# Design and Implementation of a New Permanent Magnet AC Contactor with Colenoid Actuator

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*Abstract:* - This paper focuses on presenting a new permanent magnet with colenoid actuator for the purpose of reducing the energy dissipation during a complete operation. The methodology developed is a hardware based approach. It emphasizes on minimizing the cost of operation over a specified time period rather than a fixed operating point. The practical operating concerns of proposed ac permanent magnet (PM) contactor and the coordination with a new actuator are also addressed. The developed ac PM contactor has been implemented as a prototype grade product. Test results on the experimental prototype and computer simulation model show that the energy-saving performance of this newly developed ac PM contactor is effective and feasible.

*Key-Words:* - AC PM contactor, permanent magnet, energy saving, simulation model, experimental prototype, actuator.

# **1** Introduction

In recent years, contactors have been widely used in many industrial applications for making and breaking the load current with the use of their contacts. No matter what ac or dc electromagnetic contactors are used. A great amount electric energy will be dissipated by these contactors. As the energy problem impacts the people life is increasing, attempting to find a new type of contactor with outstanding energy saving performance is devoted to more and more attention.

For a conventional ac electromagnetic (EM) contactor, both the armature and the fixed iron core commonly need to be hold by electromagnetic force during holding process. Therefore, several critical disadvantages, such that consumes lots of energy to hold the armature, produces noise at lower voltage and their coils are easy to be burnt due to continual working state. To overcome above mentioned disadvantages of the conventional ac EM contactor, the newly developed actuator is increasingly applied in the development of the ac permanent magnet (PM) contactor.

As a result of several outstanding benefits with the ac PM contactor, such as energy saving, no noise pollution, and no voltage-sags dropouts, the development related to new type of permanent magnet has attracted many researchers' attention [1-4]. Most of the past researching work is focused on the conventional ac EM contactor, such that making use of the finite element method to analysis the response of the magnetic coupling field [5-8], reduces the average bounce-duration after contacts closing [9-16], and so forth. However, little information is available on the development of new ac PM contactor.

In order to design an newly actuator with high energy-saving performance, its magnetic field and electromagnetic force acts on the armature at any armature displacement should be first accurately analyzed and computed. The main purposes of this paper aims at developing a newly actuator with hardware based electronic control module and comparing the energy-saving performance between the conventional ac EM contactor and the proposed newly ac PM contactor. The computer simulation and experimental results of the proposed ac PM contactor are provided.

# **2** Principle of Operation

Fig. 1 shows the sketch of the proposed ac permanent magnet contactor. In addition to a permanent magnet, two exciting coils, and a needed electronic control module are included in the configuration; the other mechanisms are almost the same as the conventional ac electromagnetic contactor. After the making course of the proposed

ac permanent magnet contactor (abbreviated ac PM contactor) has been completed, in principle, the armature is engaged with the fixed iron core and to be hold tightly. Therefore, during holding process, almost there is no any electrical energy is absorbed by the ac PM contactor. The energy-saving performance of the proposed ac PM contactor is often superior to the other types of contactor. In addition, to satisfy with the operation of the proposed ac PM contactor, an actuator with electronic control module (ECM) is included in the mechanism. The purpose of the ECM is not only provide the controlled ac PM contactor with making/breaking commands, but also need to supply with a breaking voltage during breaking course. Two exciting coils are designed in the central leg of the E-type fixed iron core, one of the coils, coil 1 is called as closing coil and used to be energized during closing process, while the other one coil, coil 2, is called as opening coil and used to be energized during opening process.



Fig. 1. Sketches the mechanism of the proposed ac PM contactor.

