be about 13 000(N) assuming a 10% safety factor. A large closing holding force has to be generated only by the permanent magnet. Hence, the permanent magnet has to be increased bulking up of the stationary iron core and the movable iron core (the mover). To solve this problem, a number of actuators in parallel or a lever mechanism can be used to decrease the receiving reactive force of the actuator. The former method, using a parallel actuator, brings about an increase in the size and the cost proportional to the increase of the number of actuators. In case of the latter method, involving the use of a lever mechanism, the holding force can be reduced but the stroke of the actuator must be extended, reducing the generating force considerably because the magnetic flux density is decreased in proportion to the square of the length of the air gap. In this research, the lever mechanism, of which the stroke is 30 mm, was adopted while taking the size and cost into consideration.

3.4.2 Coil

1. *Consideration of the magnetic force:* Fixing the size of the slot, the magnetomotive force (MMF) should be controlled by varying the resistance and the number of turns through a change in the diameter of the coil. If the diameter of the coil is augmented, the resistance of a coil will be diminished much more than the reduction of the number of turns. Hence, the current will be increased. In other words, the magnetic force can be controlled by the diameter of the coil because the MMF is defined by multiplying the number of turns and the current of the coil.
2. *Consideration of the limit of the current* After determining the diameter of the coil, a designer must check whether or not the current is under any restriction. The current can be diminished while maintaining the same MMF only by augmenting the slot along with an increase in the number of the coil turns because the number of the coil turns is directly proportional to the resistance and the MMF.

3.4.3 Voltage drop of capacitor: An opening capacitor and a closing capacitor were used for the operating duty test, which carries out the continuous operation of the closing and the opening for the estimation of malfunctions. The operating duty test of the 17.5 kV/40 kA VCB is the open–close–open sequence. An opening capacitor has to be operated two times continuously. Hence, the voltage drop of the opening capacitor must be checked in the design of the SPMA.

3.4.4 Opening/closing velocity: To prevent a dielectric breakdown caused by arcing between the movable electrode and the fixed electrode during the opening process, the opening velocity has to be taken into account. To prevent damage because of electrode collisions during the closing operation, the closing velocity also must be taken into consideration. The opening velocity of the 17.5 kV, 40 kA VCB is defined as the average velocity from the separate positions of two electrodes to the 2/3 position of the maximum gap of electrodes. The closing velocity is defined as the average velocity from the 1/3 position of the maximum gap of the electrodes to the contacting position of electrodes. For the 17.5 kV, 40 kA VCB, the opening velocity must exceed 1.2 m/s and the closing velocity must not be more than 1.2 m/s.

3.4.5 Abrasion: The abrasion of contacting areas of the electrodes after numerous operations must be considered. The stroke of the actuator is fixed, but the length of the gap between the movable electrode and its fixed counterpart is

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increased by abrasion as the number of operations increases. Therefore the compressible length of the spring is decreased as the gap between electrodes increases because of abrasion, meaning that the spring force is decreased in proportion to the decrease of the compressible length of the spring by abrasion. The spring has the role of the adding compressed energy to the actuator early in the opening operation to increase the opening velocity. Therefore decreased spring energy because of abrasion must be taken into consideration to satisfy the required opening velocity.

4 Prototype of SPMA

As presented in Fig. 7, the whole system of the proposed SPMA consists of the SPMA, the driver, the controller and three poles. The material of 42-MGOe, which is a kind of NdFeB, is used for the magnet of the SPMA. M45-steel is applied for the material of the mover and the stationary core. As illustrated in Fig. 8, the control/driving system is composed of the DC/DC converter, the chargers, the capacitors, the full bridge IGBT (insulated gate bipolar mode transistor), the sensors, and the micro-processor and PC. The main board of the control/driving system is composed of the 16 bit micro-processor and the flash memory for a data saving, a computation and a control; the RS-232 for the communication between the controller and the PC; the pulse width modulation (PWM) generating part for the operation of the power board; the LED displayer for the indication of the status of the driver, the controller and the sensors. Through the full bridge IGBT, the electrical power source for the SPMA is supplied by the capacitors, which are charged by the chargers.

