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Analysis of an Electromagnetic Actuator for Circuit Breakers

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Abstract – In this paper, we present an analysis of dynamic characteristics of an electromagnetic actuator for circuit breakers. It is indispensable to simultaneously analyze magnetic, electric, and mechanical phenomena to obtain the dynamic characteristics of the electromagnetic actuator because these phenomena are closely related to each other in an electromagnetic actuator system. The magnetic equations are computed by using the finite element method (FEM). The electric equations and the mechanical equations, which include the time derivative terms, are calculated by using the time difference method (TDM). The calculated results, which have been obtained by means of the FEM and the TDM, are presented with experimental data.

Keywords: Circuit breaker, Dynamic characteristic, Electromagnetic actuator, Finite element method (FEM), Time difference method (TDM)

1. Introduction

An electromagnetic actuator has been commonly used as a mechanism for low and medium voltage circuit breakers. It has many advantages including excellent performance, high reliability, long lifetime, and minimal maintenance [1], [2]. Nowadays, there are attempts to optimize the electromagnetic actuator and apply it to high voltage circuit breakers [3], [4]. It is indispensable to analyze the dynamic characteristics of the electromagnetic actuator with accuracy to succeed in theses attempts.

The dynamic characteristics of the electromagnetic actuator are very sensitive to its shape, electric elements, and mechanical elements. In order to obtain accurate dynamic characteristics of the electromagnetic actuator, it is necessary to perform a transient analysis considering the shape, electric elements, and mechanical elements of the electromagnetic actuator [5], [6]. The magnetic, the electric, and the mechanical phenomena appear in the electromagnetic actuator. Each phenomenon is mutually combined and affects the others. These phenomena are mathematically formulated into the magnetic, the electric, and the mechanical equations. In this paper, we use the finite element method (FEM) and the time difference method (TDM) to analyze the transient characteristics of the electromagnetic actuator. The magnetic equations are computed by using the finite element method (FEM). The electric and mechanical equations, which include the time derivative terms, are analyzed using the time difference method (TDM). The TDM makes use of an iterative technique. The whole time is divided into many time steps. We can get the exciting current of a coil, which is computed from the electric equations, and the displacement of an armature, which is calculated from the mechanical equations at each time step through the results of the magnetic equations. The FEM and the TDM are repeatedly performed until the calculation time is over and the final results can be achieved.

The dynamic characteristics of two kinds of actuators are analyzed and the simulated results are compared with the experimental data to prove the accuracy of the simulated results using the FEM and the TDM.

2. Description of an Electromagnetic Actuator

Fig. 1 shows the typical structure of the electromagnetic actuator. It basically consists of an armature, a static core, an opening coil, and a closing coil. The armature is a ferromagnetic body, which is able to move in an opening or closing direction. The static core is laminated and makes the path in which magnetic flux flows. The opening and closing coils, which are energized from a DC source, provide driving force to the armature.

Fig. 2 is the equivalent circuit of the electromagnetic actuator. C is the capacitor, Tr is the power electronic element based on a controller, R_{coil} is the resistance of the coil, L is the inductance of the coil, Diode is the fly-wheel diode, R_{ext} is the resistance connected with the fly-wheel diode, V_c is the voltage of the capacitor, and I is the current flowing through the coil. In some cases, the battery is substituted for the capacitor.

The closing operation for the electromagnetic actuator

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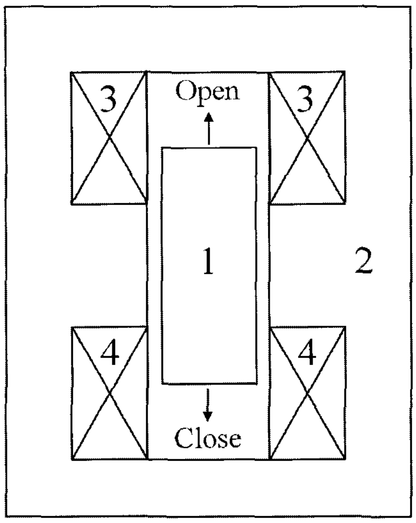

Fig. 1. The typical structure of the electromagnetic actuator
1- armature, 2- static core, 3- opening coil, 4- closing coil

