A High Performance AC Permanent Magnet Contactor

CHIEH-TSUNG CHI
Department of Electrical Engineering
Chienkuo Technology University
No. 1, Chieh Shou N. Rd., Changhua City 500, Taiwan, R.O.C
E-mail: jih@cc.ctu.edu.tw

Abstract: - This paper describes a simple colenoid actuator mechanism and its electronic control circuit (ECU) that allows new ac permanent magnet (PM) contactor to perform the making and breaking course without critical disadvantages imposed by the previous ac electromagnetic (EM) contactor, such that consumes much energy to hold armature, produces noise at lower voltage and their coils are easy to be burnt due to continual energization, and incurs abnormal dropouts owing to voltage sag. First, the control circuit of colenoid actuator is derived and then experimental tests are carried out to verify the effectiveness of the control circuit. Then, a theoretical model is built and the dynamic characteristic of the proposed colenoid actuator is identified. Finally, the fast transition and energy saving of the proposed ac PM contactor are demonstrated by experimental and simulation approaches.

Key-Words: - Electronic control unit (ECU), colenoid actuator, ac PM contactor, ac EM contactor, energy saving, voltage sag.

1 Introduction

As the increase in economic development, a large number of contactors are widely being used devices for making/breaking the power source of low-voltage apparatuses. In many industrial applications, the energy-saving performance of devices is often a very attractive benefit. In particular, devices must continue to run over a long time interval. A new type of ac contactor associated with a permanent magnet then has drawn more and more attention in recent years because of its outstanding benefits, such as energy-saving and noise-free characteristics etc. [1]-[3].

Unlike the ac PM contactor, the development of conventional ac electromagnetic (EM) contactors have been devoted to developing for a long time and widely used in many industrial applications. Lots of researchers have engaged in relating to theoretical and practical studies, and many valuable dynamic characteristic simulation results are presented [4]-[8] Currently, there are some undesirable problems associated with the ac EM contactor are not solved yet, for example, consumes much more energy to hold armature [9], produces noise at lower voltage, their coils are easy to be burnt due to continual working state [10], [11] and subjected to voltage sags [12]-[14].

Although much research has been devoted to the conventional ac EM contactor, however, only little work has been carried out on the dynamic characteristic simulation for an ac PM contactor [15], [16]. Fang et al. first presented a new PM actuator and its control circuit for developing a series of ac permanent magnet contactor [2], [3]. Based on charging and discharging an electrolytic capacitor, the closing and opening process of their designed new ac PM contactor are completed. Especially, according to their published report, their new ac PM contactor does not consume much energy during continual working state. However, there are some critical problems still existed in their control circuit, for example, in order to supply armature with an enough negative electromagnetic force during the opening process, a big-volume electrolytic capacitor is generally needed, a refresh circuit is commonly needed for compensating the high leakage current characteristic of electrolytic capacitor; so that the control circuit become complex and the cost is inexpensive. In similar applications, Lequesne proposed a new category of actuators that capable of providing high initial accelerations and, therefore, fast motion is achieved by using a repulsion force that a stationary energized coil can exert on a moving permanent magnet [17]. In addition, Ahn et al. developed a new electro mechanical valve system that uses permanent magnet/electro magnet (PM/EM) hybrid electro magnetic actuator and achieving the soft landing and the fast transition of the system [18]. A linear actuator with colenoid system is designed by Kim and Chang that also makes use of permanent magnet to attain a fast transition time and be suitable for the existing products [19].

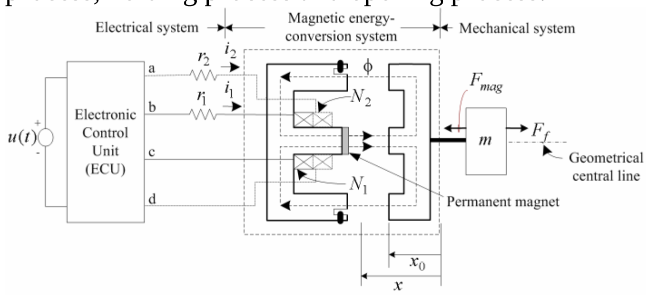
To overcome the above-mentioned drawbacks of the conventional ac EM contactor and the existed ac PM contactor, this paper aims at designing a colenoid actuator and its electronic control unit (ECU) to control the ac PM contactor. Like the reference in [2], there is a permanent magnet is arranged on the central pillar of fixed E-type core of new ac PM contactor. Since the electromagnetic force produced by the ac voltage source is dependent upon the number of windings of coil and its applying voltage source value, a large applying voltage value is adopted here for reducing the volume of breaking voltage capacitor. In the colenoid actuator, there are two types of exciting coils; the closing coil is used in the closing process, while the opening coil is used in the opening process. A voltage detector is designed in the ECU is used to monitor the operation state of ac PM contactor by reading the instantaneous ac voltage source value. Based on measured the value of ac voltage source, the ECU is then to drive the ac PM contactor in the closing process, the holding process, or the opening process. The main structure of this paper underlying the proposed ECU and its detailed operation principle will clearly be introduced. Furthermore, the feasibilities and effectiveness of the ECU and colenoid actuator in each operating process will be identified through simulation and experimental tests. For the assessment of the energy-saving performance, the proposed ac PM contactor with ECU and colenoid actuator will be compared with that of a conventional ac EM contactor.