The possibility of the digital control is useful for the CB and it is feasible by the PMA and the SPMA which use the electromagnetic energy. The self-diagnosis of the CB system is possible by analysing the data which are measured and sent by the sensors and the controller. The data include the voltage of the capacitor, the position of the moving contactor and the mover, the opening and closing velocity, and the switching time. Furthermore, the

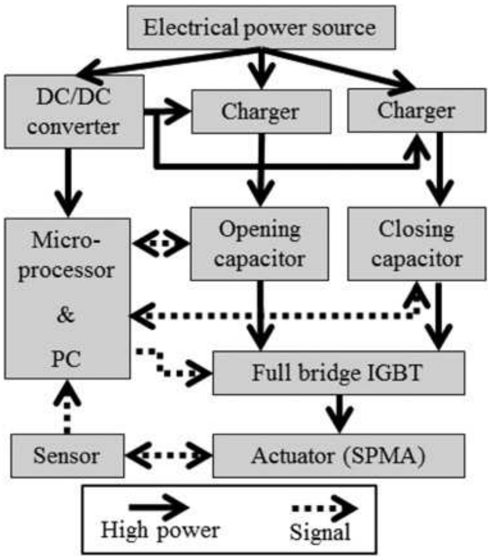

Fig. 8 *Block diagram of the control/driving system for the SPMA*

integrated management system for the CB is practicable by connecting the network. Hence, the proposed SPMA is suitable for the intelligent power system combined with the digital control and the network.

5 Comparison between experiment and analysis

5.1 Opening operation

As illustrated in Fig. 9*a*, the SPMA maintains the closing state by using the upper and the lower permanent magnets. When the opening coil is excited for the opening operation as described in Fig. 9*b*, the mover starts to move. As presented in Fig. 9*c*, after the mover arrives to the opening position, the opening coil is turned off and the opening state can be maintained by using only the lower permanent magnet.