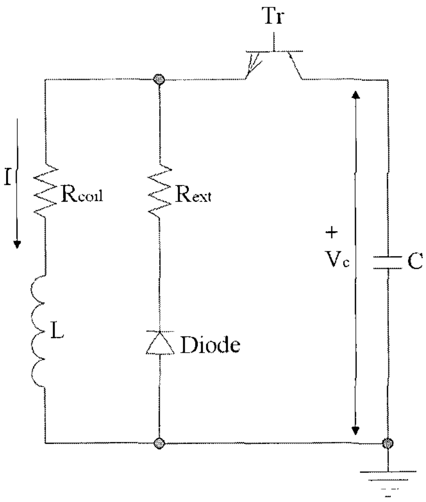

Fig. 2. The equivalent circuit of the electromagnetic actuator

is in regular sequence as follows. Without any exciting current in the closing coil, the armature is held at the opening terminal position. After the closing coil is switched on, the exciting current increases. According to the exciting current rise, the magnetic force in the closing direction rises. When the force toward the closing direction is more than the open holding force, the armature starts to move toward the closing direction. Due to the increase in the magnetic force from exciting current, the armature continuously moves to the closing direction. After the armature reaches a closing terminal position, the exciting current is switched off.

The opening operation is similar to the closing operation. At first, the armature is at the closing terminal position. If the opening coil is excited, the armature moves to the opening direction. When the armature reaches an opening terminal position, the exciting current is switched off.

3. Analysis of Dynamic Characteristics

The electromagnetic actuator has magnetic, electric, and mechanical phenomena. Each phenomenon is mutually combined and affects the others. These are mathematically formulated into magnetic, electric, and mechanical equations. In this paper, the FEM and the TDM are used to obtain dynamic characteristics of the electromagnetic actuator. The magnetic flux and the magnetic force are obtained using the FEM from the magnetic equations. The electric equations and the kinematical equations, which include the time derivative terms, are analyzed using the TDM. The TDM makes use of an iterative technique. The solutions of the electric equations and the kinematical equations are computed by dividing the whole time into many time steps. The previous solution is used to calculate the present solution in a current step, and then the next solution is obtained using the present solution. Through this process, we can get the exciting current, the voltage of the capacitor, the velocity, and the displacement of the armature.

3.1 Magnetic Equations

The two fundamental differential equations for magnetostatics are

$$\nabla \cdot \vec{B} = 0 \ , \tag{1}$$

$$\nabla \times \vec{H} = \vec{J}_0 \ , \tag{2}$$

where $\vec{B}$ is the magnetic flux density, $\vec{H}$ is the magnetic field intensity, and $\vec{J}_0$ is the external current density. $\vec{B}$ is solenoidal, therefore, it can be expressed as the curl of vector

$$\vec{B} = \nabla \times \vec{A} \ , \tag{3}$$

where $\vec{A}$ is the vector magnetic potential. If there are permanent magnets and the external current source, the magnetic flux density can be expressed as follows

$$\vec{B} = \mu_0 \left\{ (1 + \chi_m)\vec{H} + \vec{M} \right\} \ , \tag{4}$$

where μ_0 is the permeability of free space, χ_m is the magnetic susceptibility, and $\vec{M}$ is the magnetization. From (2), (3), and (4), the governing differential equation is formulated as follows

$$\nabla \times \nu (\nabla \times \vec{A}) = \vec{J}_0 + \nabla \times (\nu \mu_0 \vec{M}) \ , \tag{5}$$

where ν is the reluctivity, which is defined as $\nu = 1/\mu_0(1+\chi_m)$.

The vector magnetic potential is obtained from (5) using the FEM. The magnetic force and the magnetic flux are calculated from this vector magnetic potential.