2 Mathematical Model

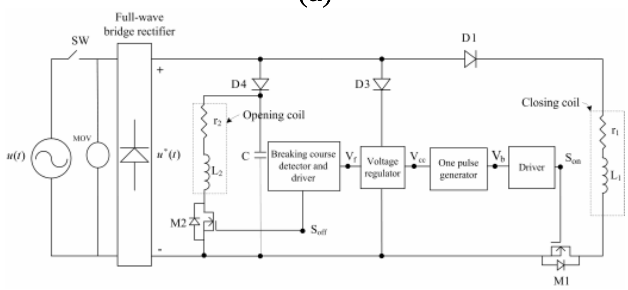
2.1 Structure and Operating Principle

As can be shown in Fig. 1(a), the mechanism of the proposed ac PM contactor includes three subsystems: such as electric system, magnetic energy-conversion system, and mechanical system. The magnetic energy-conversion system of the ac PM contactor consists of a permanent magnet, and it is arranged on the fixed E-type core, of course, it can also be arranged on armature as well [3]. This permanent magnet is made of Nd-Fe-B material; hence, its volume is small. Moreover, to decrease the energy losses, all cores existed in the magnetic circuit are made of the ferromagnetic material. Fig. 1(a) depicts a new colenoid actuator that is built in the proposed ac PM contactor is controlled by an electronic control unit (ECU). The ECU is composed of simple digital and analog hardware components, so that it is cost-effective. The contactor two sets of exciting coils, that is, closing coil N_1 and opening coil N_2. The closing coil is only driven by external ac voltage source, while the opening coil is driven by a breaking capacitor voltage. Fig. 1(b) shows the schematic block diagram of ECU. Obviously, the making course and breaking course of this new ac PM contactor is controlled by an independent control circuit.

In the following, for further explaining the operation principle of ac PM contactor and its ECU, a complete operation of an ac PM contactor is divided into three sub-processes, such as closing process, holding process and opening process.



(a)



(b)

Fig. 1. Two sketches related to ac PM contactor, (a) mechanical structure (b) schematic block diagram of ECU.

2.1.1 Closing process

In the initial state, the armature of ac PM contactor is situated at an opening position. The magnetic force, which acts on armature, only includes the permanent-magnet force. The strength of the magnetic force is insufficient for overcoming the spring anti-force, so that armature will continue to be held at the opening position. However, when the ac voltage source value is larger than the minimum closing voltage, the closing process starts and the closing coil is being energized by a rectified ac voltage source, as shown in Fig. 2. As long as the current flows through the closing coil, hence, armature is forced by a resultant magnetic force which is composed of a permanent-magnet force and an electromagnetic force. If this resultant magnetic force is large enough to overcome the spring anti-force, armature begins moving toward the fixed part of the magnetic circuit. When the movable core and the fixed core are closed together, the closing process ends. The air gap between armature and fixed core disappears; the total equivalent reluctance in the magnetic circuit is reduced significantly. The resultant magnetic force is greatly increased under the same magnetic mmf.

By applying the Kirchhoff's voltage law in the equivalent electrical circuit, as shown in Fig. 2, the voltage equation can be written as follows:

$$u^*(t) = i_1 r_1 + \frac{d\lambda_1}{dt} = \left|\sqrt{2}U_{rms}\sin(\omega t)\right| \tag{1}$$

where the rectified ac sinusoidal voltage source $u^*(t)$ is equivalent to the absolute value of the ac sinusoidal voltage source $u(t)$. The frequency of $u^*(t)$ is two times of the $u(t)$. Symbol U_{rms} represents the root-mean-square value of the ac voltage source. The mathematical expression is given by

$$\begin{cases} u^*(t) = \sqrt{2}U_{rms}\sin(wt) \\ n\pi \le wt \le (n+1)\pi, \quad n = 0,1,2,... \end{cases} \tag{2}$$

Commonly, the flux in the magnetic circuit can not be changed instantaneously [9]. Hence, the equivalent inductance shows a constant value. The expression of linkage flux $\lambda_1 = L_1(x)i_1$ is substituted into (1) and yields

$$u^*(t) = i_1 R' + L_1(x)\frac{di_1}{dt} \tag{3}$$

where the generalized resistor is defined as $R' = r_1 + (vdL_1)/dx$. Equation (3) is simply a reduced first-order differential equation. If the initial value of coil current is set to be zero, the complete response of coil current to the full-wave rectified ac sinusoidal excitation, as shown in (2), may be expressed as

$$i_1(t) = Ke^{-\frac{t}{\tau}} + \frac{V_m}{|Z|}\sin(wt + \theta - \phi) \tag{4}$$

where $V_m = \sqrt{2}U_{rms}$ is the amplitude of ac sinusoidal excitation. The first term is a transient part while the second term is a steady-state part. The time constant τ is L_1/R', the impedance $|Z|$ is $\sqrt{(R')^2 + w^2 L_1^{\,2}}$, and the power factor angle ϕ is $\tan^{-1}(wL_1/R')$, respectively. Constant K can be determined by the initial condition of coil $i_1(0) = 0$, that is

$$i_1(0) = 0 = K + \frac{V_m}{|Z|}\sin(\theta - \phi) \tag{5}$$

Thus,

$$i_1(t) = -\frac{V_m}{|Z|}\sin(\theta - \phi)e^{-t/\tau} + \frac{V_m}{|Z|}\sin(wt + \theta - \phi) \tag{6}$$