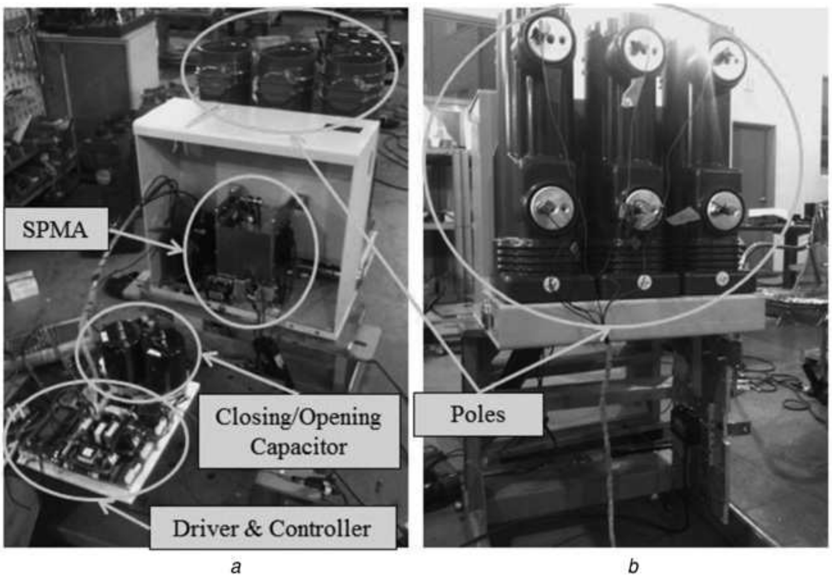

Fig. 7 *Prototype of the SPMA*

a Front view
b Backside view

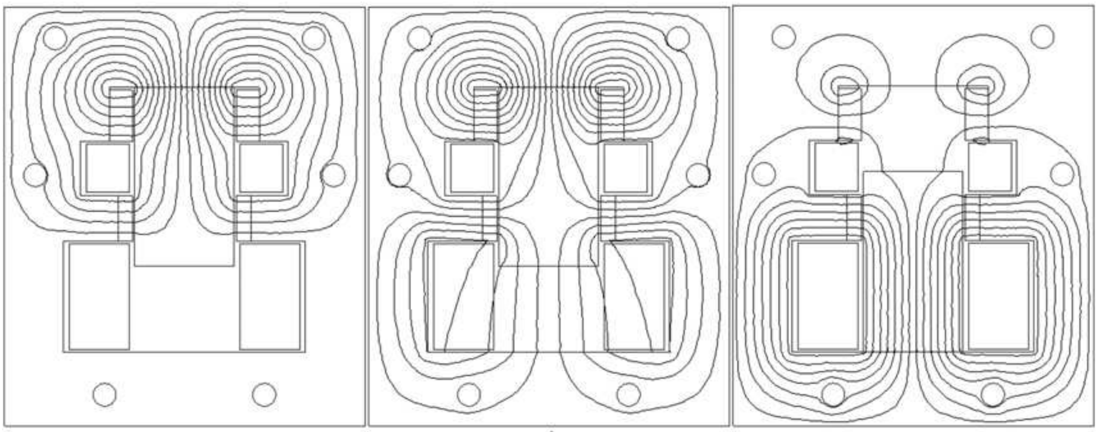

Fig. 9 *Analysis result using FEM for the opening of the SPMA*

a Closing state
b Excitation of the opening coil before the motion of the mover
c After finishing opening operation and switching off the opening coil

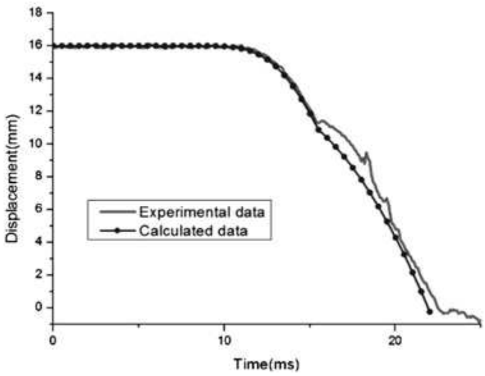

Fig. 10 *Displacement of the mover during the opening operation*

As shown in Fig. 10, the mover started to move at 12 ms and stopped at 22.5 ms. Therefore the suggested SPMA completed its opening operation in the required opening time of 50 ms. In the state of Fig. 9*a*, the current was continuously increased immediately before the mover starts its motion, as illustrated in Fig. 11. Directly after the mover begins to move, the current is decreased by the MEMF, which is induced from the motion of the mover. The opening capacitor voltage was dropped in proportion to the current of the opening coil. The minute difference between the experimental data and the calculated values is induced from the nonlinearity of the material. The opening velocity was over 1.2 m/s meeting the requirement to prevent a dielectric breakdown. The voltage drop was under 10 V, satisfying the demand for the operating duty test.

5.2 Closing operation

If the closing coil is excited as illustrated in Fig. 12*b*, the mover starts the motion. As elucidated in Fig. 12*c*, when the mover arrives to the closing position, the closing coil is turned off and the closing state can be maintained by using