The magnetic flux is used to calculate the inductance. This magnetic flux is computed by (6) as follows

$$\Phi = \oint \vec{A} \cdot d\vec{l} \quad , \tag{6}$$

where Φ is the magnetic flux, and l is the winding path of the coil. During the operation of the PMA, the armature moves by virtue of the magnetic force generated by the permanent magnets and the exciting current. The magnetic force acting on the armature is calculated using the Maxwell stress tensor method, as

$$\vec{F}_{mag} = \iint_S \left(\frac{1}{\mu_0}(\vec{B}\cdot\vec{n})\vec{B} - \frac{1}{2\mu_0}B^2\vec{n}\right)dS \quad , \tag{7}$$

where F_{mag} is the magnetic force, $\vec{n}$ is the unit vector of the normal direction along the surface, and S is the area of the outer surface around the armature.

3.2 Electric Equations

The electric equations are solved by the TDM, and the exciting current of the coil and the voltage of the capacitor are obtained.

The electromotive force (emf), which is induced in the coil by a time rate of the change in magnetic flux, should be calculated exactly in order to obtain the precise dynamic characteristics, because the emf has a great influence on the dynamic characteristics of the PMA. The exciting current and the displacement of the armature are variables of the magnetic flux, and the emf can be formulated as follows

$$e = -N\frac{d\Phi(I,x)}{dt} \quad , \tag{8}$$

where e is the emf, N is the number of turns of the coil, I is the exciting current, x is the displacement of the armature, and dt is the unit time step.

The inductance, which is defined as the magnetic flux linkage per unit current, can be expressed as follows

$$L_i = N\frac{\partial\Phi(I,x)}{\partial I} \quad , \tag{9}$$

where L_i is the inductance. Similar to the inductance, L_x can be defined as the magnetic flux linkage per unit length. It is written as follows

$$L_x = N\frac{\partial\Phi(I,x)}{\partial x} \quad . \tag{10}$$

When L_i is calculated, the displacement of the armature is a constant value, and then (9) can be converted as follows

$$L_i^n = N\frac{d\Phi^n(I)}{dI^n} = N\frac{\Phi^n(I)-\Phi^{n-1}(I)}{dI^n} \quad , \tag{11}$$

where n means the current step, and n-1 is the previous step. In a similar way, the exciting current is fixed to compute L_x, therefore (10) can be changed as follows

$$L_x^n = N\frac{d\Phi^n(x)}{dx^n} = N\frac{\Phi^n(x)-\Phi^{n-1}(x)}{dx^n} \quad . \tag{12}$$

To obtain the dynamic characteristics of the electromagnetic actuator, the motion of the armature has to be considered accurately. When the armature is at the opening or closing terminal position without any motion, the exciting current can be calculated from (13), which is only considered using the transformer emf

$$\begin{cases} V_c^n = (I^{n-1}+dI^n)R_{coil} + L_i^{n-1}\dfrac{dI^n}{dt} \\ \Leftrightarrow dI^n = \dfrac{dt(V_c^n - I^{n-1}R_{coil})}{R_{coil}dt + L_i^{n-1}} \end{cases} \quad , \tag{13}$$

where V_c is the voltage of the capacitor, and R_{coil} is the resistance of the coil. The first time step, dt^1, is calculated from (14) with the assumed value of dI^1

$$\begin{cases} V_c^0 = (I^0+dI^1)R_{coil} + L_i^1\dfrac{dI^1}{dt^1} \\ \Leftrightarrow dt^1 = \dfrac{L_i^1 dI^1}{V_c^0 - (I^0+dI^1)R_{coil}} \end{cases} \quad , \tag{14}$$

where V_c^0 and I^0 are the initial values of the voltage of the capacitor and the exciting current.

While the armature is moving, the motional emf is generated and the related term should be considered in (15) as follows

$$\begin{cases} V_c^n = (I^{n-1}+dI^n)R_{coil} + L_i^{n-1}\dfrac{dI^n}{dt} + L_x^{n-1}\dfrac{dx^n}{dt} \\ \Leftrightarrow dI^n = \dfrac{dt(V_c^n - I^{n-1}R_{coil}) - L_x^{n-1}dx^n}{R_{coil}dt + L_i^{n-1}} \end{cases} \quad . \tag{15}$$

After dI is calculated from the electric equations, the exciting current and the time are updated as follows

$$I^n = I^{n-1} + dI^n \quad , \tag{16}$$

$$time^n = time^{n-1} + dt \quad , \tag{17}$$

and then the magnetic flux in a next step is calculated by using FEM with the updated external current density.