When an ac voltage source is applied to the ac PM contactor, the ac sinusoidal excitation is rectified and converted into a pulse dc voltage source  $V_o$ . This rectified pulse dc voltage source is, on one hand, directly used to drive the contactor coil; on the other hand, it is again regulated to be dc voltage source with a fixed voltage,  $V_{cc}$ , which is used to supply with the voltage source of the control circuits including in the ECM. As the functional block diagram of the proposed ac PM contactor shown in Fig. 2, during making course, the coil voltage is controlled by switching the power MOSFET M1. The driving signals are generated by a hardware circuit, called as single pulse generator. The maintaining time of signal S<sub>on</sub> which is obtained

from a logical signal V<sub>b</sub> is amplified during the power MOSFET M1 switched on is about 30 ms. As the driving signal of the S<sub>on</sub> becomes low voltage, the power MOSFET M1 is switched off, the electromagnetic flux is removed and the permanentmagnet flux becomes the only remaining magnetic flux in the magnetic circuit. Fortunately, the total reluctance in the magnetic circuit is reduced greatly due to the engagement of the contacts. So that the remaining permanent-magnet flux is sufficient to overcome the spring anti-force and the armature is then to be hold tightly with the foxed iron core. When the ac voltage source is cut off, a breaking information  $V_f < V_{cc}$  will be detected by a breaking detector which is built in ECM. There is a logical breaking signal is produced by the breaking detector and again amplified by a transistor driver yields the driving signal of the breaking power MOSFET M2, Soff . During power MOSFET M2 switched on, the opening coil is energized by a breaking voltage supplied from an electrolytic capacitor, called as breaking capacitor. Since the spring anti-force is overcome by the electromagnetic force in the reverse direction, the armature disengaged from the fixed iron core and moved back to the opening position.

Compared with the conventional ac electromagnetic contactor, the new design of actuator using permanent magnet excitation needs no electric power in the holding process during the holding force of the permanent magnet. The coil current is required only at the starting and ending transition stages. Fig. 3 shows the current command profiles with the operation in the conventional ac contactor and the newly designed colenoid system with permanent magnet excitation. During closing process, the transition time in the proposed ac PM contactor is shorter than that in the conventional ac electromagnetic contactor due to the permanent magnet excitation. After contacts closing, the armature of the proposed ac PM contactor is tightly engaged with the fixed iron core relies upon the holding force of permanent magnet. Little electric power energy is absorbed by the ac PM contactor. In contrast, the conventional ac electromagnetic contactor needs to produce an electromagnetic force with the use of some electric energy for keeping on holding the closure status between the iron cores of the electromagnetic contactor. Finally, when the maximum releasing voltage is detected by the contactor, the conventional ac electromagnetic contactor as long as relies upon the spring tension force, the iron cores is disengaged from each other. However, the newly proposed ac PM contactor should be first applied an inverse electromagnetic force to counteract the holding force of the permanent magnet. To wait the armature moves

away the fixed iron core till the total reluctance in the magnetic becomes large enough. The inverse



Fig. 2. Shows the electronic control module with functional block diagram.



(a)



(b)

Fig. 3. Current command profiles with the operation (a) conventional ac electromagnetic contactor (b) newly developed ac PM contactor.

electromagnetic force is combined with the spring tension force, so that the proposed ac PM contactor will be hurried to open in the later stage of the opening process. From the current command profiles shown in Fig. 3, we can see that the more time the proposed ac PM contactor is operated in the holding process, the more evident the energy-saving performance is.

# **3** Mathematical Models

As the configuration of the proposed ac PM contactor shown in Fig. 4 is composed of an electrical system, a magnetic energy-conversion system and a mechanical system. The exciting coil consists of two sets of coil. One of the coils is called as closing coil is responsible for energizing the ac PM contactor to produce a positive electromagnetic force. It is integrated with the holding force of the permanent magnet for the closing operation of the contactor. The other one coil is called as opening coil is used to energize the ac PM contactor to produce a negative electromagnetic force. This inverse electromagnetic force is first used to counteract the holding force and then is incorporated into the spring tension force for the opening operation of the contactor. For convenience, all the loss produced in the magnetic energyconversion system is assumed to be considered in terms of the loss in both electrical system and the mechanical system. In addition, assuming this magnetic coupling field is conservative. In order to explore the equivalent mathematical model of the proposed ac PM contactor in each of operation processes, one complete operation process of the proposed ac PM contactor is partitioned into three sub-processes.



Fig. 4. Sketches the configuration of the newly proposed ac PM contactor.