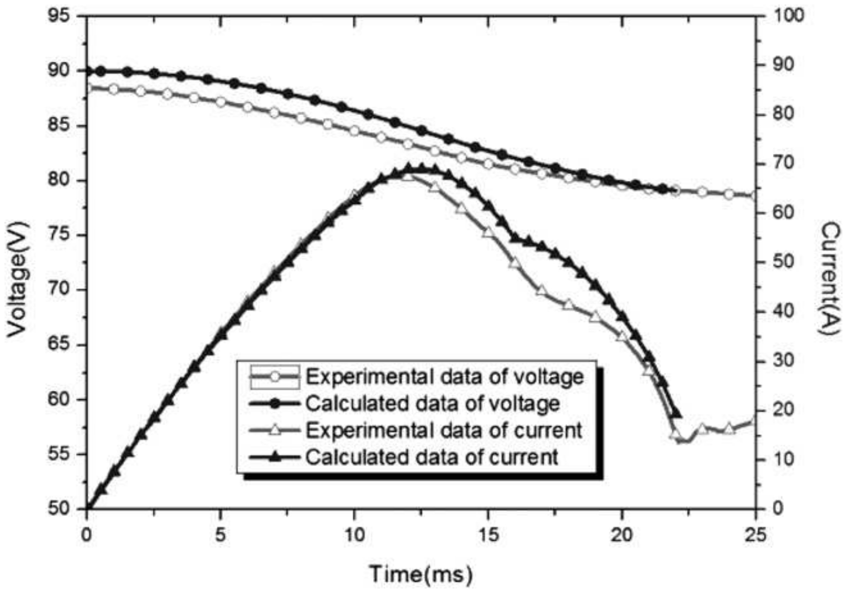

Fig. 11 *Voltage of the opening capacitor and the current of the opening coil during the opening operation*

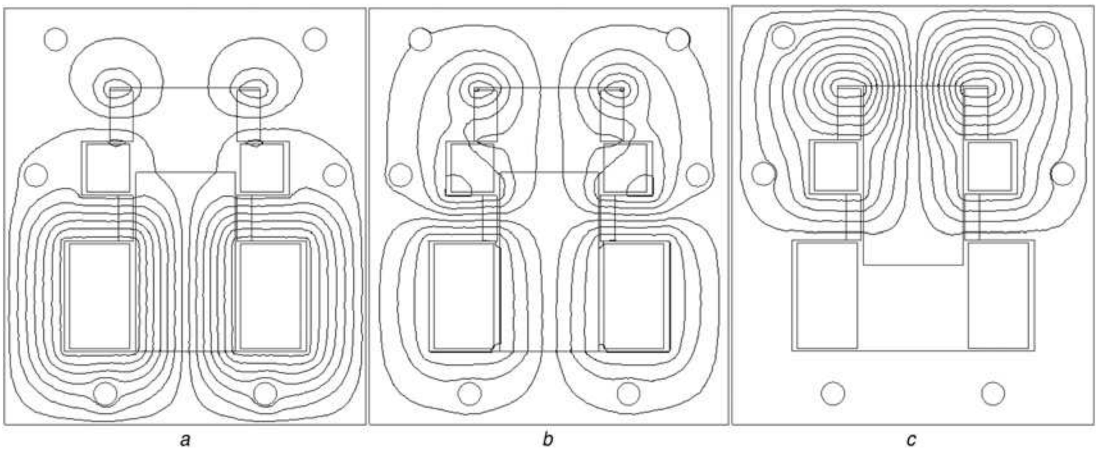

Fig. 12 *Analysis result using FEM for the closing of the SPMA*

a Opening state
b Excitation of the closing coil before the motion of the mover
c After finishing closing operation and switching off the closing coil