It is evident that the coil current $i_1(t)$ includes a dc offset when the circuit is being energized at a point of the wave other than at $\theta = \phi$, and this dc-offset component decays exponentially at a rate equal to L_1/R' time constant of the electric portion of contactor.

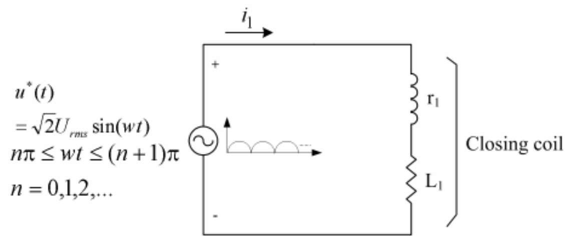


Fig. 2 The equivalent electrical circuit during the closing process.

2.1.2 Holding process

After armature has been engaged with the fixed core, the holding process of contactor begins. Because the external applied voltage source of ac PM contactor is completely cut off by ECU, of course, the ac PM contactor will not dissipate any input electrical energy. As shown in Fig. 2, in the closing process, the equivalent inductor L_1 is constant due to no armature displacement and the rectified ac voltage source $u^*(t) = 0$, so that the current flows through the coil would be decayed exponentially to zero. ECU generally need absorbs a little electrical energy so as to keep on monitoring the operating state of contactor, but total required input electrical energy is very small. Currently, the armature of ac PM contactor is held tightly at closing position only relies upon the permanent-magnet force. No noise pollution is produced at lower ac voltage source value. Their coils can not be burnt due to continual working state. No abnormal dropout results in power line disturbances like voltage sags due to the disconnection of ac voltage source.

2.1.3 Opening process

Before this process begins, an initial voltage across the capacitor C indicated in Fig. 1, named as breaking capacitor, has been charged to attain the amplitude of ac voltage source $V_{co} = \sqrt{2}U_{rms}$. Once the breaking course detector detects that the external ac voltage source is reduced to a maximum releasing voltage, this represents that the opening process begins. In the opening process, the equivalent electrical circuit is shown in Fig. 3. The opening coil is being energized by an initial voltage V_{co} across the capacitor C. The produced electromagnetic force counteracts the permanent-magnet force. The remaining magnetic force is integrated with spring anti-force in the same direction. We can see that armature will be moved back the fixed part of the magnetic circuit for increasing the isolated voltage gradient. According to the KVL, the voltage equation of the electrical circuit shown in Fig. 3 yields

$$V_{co} = i_2 r_2 + L_2 \frac{di_2}{dt} + \frac{1}{C}\int i_2 dt \tag{7}$$

where i_2 is the current flows through the opening coil, L_2 is the equivalent inductance in this process, and r_2 is the resistance of opening coil. The solution of current i_2 can be given by the following.

$$i_2(t) = \frac{V_{co}}{r_2} e^{-\frac{r_2}{L_2}t} \sin(wt) \tag{8}$$

Obviously, the coil current has a negative peak value and attenuates exponentially.

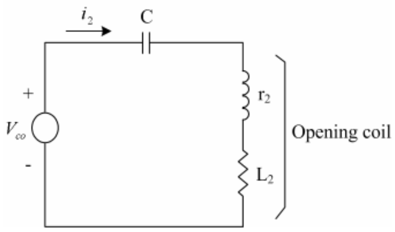


Fig. 3. The equivalent electrical circuit in the opening process.

2.2 Magnetic Field Analysis

On the basis of the mechanical structure of ac PM contactor is axial symmetrical, the magnetic model can be simplified as 2-D topology. Like the eddy current and hysteresis effects are ignored here. The behavior of the magnetic energy-conversion system is satisfied with the following equations [3]:

$$\begin{cases} \frac{\partial}{\partial x}(V\frac{\partial \vec{A}_z}{\partial x}) + \frac{\partial}{\partial y}(V\frac{\partial \vec{A}_z}{\partial y}) = -\vec{J}_s \\ \nabla \times V(\nabla \times \vec{A}_z - \vec{B}_r) = 0 \\ \vec{A}_z = 0 \end{cases} \tag{9}$$

where $\vec{A}_z$ is magnetic vector potential, $\vec{B}_r$ is residue flux density, V is the magnetic reluctivity and $\vec{J}_s$ is the current density.

