Contact-Bounce Control and Remote Monitoring Interface Implementation of a PM Contactor

Chih-Yu Hung
Department of Electrical Engineering
Chienkuo Technology University
No. 1, Chieh Shou N. Rd., Changhua City 500, Taiwan, R.O.C
hcy@cc.ctu.edu.tw

Abstract: - An ac PM actuator and its ECU are designed to develop an ac permanent magnet contactor in this paper. A computer simulation model of the proposed ac PM actuator is also addressed. The ac PM actuator is energized at various closing phase angles of the ac voltage source. The experimental and simulation results show that the moving velocity or the kinetic energy of armature before two contacts collision is a function of the closing phase angle of the ac voltage source. Therefore, if the ac PM actuator is switched on at a purposely selected closing phase angle of ac voltage source, minimum bounce duration after contacts closing is able to be achieved. The lifespan of proposed contactor is prolonged and its operating reliability is improved as well. In addition, when the armature reaches its closed position, it will be held tightly by the PM even though the coil voltage is cut off. Only a little input electrical energy is dissipated in the ECU. If the ac PM contactor is used for a long time, experimental results show that the final energy-saving performance of ac PM contactor is very outstanding. At the same time, some critical disadvantages produced by ac EM contactor are overcome by the ac PM contactor too. Experimental and simulation results show that the ac PM actuator is in agreement with its control circuit.

Key-Words: - AC PM contactor, AC EM contactor, Kinetic energy, Energy saving, Closing phase angle

1 Introduction

As we know, contactors are simple and inexpensive devices. They have been extensively used in all low-voltage apparatus. The trend is that contactors are increasingly applied in the development of the industry. So that more and more engineers concern about the contactor's using lifespan, energy dissipation and operating reliability. When contactors and the other switching devices perform the closing operation, arcs are often produced. The amount of arc during operation is deeply determined by the particular operating and loading conditions. For certain loads, such as induction motors, the direct on-line starting current is perhaps ten times the rated current of the load. Contact bounces are generally produced after the mechanical contacts closing. If the bouncing problem of contacts is integrated with the starting current of motors, arcs are produced between the contacts, not only related to contact erosion and possible contact welding, but also since it causes electromagnetic interference (EMI), which leads to problems with electronic control circuits [1-2].

Significant disadvantages are often found in the applications of the ac electromagnetic (EM) actuator. For example, those ac EM actuator produces noise pollution at lower voltage, consumes much more energy to hold the armature during the holding process, their coils are easy to be burnt due to frequent working state and the abnormal dropouts are resulted from the power line disturbances like voltage sag events. To overcome these drawbacks produced by ac EM actuators, a variety of the permanent magnet (PM) actuators are designed for the development of the ac PM contactor.

Lots of studies regarding the contact bounce of the ac EM actuator have been presented before. Many approaches have ever been suggested to improve the switching performance of these devices during the closing process. In principle, when two finite bodies with initially different velocities collide, it is impossible for their interface to remain in contact and namely contact bounce occurs. So that all designed methods related to the contacts bounce control are hope to minimize the kinetic energy at the moment of impact or maximize the rate of dissipation. In 1997, Nouri and his co-workers presented a method based on controlling the strength of the magnetic field to reduce the kinetic energy before two contacts closing. They changed the voltage value of contactor coil during the closing process by timing the coil energizing period [2]. Later, many types of new ac EM contactor based on the similar designing idea, that is to depress the making speed of contacts during the closing process as much as possible, were developed [3-6]. Their ac EM actuators should be switched on at a purposely selected closing phase angle of the ac voltage source. However, we can see that the dynamic displacement of armature is often one of the necessary variables in most of previous controlling methods [7-9]. Li *et al.* [3] showed that the moving velocity of armature is profoundly affected by different closing phase angles during closure process. Hence, the optimizing closing phase angle of ac voltage source was found by taken as the optimization objective [5], taking moving velocities lower than their worst values as restrictions, the optimization model was established. Game theory was adopted to solve this optimization problem. Xu and Zhang [6] proposed a special contact de-bounce method to solve the bouncing issues. Recently, some closing methods used by contactor are further based on intelligent approaches for the calculation of the dynamic armature displacement [15-17] and the closing control of the ac EM actuator is completed as well. Therefore, some important drawbacks, such that the manufacturing cost of the contactor is inexpensive, the armature mass is increased and the using endurance is reduced, are then overcome. Although many studies related to the closing contact-bounce control of the conventional ac EM actuator have been published, little attention has been paid to control the closing contact bounce regarding the ac PM actuator [11-13]. The main purpose of this paper is to develop a new ac PM actuator and to design a microcontroller-based control circuit well matched with the developed actuator. Based upon choosing a better closing phase angle, contacts closing with lower bounce duration during the closing process would be obtained [20]. Meanwhile, the objective of energy-saving requirement during the holding process is also together considered here. Some useful simulation and experimental results of the developed actuator are also provided and analyzed.