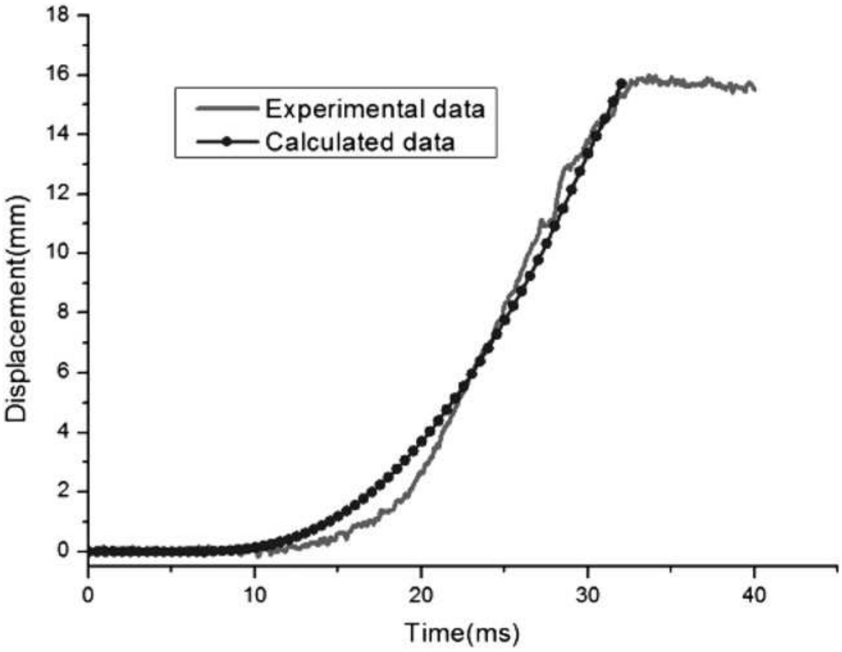

Fig. 13 *Displacement of the mover during the closing operation*

both the upper and the lower permanent magnets without any electrical power consumption.

As illustrated in Fig. 13, the mover began its motion at 10 ms and completed the closing operation at 32 ms. Therefore the actuator finished the closing operation under the limit, 60 ms. The closing velocity was 1.1 m/s, which did not exceed the velocity restriction of 1.2 m/s to avoid damage to the electrodes. The actuator consumed a high amount of power during the closing operation, as displayed in Fig. 14, because the closing operation did not require the continuous operation during the operation duty test.

6 Conclusions

The important point to note in this research is that a novel and efficient SPMA is proposed. Owing to the fairly high efficiency of the proposed SPMA, the size and cost are significantly reduced compared to the conventional actuator.

The analysis and design method for the SPMA is also proposed in this paper. This has significant meaning in that the proposed analysis and design method can reduce the lost time and the cost incurred by experimental trial-and-error process.

Additionally, in this study the SPMA was designed and prototyped. Hence, the usefulness of the SPMA for a VCB and the correctness of the proposed analysis and design method were confirmed through an experiment.

7 Acknowledgment

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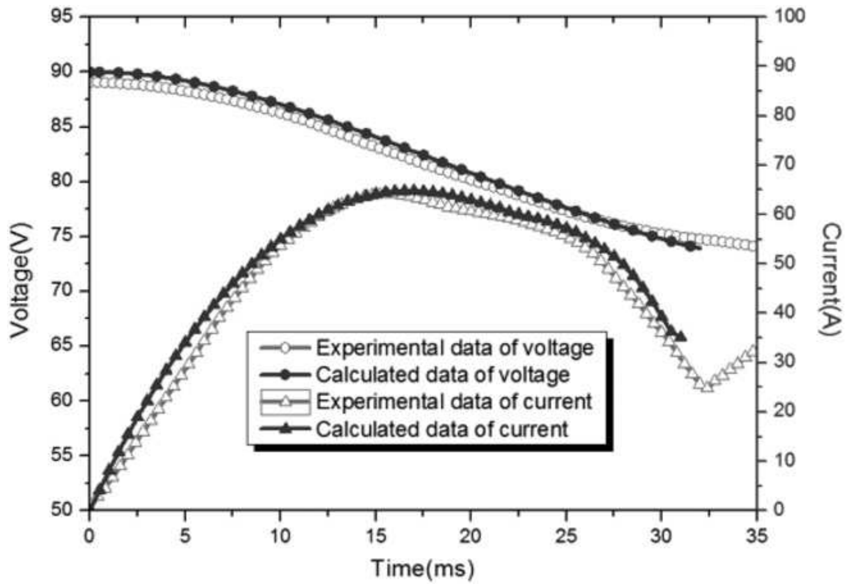

Fig. 14 *Voltage of the closing capacitor and the current of the closing coil during the closing operation*

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