#### 3.1 Closing process

By applying the Kirchoff's voltage law, KVL, to the electrical system of the proposed ac PM contactor indicated in Fig. 5, the voltage equation is obtained and presented below:

$$u'(t) = i_1 r_1 + \frac{d\lambda_1}{dt} = \left| \sqrt{2} U_{rms} \sin(\omega t) \right|$$
(1)

where the flux linkage  $\lambda_1$  is equivalent to the inductance times the coil current.  $U_{rms}$  is the rms value of the ac voltage source.  $r_1$  is the resistance included in the coil and conductors.  $i_1$  is the current flows through the closing coil. The rectified ac voltage source u'(t), in principle, is the coil voltage while the ac PM contactor is energized and it can be expressed over a period time as follows:

$$u'(t) = \begin{bmatrix} \sqrt{2}U_{rms}\sin(wt) \\ when \ 2n\pi \le wt \le (2n\pi+1)\pi, \ n = 0, 1, 2, \dots \\ and \\ 0 \\ when \ otherwise \end{bmatrix}$$
(2)

Substituting (2) into (1), and the initial coil current is set to be zero. The complete solution of the coil current over a period of ac voltage source as shown below:

$$i(t) = \frac{\sqrt{2}U_{rms}}{\sqrt{r_1^2 + w^2 L_1^2}} \left[ \sin(wt - \delta) + \sin(\delta)e^{-\frac{r_1}{L_1}t} \right]$$
(3)

where the angle  $\delta$  is defined as  $\tan^{-1}(wL_1/r_1)$ .



Fig. 5. Shows the equivalent electrical circuit of ac PM contactor during closing process.

#### **3.2 Holding process**

After the armature has engaged with the fixed iron core, the holding process of the proposed ac PM contactor begins. As long as the permanent-magnet force exists, the resultant magnetic force acts on the armature is sufficient to overcome the spring antiforce. Even though the ac voltage source is removed, the armature is also hold tightly. Therefore, there is no any ac voltage source is applied to the closing coil or the opening coil.

#### 3.3 Opening process

As can be seen in Fig. 2, as the proposed ac PM contactor is applied to an ac voltage source, the electrolytic capacitor C is charged through a diode D4. The voltage across the capacitor C is approximately equivalent to the amplitude of the ac voltage source, that is

$$V_{co} = \sqrt{2}U_{rms} \tag{4}$$

During opening process, the ac voltage source is cut off. No external voltage source can be provided to the contactor again. The voltage across the capacitor C is charged in advance and used to provide with the opening coil for producing a reverse electromagnetic force to counteract the holding force of the permanent magnet excitation. Therefore, this capacitor C is also called as breaking capacitor and the voltage across the capacitor C is called as breaking voltage, it equals  $V_{co}$  here. The equivalent circuit of the electrical system during opening process is corresponding to a RLC circuit and shown in Fig. 6. By KVL, the voltage equation is given below:

$$V_{c0} = i_2 r_2 + L_2 \frac{di_2}{dt} + \frac{1}{C} \int i_2 dt$$
 (5)

where  $i_2$  is the current flows through the opening coil,  $L_2$  is the inductance and  $r_2$  is the resistance of both the coil and conductors.

$$i_2(t) = CV_{co}(\frac{1}{q}+q)e^{pt}\sin qt$$
 (6)

where the symbols p and q are respectively defined as below:

$$p = -\frac{r_2}{2L_2}$$
,  $q = -\frac{r_2}{2L_2}\sqrt{\frac{4L_2}{r_2^2C}-1}$  (7)



Fig. 6. Shows the equivalent electrical circuit of ac PM contactor during opening process.