2.2.1 Force analysis

According to the reference [3], in fact, no matter how the permanent magnet is arranged on the armature or the fixed part of the magnetic circuit, the effect of the permanent-magnet force upon armature is near to equal. The total resultant force, which acts on armature, includes the gravitational force, friction force, and magnetic force. Since the normal line of installation platform is commonly parallel with to the geometrical central line of contactor mechanism, as shown in Fig. 1(a), the gravitational force almost does not affect on the total resultant force; therefore, the final resultant force can be simply expressed as shown below:

$$F = F_{mag} - F_f \tag{10}$$

where F_{mag} is the magnetic force which consists of electromagnetic force and permanent-magnet force. F_f means the spring anti-force. In the closing process, F_{mag} is the addition of the electromagnetic force and permanent-magnet force and larger than the spring anti-force. In the holding process, F_{mag} is only equivalent to the permanent-magnet force, but the resultant magnetic force is still capable of overcoming the spring anti-force due to the great reduction of reluctance in the magnetic circuit. In the opening process, the electromagnetic force first counteracts the permanent-magnet force and the remaining magnetic force F_{mag} is then integrated with the spring anti-force, the armature is disengaged from the fixed part of the magnetic circuit as quickly as possible. As seen in Fig. 4, the equation governing the motion of armature is often directly formulated from Newton's law of motion.

$$F_{mag} - F_f = m\frac{d^2x}{dt^2} \tag{11}$$

where m is the mass of armature and x is armature displacement.

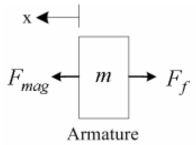


Fig. 4. Armature is viewed as a typical force-mass system.

3 Circuit

Fig. 5 shows the complete schematic diagram of the electronic control unit (ECU). As can be seen in Fig. 5, the ECU only includes simple digital and analog components. The operation of ECU is determined by the voltage value detector. The control circuit is designed for controlling the closing process is independent of the one for the opening process. The remainder of this section describes the operation of the electronic control unit. Each functional block shown in Fig. 5 is described in a separate paragraph.

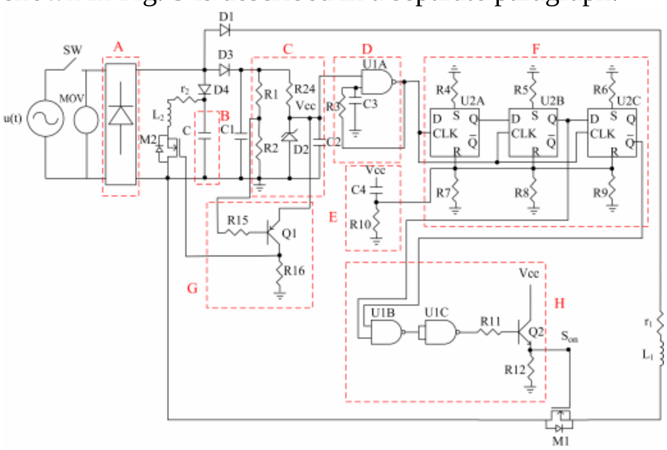


Fig. 5. Schematic diagram of completed electronic control unit (ECU).

(1) Rectifier

Operating from an ac sinusoidal voltage source $u(t)$ full-wave bridge rectifier, as indicated in Fig. 5, is equipped with the input portion of the ECU. It is responsible for converting the ac sinusoidal voltage source to a pulse dc voltage $u^*(t)$, as denoted in Fig. 1. The rectified ac voltage source $u^*(t)$ has the same amplitude as the external ac voltage source. However, the frequency of the former is two times of the latter. A metal-oxide varistor (MOV) is arranged to parallel with the rectifier and used to prevent transient over-voltage in ac voltage source from damaging the ECU.

(2) Breaking capacitor

The breaking capacitor C is charged by the rectified ac voltage source through a diode D4. The charged voltage across the breaking capacitor, abbreviated breaking voltage, should be approximately equivalent to the peak value of $u(t)$ or

$$V_{co} = \sqrt{2}U_{rms} \tag{12}$$

The breaking capacitor C stores the energy that is required to open the ac PM contactor. The reverse electromagnetic force value is determined by the charged voltage value across of breaking capacitor C and the number of windings of coil. So that, we can see that these two factors determine the length of transition time during the opening process.

(3) Voltage regulator

As indicated in Fig. 5, if the ECU is anticipated to work normally, a stable and fixed dc voltage source is required. Fig. 5 shows an electrolytic filter capacitor C1 that is used to convert the pulse dc voltage $u^*(t)$ to a relatively ripple-free dc voltage. In addition, a resistor with fixed resistance is integrated with a zener diode to form a simple voltage regulator. As long as the rectified ac voltage source is high enough to make the zener-diode break down. The voltage Vcc across the zener diode D2 should be held a constant value.

(4) Clock generator

As the part D indicated in Fig. 5, it shows that the clock generator includes a resistor R3, a capacitor C3, and a NAND-gate U1A. If the fixed dc voltage source Vcc is achieved, the clock generator begins producing a series of clocks. These clocks are served as the reference clock of single pulse (ON-time) generator.