Before the controller switches off the circuit, the voltage of the capacitor is obtained from (18) as follows

$$V_c^n = V_c^{n-1} - \frac{1}{C} I^n dt \quad , \tag{18}$$

where C is the capacitance of the capacitor. If the source of the electromagnetic actuator is not the capacitor but the battery, V_c^n is equal to V_c^{n-1}.

3.3 Mechanical Equations

The velocity and the displacement of the armature are calculated from the kinematical equations. The basic kinematical equation is

$$m(\frac{d^2x}{dt^2} + g) = F_{mag} - F_{fric} \quad , \tag{19}$$

where m is the mass of the moving part, g is the acceleration of the gravity, and F_{fric} is the frictional force. The formula for the velocity is

$$v = \frac{dx}{dt} \quad , \tag{20}$$

where v is the velocity. Then (21) can be converted into as follows

$$\begin{cases} m(\dfrac{dv^n}{dt} + g) = F_{mag}^n - F_{fric}^n \\ \Leftrightarrow dv^n = \dfrac{dt(F_{mag}^n - F_{fric}^n - mg)}{m} \end{cases} . \tag{21}$$

After dv is obtained, the velocity is updated and the displacement is calculated as follows

$$v^n = v^{n-1} + dv^n \quad , \tag{22}$$

$$dx^n = v^n dt \quad , \tag{23}$$

$$x^n = x^{n-1} + dx^n \quad . \tag{24}$$

3.4 Iterative Procedure

Fig. 3 is the flow chart for the iterative procedure proposed in this paper. At first, the initial values are set, and then the solutions of Φ^1, F_{mag}, L_l^1, dt^1, and V_c^1 in the first step are computed from (7), (11), (14), and (18) with the assumed value of dI_1. Next, Φ^n and F_{mag}^n are calculated from the magnetic equations, then I^n and V_c^n are obtained from the electric equations. After checking the force acting on the armature and displacement of the armature, the mechanical equations are solved. The displacement and the velocity of the armature are obtained from the mechanical equations. This process is repeated until the terminal time.

4. Results of Dynamic Characteristics

This paper includes the results of dynamic characteristics of two different actuators. One is the permanent magnetic actuator (PMA) for a vacuum circuit breaker (VCB), the other is the actuator for a molded case circuit breaker (MCCB).

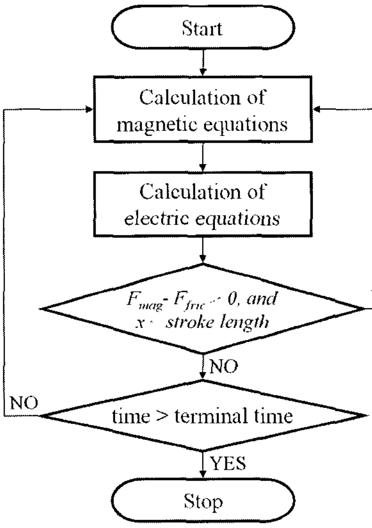

Fig. 3. The flow chart for the iterative procedure

4.1 Permanent Magnetic Actuator for Vacuum Circuit Breakers

Fig. 4 shows the structure of the PMA. The PMA has permanent magnets which provide holding force without any exciting current of a coil. By virtue of this holding force, the armature is held at opening or closing terminal position.

The experimental model is the PMA for a 17.5 kV VCB as illustrated in Fig. 3. This model has a 20 mm stroke length, 3700 N open holding force, and 5700 N close holding force. The initial voltage of the capacitor is 80 V and the resistance of the coil is 1 Ω. As the frictional force is not measured, this force is assumed as a proper value in the simulation.

Fig. 6 and Fig. 7 show the comparison between the simulated results and the experimental results of the PMA during the closing operation. The displacement of the armature is revealed in Fig. 6. The armature starts to move in the closing direction at 30 ms, and it reaches the closing terminal position at 45.2 ms. Fig. 7 shows the exciting current of the closing coil. If there is no armature motion, the exciting current increases. While the armature is moving, the exciting current decreases due to the motional emf. When the armature is located at the closing terminal position, the exciting current rises again. As a potentiometer is used to measure the displacement of the armature, there is a little oscillation in the experimental results of Fig. 6. If this oscillation is neglected, the calculated results, such as the displacement of the armature and the exciting current of the closing coil, have a good match with the experimental results.