#### **3.4 Motion governing equation**

By employing Newton's law of motion, the motion governing equation in the mechanical system can be described as follows [17]:

$$\frac{d^2x}{dt^2} = \frac{F_{mag} - F_f}{m} \tag{8}$$

where the  $F_{mag}$  and  $F_f$  are the resultant magnetic force and the spring anti-force, respectively. *m* is the total mass of the armature. In addition, the moving velocity of armature during closing and opening processes is given by the derivative of the armature displacement *x*, that is v = dx/dt. Assuming the work done by the mechanical system  $W_m$  can be written in terms of the integral of the resultant magnetic force  $F_{mag}$  with respect to the differential armature displacement dx. Namely,

$$W_m = \int F_{mag} dx \tag{9}$$

Moreover, the input electrical energy of the ac PM contactor can be given by the integral of the flux linkage  $\lambda$  with respect to the differential coil current *di* and written as follows:

$$W_e = \int \lambda di \tag{10}$$

As mentioned in the preceding section, since the magnetic energy-conversion system is assumed to be conservative and lossless, hence, both (9) and (10) should be equal in magnitude. Therefore, the resultant magnetic force  $F_{mag}$  is the derivative of the mechanical work with respect to the differential armature displacement dx.

$$F_{mag} = \frac{\partial W_m}{\partial x} = \frac{1}{2}i^2 \frac{\partial L(x)}{\partial x}$$
(11)

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### **4** Circuits

Fig. 7 shows a complete electronic control circuit, it is referred to as an electronic control module (ECM) here. As indicated in Fig. 7, ECM is merely composed of some simple digital and analog components. The operation of ECM is determined by the instantaneous voltage across the two terminals of the coil. The designing purpose of the ECM is integrated with two exciting coils to form an actuator for driving the breaking or making course of the proposed ac PM contactor. By taking the energy saving into consideration, the proposed ac PM contactor is only driven by the ECM during closing and opening processes, but does not be driven during holding process. The remainder of this section describes the operation of the ECM. Each functional block shown in Fig. 7 will be described in a separate paragraph.

#### **4.1 Rectifier circuit**

Operating from an ac sinusoidal voltage source u(t), a full-wave bridge rectifier, as indicated the part A in Fig. 7, is equipped with the input portion of the ECM. It is responsible for converting the ac sinusoidal voltage source into a pulse dc voltage u'(t). The rectified ac voltage source u'(t) has the same amplitude as u(t). However, the frequency of the former is two times of the latter. A metal-oxide varistor (MOV) (it is not drawn in Fig. 7) is connected with the full-wave bridge rectifier in parallel. The installing objective of this MOV is to prevent transient over-voltage in ac voltage source from damaging the ECM.

#### 4.2 Breaking capacitor

When the external ac voltage source is applied to the ac PM contactor, it is similar to the SW is turned on shown in Fig. 7, the electrolytic capacitor C will be charged a voltage  $\sqrt{2}U_{rms}$  through the diode D4, as seen the part B in Fig. 7. Since this charged voltage will be used to the breaking course of the ac PM contactor, thus, it is referred to as breaking capacitor. To overcome the holding force of the permanent magnet, sufficient inverse а electromagnetic force is needed. As the representation of the electromagnetic force depicted in (11), it depends upon the coil current and the number of windings of opening coil. In addition, from the expression of opening coil current shown in (6), the current flow through the opening coil is again determined by the breaking voltage. Here, the designed breaking voltage is approximately equivalent to the amplitude of the ac voltage source.

#### 4.3 Voltage regulator

As indicated the part C in Fig. 7, in fact, part C includes two aspects: the first aspect is the coil-voltage detector. It is composed of resistors R1 and R2 and they are connected in series. The second aspect is related to the dc voltage regulator. It consists of a fixed resistor Rz, a zener diode D2 and a capacitor C2. If the ac voltage source is

established, the rms value of rectified dc voltage is much larger than the zener diode voltage and results in the zener diode breakdown. A constant zener voltage Vcc is produced across the zener diode. An electrolytic capacitor C2 is connected with the zener diode in parallel and used to act as a voltage buffer.

#### 4.4 Clock generator

As seen the part D in Fig.7 shows the clock generator of the ECM. It consists of a NAND gate, a fixed resistor R3 and a capacitor C3. The output of the clock generator is provided to the making signal generator for its reference clock input. The frequency of the clock-generator output is determined by the values of both the capacitor C3 and the fixed resistor R3.