(5) Reset circuit

The reset circuit a differential circuit which only consists of a capacitor C4 and a resistor R4, as the part E shown in Fig. 5. In the establishing process of dc voltage source Vcc, a logical high signal will be produced by this reset circuit. This reset signal is used to initialize all the output of the shift register in ON-time generator to logical low level.

(6) ON-time generator

As mentioned earlier, the output of the clock generator is a series of clocks, that is, logical-level square waves. They are served as the reference clock of the ON-time generator for generating a logical single pulse V_b over a period of time. This logical single pulse is amplified by transistor Q2 and then used to turn on the power MOSFET M1. Thus, the contactor begins conducting the closing process. As seen in Fig. 5, ON-time generator contains three D-type Flip-Flops and six fixed resistors. The total ON-time calculation is based on the frequency or period value of clock generator. Once the dc voltage source Vcc is present, clock generator is then enabled. The output frequency f of clocks is determined by the value of resistor R3 and capacitor C3.

(7) Breaking course detector and driver

In fact, the breaking course detector in ECU is implemented by a transistor-based comparator. It is composed of two fixed resistors, R15 and R16, and a PNP-type transistor Q1. When the external ac voltage source is removed, the base voltage of transistor Q1 which across the fixed resistor R2 must be reduced immediately. However, since the zener diode is parallel with a filter capacitor C2, therefore, the decaying speed of dc voltage Vcc (i.e. the emitter voltage of transistor Q1) should be slower than the base voltage of transistor Q1. Hence, during a period time, the emitter voltage is larger than the base voltage. The transistor Q1 begins to conduct. A voltage signal S_{off} across the resistor R16 is produced and its value near to the dc voltage value. It is used to drive the power MOFFET M2 to conduct. Thus, the breaking course of contactor starts.

(8) Making course and driver

After the dc voltage value Vcc has been fixed and stable, the reset circuit produces a logical high level signal to initialize the states of all shift registers (ON-time generator). The combinational state of shifter register is shifted from the initialized state and counted in turn. All the possible state transitions are displayed in Table 1, 1 and 0 represent logical high and low levels, respectively. From the state machines shown in Table 1, we can see that if state 2 (Q1Q2Q3=110) occurs, there is a logical high level one pulse V_b (refer to Fig. 1) is produced. As the part H shown in Fig. 5, V_b is amplified by the transistor Q2. The ON-time pulse S_{on}, namely the voltage across the resistor R12, is produced to turn on the power MOSFET M1 and the closing process starts.

4 Tests and Discussions

For convenience, an experimental contactor prototype, which is manufactured by a famous company, Shilin, has been established in our laboratory. The contactor is allowed to be applied with a rated rms voltage 220 V of voltage source. Type of contactor is S-C21L. The contact capacity is 5.5 KW and the nominal value of the coil current is 24 A. The number of windings is 3750 turns, the coil resistance is 285 Ω, and the mass of armature is 0.115 Kg. The contact's gap is 4 mm. The air gap between movable core and fixed part in the magnetic circuit is about 6 mm. In addition to the laboratory tests over the ac PM contactor prototype are performed, this paper presents a simulation model using the Matlab/Simulink software tool, in which both simulation model and experimental prototype can show the behaviors of the ac PM contactor during the closing, holding and opening processes, respectively. Then, the independent variable curve is constructed to identify the characteristics of the ac PM contactor in each of operating process. The curves obtained from the experiment are compared with the ones obtained from the simulation. This comparison is essential in order to verify the correctness of the developed ac PM contactor model used in the simulation.

Table 1.
States Machine of ON-time Generator

State	Q1	Q2	Q3	Output
Initial state	0	0	0	No
State 1	1	0	0	No
State 2	1	1	0	Yes
State 3	1	1	1	No

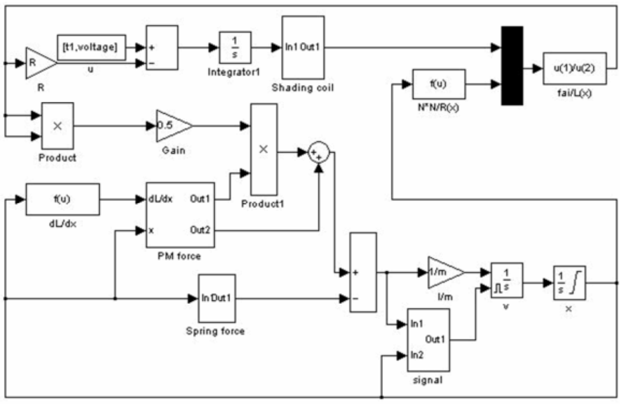


Fig. 6. Simulation model of proposed ac PM contactor model.

4.1 Establishment of Simulation Model

The dynamic simulation model of contactor is established by means of governing equations of proposed ac PM contactor [20], [21]. Moreover, the moving velocity of armature is the derivative of armature displacement, i.e. $v = dx/dt$. First, individual simulation modules are established respectively and then combined with each other in proper order and results in a complete ac PM contactor model, as shown in Fig. 6.