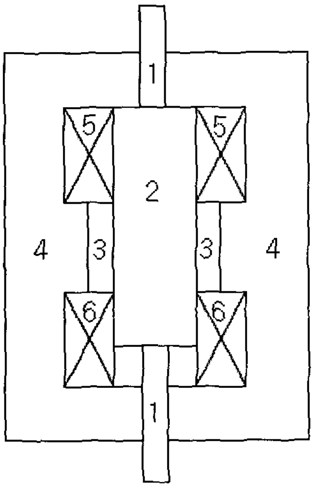

Fig. 4. The structure of PMA
1- transmission rod, 2- armature, 3- permanent magnet, 4- static core, 5- opening coil, 6- closing coil

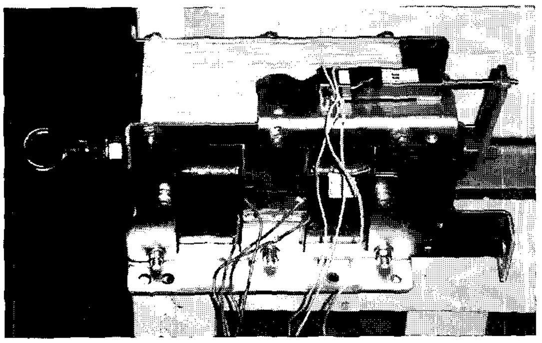

Fig. 5. Experimental model of the PMA for a 17.5 kV VCB

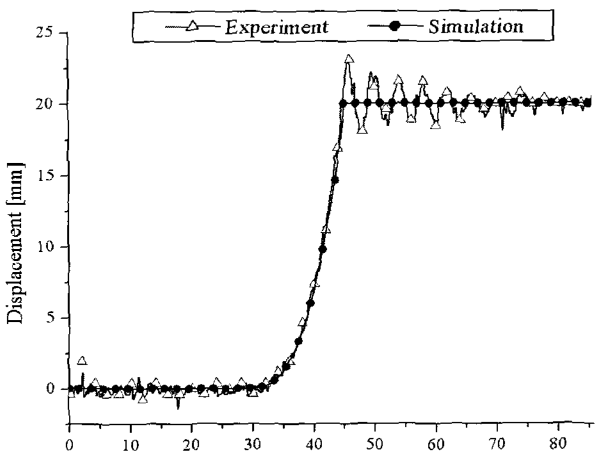

Fig. 6. The displacement of the armature of PMA during the closing operation

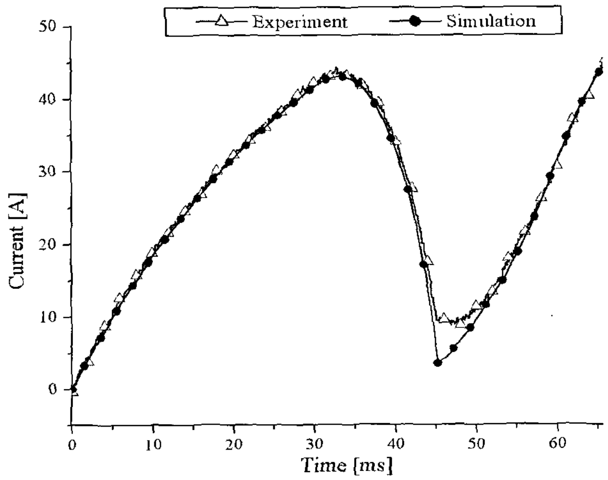

Fig. 7. The exciting current of PMA during the closing operation

4.2 Actuator for Molded Case Circuit Breakers

The actuator for MCCBs has no holding force because there is no permanent magnet in it. Fig. 8 indicates the structure of the actuator for MCCBs. The MCCB is operated using remote control by means of this actuator.

In the experimental model, the stroke length is 26 mm, the voltage of the battery is 24 V, and the resistance of the coil is 3 Ω. The frictional force is not considered in this case.