#### 4.5 Reset circuit

As shown the part E in Fig. 7, there are a fixed resistor R10 and a capacitor C4 to form a reset circuit. When the external ac voltage source is applied and the dc voltage source is established as well, the reset circuit, that is a high pass circuit, produces a logical high signal and maintaining a time interval. The produced signal of the reset circuit is aimed at initiating the action of the making signal generator. After the making signal generator

has been initialized, the making signal generator begins working.

#### 4.6 Making signal generator and driver

After the dc voltage value has been established and the making signal generator is initialized, that is all the outputs of the three shift registers are cleared to the initial state of making signal generator. The next action of the making signal generator that follows the clock reference input. All the transitions related to making signal generator are listed in Table 1. At state 2, that is Q1Q2Q3=110, the NAND gate U1B outputs logical high signal over a period of time. The driving capacity of this logical high signal is again strengthened by a transistor Q2 and finally obtains a power MOSFET driving signal S<sub>on</sub>.

#### 4.7 Breaking signal generator and driver

Before opening process starts, a breaking voltage across the electrolytic capacitor C8 should be charged to the amplitude of ac voltage source, that is  $\sqrt{2U_{rms}}$ . If the coil voltage value is lower than the maximum releasing voltage of the ac PM contactor and leads to the base voltage is lower than the emitter voltage of the transistor Q1, the transistor Q1 begins conducting and there is a voltage across the fixed resistor R14 is produced, that is the breaking signal produced for driving the power MOSFET M2 to switch on.

Table 1. Truth table of the making signal generator.

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



Fig. 7. Shows the schematic electrical circuit of the electronic control module (ECM).

### **5** Tests and Discussions

For conducting the relevant experiments, an experimental contactor prototype and a computer simulation have been established in our laboratory. This experimental contactor prototype is allowed to be supplied with a rated rms voltage 220 V of ac 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  $\Omega$ , and the armature mass is 0.115 Kg. The aperture between the movable contact and the fixed contact is 4 mm. The air gap between the movable iron core and the fixed iron core in the magnetic circuit is about 6 mm. A permanent magnet is arranged on the central leg of the E-type armature.

# 5.1 Permanent-magnet affections during making course

Fig. 8 shows the testing rig of the permanentmagnet force versus the armature displacement curve. The permanent-magnetic force is measure by a force gauge, while the armature displacement is synchronously and indirectly measured by a laser position sensor. Each of differential armature displacement, the permanent-magnet force acts on the armature and the corresponding armature displacement are read and recorded. After the closing path of has been conducted, with the use of curve fitting technique to the recoded the permanent-magnet force and the corresponding armature displacement data. The static permanentmagnet force versus the armature displacement curve is then obtained.





Fig. 8. Demonstrates the testing rig designed for the measurement of the permanent-magnet force versus the armature displacement, (a) side view and (b) frontal view.

The holding force of permanent magnet force, electromagnetic (EM) force, spring anti-force, and the PM and EM hybrid force are together diagrammed by time-varying curves in Fig. 9. Obviously, if the ac PM contactor simply relies upon the permanent-magnet force, it is impossible to attract the armature moves towards the fixed iron core. Therefore, the PM force should be combined with another EM force leads to the hybrid force. This hybrid force is large enough to overcome the spring anti-force.



Fig. 9. Plots the time-varying curves, (a) armature displacement and (b) each type of force.

# **5.2** Characteristic behaviours in both ac EM contactor and ac PM contactor

In order to realize the characteristic differences between ac EM contactor and ac PM contactor, individual contactor model is setup. Fig. 10(a) shows the computer simulation model of the conventional ac EM contactor. In contrast, Fig. 11(a) shows the computer simulation model of the proposed ac PM contactor. When an ac sinusoidal excitation was applied to input of the ac EM contactor model, Figs. 10(b) to 10(d) indicated the time-varying curves of the armature displacement, the coil current, and the electromagnetic force and spring tension force. On one hand, from the curves difference between the experimental results and the simulation results shown in Figs. 10(b) and 10(c) is lower than ten percentages of the average of the experimental results; the accuracy of the ac EM contactor model is verified to be acceptable. On the other hand, the coil current is also a sinusoidal waveform and the frequency is the same as the ac voltage source. The coil-current value attenuates exponentially with time. The stationary coil current during holding process is smaller than that during closing process. From the time-varying force curves shown in Fig. 10(d) depicts no movement in the armature before time 0.025 sec because the electromagnetic force is insufficient to overcome the spring tension force. Moreover, during closing process, the electromagnetic force acts on the armature is exactly allowed to be lower than the spring tension force.