4.2 Simulation and Experimental Tests

During the closing process, the produced permanent-magnet force is integrated with the electromagnetic force to form a hybrid magnetic force. This hybrid magnetic force first overcomes the spring anti-force and then forces armature to engage with the fixed core over a fast transition time. Regardless of the transition is during the closing process or opening process. The transition time in ac PM contactor is generally shorter than the one in ac EM contactor. Moreover, the proposed ac PM contactor has two coils; however, the conventional ac EM contactor only has one coil. In the following, for an ac PM contactor is controlled by ECU, the dynamic behaviors will be evaluated and discussed by using the simulation and experimental testing results. In addition, the difference between simulation model and experimental prototype will be explored as well.

4.2.1 Closing process

As the simulation model shown in Fig. 6, the ac PM contactor model is directly applied by a pulse dc voltage or rectified sinusoidal excitation voltage source $\left|\sqrt{2}U_{rms}\sin(wt)\right|$, a simulated coil current is then obtained. In addition, the same pulse dc voltage is also supplied with the experimental prototype; a measured coil current is obtained as well. For convenient comparison, the measured and simulated coil currents are together diagrammed in Fig. 8. The average difference between simulated and measured coil current is below 10% of the measured coil current value, so that stands for the accuracy of the computer simulation model of ac PM contactor is acceptable. As time-varying curve of coil voltage shown in Fig. 7, ac PM contactor is being energized at time 0.018 second. At the moment, the electromagnetic force value is zero; so that armature is stationary due to the permanent-magnet force can not overcome spring anti-force yet, time-varying force curves demonstrated in Fig. 9 also verify this result. In Fig. 8, after the time 0.02 second, the coil current begins increasing, the resultant magnetic force, which is the combination of electromagnetic force and permanent-magnet force, is high enough to overcome spring anti-force; armature begins to move forward to the fixed core of the magnetic circuit. This phenomenon can also be identified by time-varying armature displacement curve shown in Fig. 10.

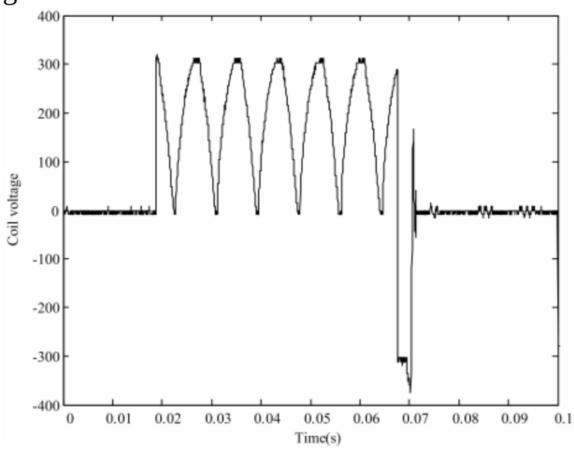


Fig. 7. Time-varying coil voltage curve during the closing process.

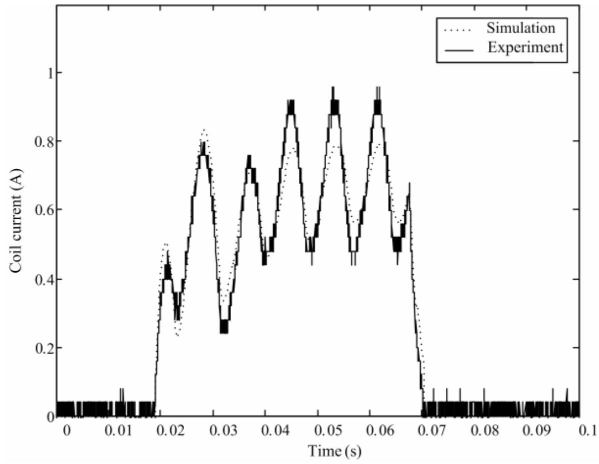


Fig. 8. Time-varying coil current curve during the closing process.

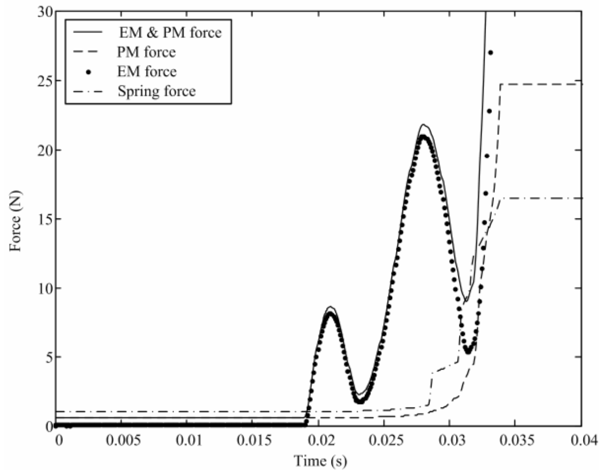


Fig. 9. Time-varying magnetic force curve during the closing process.