Fig. 9 and Fig. 10 respectively show the displacement of the armature and the exciting current of the closing coil during the closing operation. The armature starts to move in the closing direction as soon as the closing coil is switched on and energized. If the speed of the armature is low, the exciting current increases. While the armature moves fast, the motional emf is large and the exciting current decreases. Once the armature reaches the closing terminal position, the exciting current rises again.

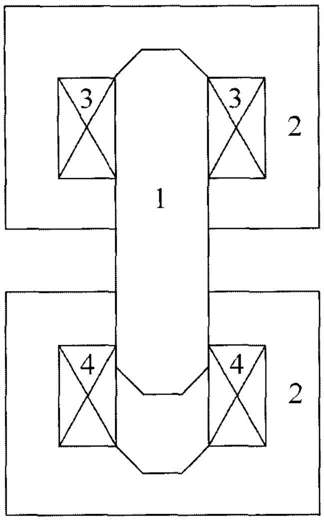

Fig. 8. The structure of actuator for MCCBs
1- armature, 2- static core, 3- opening coil, 4- closing coil

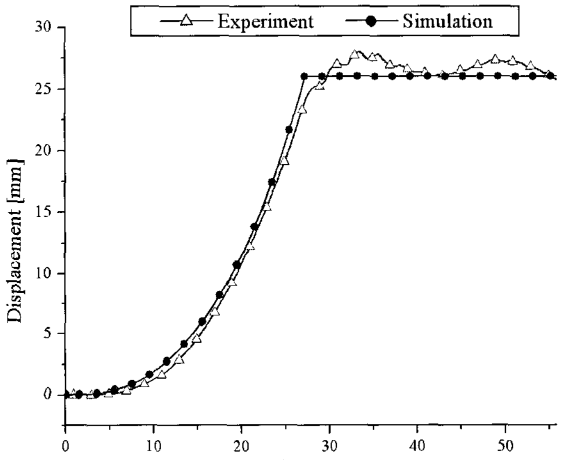

Fig. 9. The displacement of the actuator armature for MCCBs during the closing operation

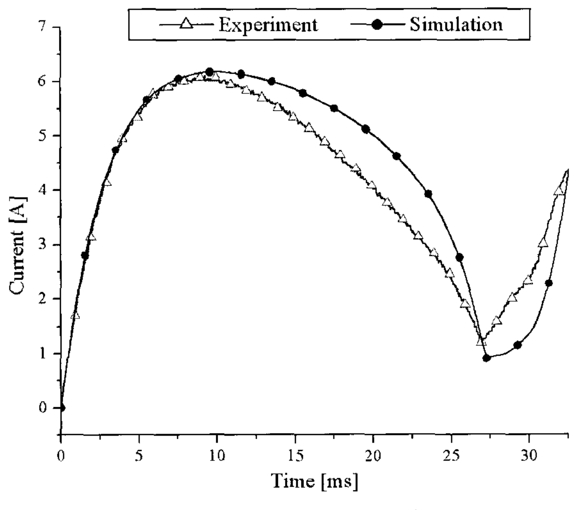

Fig. 10. The exciting current of actuator for MCCBs during the closing operation

Table 1. The comparison between simulation and experiment during the closing operation

	PMA for VCBs		Actuator for MCCBs	
	Simulated results	Experimental results	Simulated results	Experimental results
Closing time	45.2 ms	45.4 ms	27.2 ms	27.0 ms
Maximum exciting current	43.0 A	44.0 A	6.2 A	6.0 A

5. Conclusion

In this paper, we present the analysis of the dynamic characteristics of the electromagnetic actuator using the FEM and the TDM. Table I shows the comparison between the simulated results and the experimental results during the closing operation. The simulated results are similar to the experimental results. We conclude that the method proposed in this paper can accurately analyze the transient characteristics of the electromagnetic actuator.

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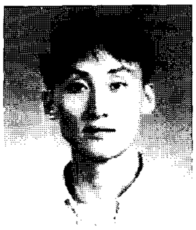

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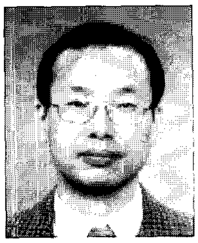

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