Furthermore, in a similar manner as mentioned above, the feasibility of the ac PM contactor model is validated and shown in Figs. 11(b) to 11(g). Here, the coil current and the armature displacement are selected as the independent variables. The operating characteristic of the ac PM contactor during a complete operation is characterized by three subdivisions, such as the closing process, the holding process, and the opening process. Compared the closing time of the ac EM contactor illustrated in Fig. 10(b) with that of the ac PM contactor shown in Fig. 11(b), the latter is merely the half the former. This means that ac PM contactor has the more fast transition from the opening position to the holding stage. During holding process, there is small current approximating to zero flows through the coil, as the time-varying coil-current curve shown in Fig. 11(e). Since the input electric energy only supplies with the ECM, but not the contactor body, this is also the common reason why the little energy is absorbed by the ac PM contactor. During opening process, the time-varying armature displacement curve shown in Fig. 11(f) indicates that a short transition time is needed to complete the opening process. A Lenz's induced voltage is produced across the opening coil is incorporated into the breaking voltage is applied to the opening coil, the current flows through the opening coil in the negative direction. An inverse electromagnetic force is produced to counteract the holding force of the permanent magnet. The remaining electromagnetic force is combined with the spring anti-force to make the armature return to its initial opening position as quickly as possible.







Fig. 10. Illustrates the characteristics of the conventional ac electromagnetic contactor, such that (a) is the completed simulation model, (b) shows the armature displacement, (c) shows the coil current, and (d) shows the spring anti-force and the electromagnetic force.











Fig. 11. Illustrates the coil current and the armature displacement of the newly proposed ac PM contactor, such that (a) is the completed simulation model, (b) and (c) show the closing operation, (d) and (e) show the holding operation, and (f) and (g) show the opening operation.

#### **5.3 Energy-Saving performance**

Testing rigs shown in Fig. 12 aims to measure the electric energy dissipation of the conventional ac electromagnetic contactor and the proposed ac PM contactor over one-year period. In Fig. 12, the coil current of contactor is detected by using an inductive sensor, typed E3N, based on Hall Effect. The measured coil current is dynamically sampled and recorded by a digital scope. In addition, the coil voltage is also obtained by using the digital scope with the use of an isolated voltage probe. As we known, once three key parameters related to the power energy calculation, such as the coil current, the coil voltage and the run time interval, are obtained, the energy dissipation during the contactor

operation, of course, is simply acquired. Compared with the testing rig for the measurement of the input electric energy in the conventional ac electromagnetic contactor, another one similar testing rig is arranged aims at the measurement of input electrical energy dissipation for the proposed ac PM contactor. Because the inherent characteristic of the newly proposed ac PM contactor, a new actuator including an ECM should be equipped with between the ac voltage and contactor body. The proposed ac PM contactor is merely energized during closing and opening processes over a short time interval. Normally, the coil voltage of ac PM contactor is removed most of operation time. Only the ECM dissipates electric energy during holding process. It is an anticipated result that little energy will be absorbed in the proposed ac PM contactor.



Fig. 12. Testing rigs for the measurement of electric energy dissipation in (a) ac electromagnetic (EM) contactor and (b) ac PM contactor.

Energy saving characteristic that offered by the proposed ac PM contactor is its superior benefit. As listed in Table 2, both ac PM contactor and ac EM contactor are assumed to be operated in the holding process for one year. The total energy is dissipated by ac PM contactor is only 27% of that by ac EM contactor. Moreover, the number of coils equals 2000 turns, which is approximately half of the currently needed coil windings of ac EM 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	3.036
Total energy (KWH)	152.44152	26.59536
Fee (NT dollars)	457.32456	79.78608

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