4.2.2 Holding process

After the time about 0.03 second, the armature displacement shown in Fig. 10 denotes the armature has completely engaged with the fixed core. From time-varying coil voltage and coil current curves as seen in Figs. 7 and 8, the ac PM contactor is still applied a ac voltage source over a time interval from 0.03 second to 0.065 second, coil current is also a sinusoidal waveform and its phase angle lagging the coil voltage by about 90 degree. Since the air gap in the magnetic circuit is removed, the reluctance is then reduced greatly and the inductance is independent of the time. In contrast, Fig. 9 shows the permanent-magnet force is significantly increased and larger than spring anti-force as well. In spite of the electromagnetic force is removed due to the disconnection of external voltage source (i.e. contactor coil), armature only depends upon the remaining magnetic force or the permanent-magnet force is sufficient to overcome spring anti-force. Thus, armature will be held tightly with the fixed core. Although there is a little input electrical energy is dissipated in ECU, the percentage is small. This is the reason why the energy-saving performance of this new ac PM contactor is superior to the conventional ac EM contactor.

Fig. 9 clearly indicates the remaining magnetic force or the permanent-magnet force in the holding process is much larger than spring force anti-force as well, therefore, the armature is attracted tightly. Abnormal statuses, like voltage sag, low-voltage disengagement and mechanical vibration, do not influence upon the closing state of ac PM contactor.

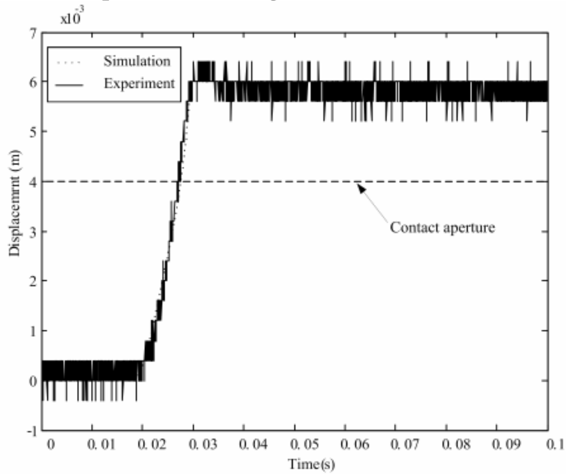


Fig. 10 Time-varying armature displacement curve during the closing process.

4.2.3 Opening process

Before the opening process begins, the voltage across the capacitor C, i.e. breaking voltage, should be charged approximately about $\sqrt{2}U_{rms}$. If the ac PM contactor is assumed to be opened at time 0.068 second, thus, the breaking capacitor C is being discharged through the opening coil. The initialized voltage across breaking capacitor V_{co} is decayed exponentially at a rate of time constant of the equivalent electrical circuit of ac PM contactor model, as indicated in Fig. 11. Fig. 12 shows the coil current almost has the same variation as the coil voltage. As depicted in Figs. 11 and 12, the coil voltage and coil current are negative value. Hence, the electromagnetic force is produced by the breaking-capacitor voltage is also a negative value. Its value depends upon the number of windings of opening coil and the initialized breaking-capacitor voltage value. It is responsible for counteracting the permanent-magnetic force and in compliance with spring anti-force to open the contactor. As can be seen in Fig. 14, the resultant magnetic force value at time 0.105 second begins to be lower than spring anti-force value, so that armature begins disengaging from the fixed core, this phenomenon can be viewed from the time-varying armature displacement curve in Fig. 13 as well.

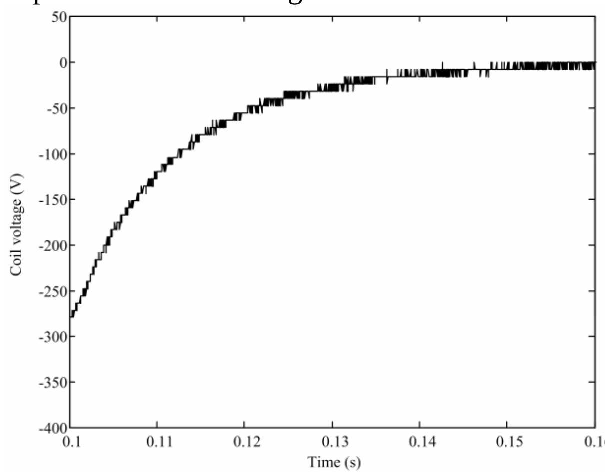


Fig. 11. Time-varying coil voltage curve during the opening process.

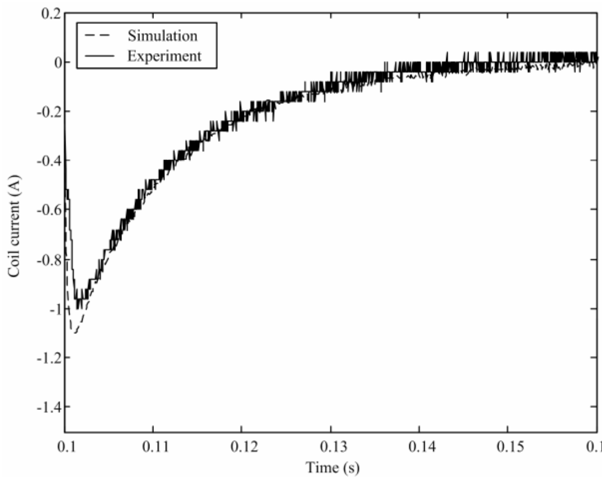


Fig. 12. Time-varying coil current curve during the opening process.

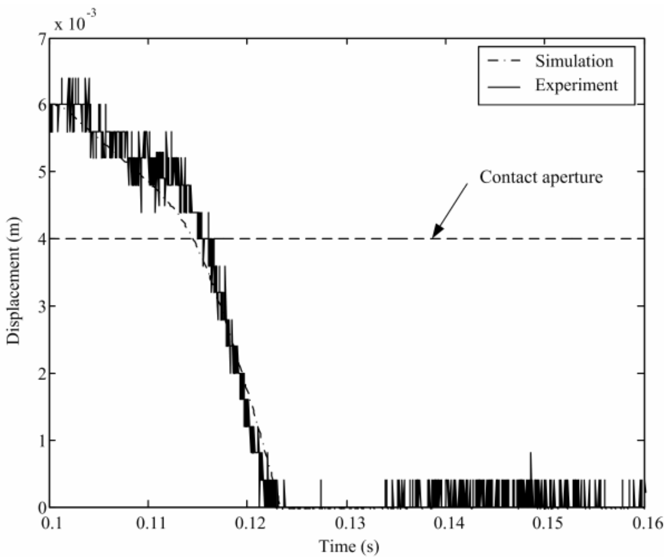


Fig. 13. Time-varying armature displacement curve during the opening process.

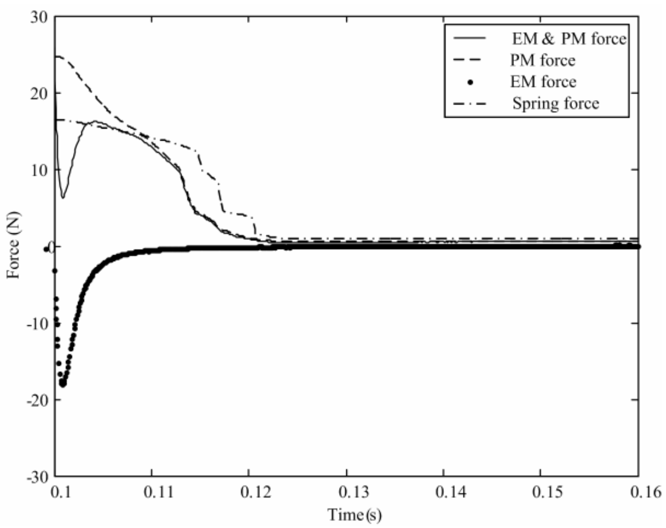


Fig. 14. Time-varying force curves during the opening process.

4.3 Assessment of Energy Saving

Energy-saving characteristic is one of the important advantages of proposed ac PM contactor. As listed in Table 2, both proposed ac PM contactor and conventional ac EM contactor are assumed to be operated in the holding process for one year. The total energy dissipated in ac PM contactor is only 27% of that in ac EM contactor. Moreover, the number of coils equals 2000 turns, which is almost half of the currently needed coil windings of ac EM contactor. In other words, both the energy-saving and material-saving results are capable of being obtained simultaneously by using developed ac PM contactor.

Table 2
Energy saving comparison between ac EM contactor and ac PM contactor.

Item	EM type	PM type
Voltage (V)	220	220
Coil current (A)	0.0791	0.0138
Volt-Ampere (VA)	17.402	3.0360
Total energy (KWH)	152.44152	26.5953
Fee (NT dollars)	457.32456	79.7860

4 Conclusions

This paper presents a new magnetic mechanism at which a permanent magnet is arranged on the E-type fixed core of magnetic circuit. There are two coils, such as closing coil and opening coil, are wound on the E-type fixed core. In addition, in order to control the operation of new ac PM contactor, a cost-effective ECU is designed and implemented by hardware circuit which is only made of simple and inexpensive digital and analogue components. Through ECU and permanent-magnet force are involved, compared with ac EM contactor, the transition time of proposed ac PM contactor is shortened. In particular, based on the voltage source of contactor coils is completely interrupted during the holding process, such that much electrical energy is saved, no noise pollution is produced at lower voltage, coils can not be burnt due to continual working stage and no voltage sag event results in abnormal dropout. Moreover, since the breaking voltage across the breaking capacitor is almost charged to the amplitude of ac voltage source before opening process starts, thus, only a small-volume breaking capacitor is satisfactory. The feasibility of ECU and effectiveness of new magnetic mechanism are validated through the simulation and experimental tests. From the simulation and experimental results, we can see that the function of ECU actually agrees well with the predicted operation of ac PM contactor.

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