2 PM Contactor Model

As can be shown in Fig. 1, the mechanism of a proposed ac PM actuator is composed of three subsystems: such as an electric system, a magnetic energy-conversion system, and a mechanical system. The magnetic energy-conversion system of the ac PM actuator especially includes a permanent magnet arranged on armature. This permanent magnet is often made of Nd-Fe-B material; hence, its volume is very small. For reducing the energy losses, all cores in the magnetic circuit are made of the pure iron with high permeability. Fig. 1 also depicts the connection between the developed ac PM actuator with colenoid and its control circuit (ECU). Especially, two sets of coil are included, one is referred to as a closing coil N_1 and the other one is referred to as a opening coil N_2. When the closing coil of actuator at the opened position is applied an ac voltage source, the armature will move left due to the electromagnetic force produced by the current flowing in the closing coil. Once the armature is engaged with the E-shape fixed iron core, it will be closed tightly by the PM force even though the current of closing coil is removed. Contrarily, if a current is applied to the opening coil, the negative electromagnetic force produced by the current will overcome the holding force produced by the permanent magnet and make armature moving away the E-shape fixed iron core. When the armature is moved left or right, the actuator drives contactor opened or closed.

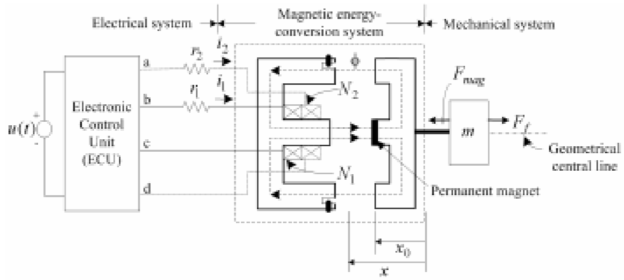


Fig. 1. Show the configuration of a proposed ac PM actuator and the connection with its ECU

2.1 Modeling actuator

To clearly explain the operation principle, one complete operating process of the developed ac PM actuator is partitioned into three working stages: closing process, holding process and opening process.

2.1.1 Opening process

Before the opening process, the breaking capacitor C shown in Fig. 2 has been charged by the rectified dc voltage source. The charged voltage across the breaking capacitor is almost equivalent to the peak value of ac voltage source $V_{co} = \sqrt{2}U_{rms}$. The equivalent circuit of the electrical system is shown in Fig. 2(b). When one wants to switch the contactor off, the breaking voltage V_{co} makes a current flow through the opening coil, so that the actuator drives the contactor off. In fact, the electromagnetic force produced by the opening coil and the breaking voltage is first used to counteract the permanent-magnet force. The remaining magnetic force is then incorporated into the tension force of the spring system to drive the contactor off as fast as possible. By KVL, the voltage equation related to the electrical circuit during the holding process yields

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

where
i_2 : current flows through the opening coil,
L_2 : inductance of the opening coil,
r_2 : resistance of the opening coil.
For brevity, the charged voltage across the breaking capacitor is viewed as an independent voltage source, therefore, it represents their initial electric can be assumed as zero. Meanwhile, the initial current $i_2(0)$ flowing through the equivalent electric circuit, as shown in Fig. 2(b), is zero. The solution of the current flows through the opening coil, i_2, during the opening process can be given by

$$i_2(t) = \frac{V_{co}}{r_2} e^{-\alpha t} \sin(\beta t) \quad (2)$$

where the parameters shown in (2) α and β are defined as $r_2 / 2L_2$ and $\sqrt{r_2^2 - (4L_2 / C)} / 2L_2$, respectively. Obviously, the dynamic behavior of the coil current i_2 is a negative peak value and it is attenuated exponentially as well.

2.1.2 Holding process

Once the armature is engaged with its closed position, it will be held by the permanent-magnet force even if the ac voltage source is removed. Therefore, the ac PM actuator almost dissipates none of the input electrical energy. In fact, only a little electrical energy will be dissipated in ECU for maintaining to detect the operation of the contactor. During this process, because L_1 is a constant value and $u^*(t) = 0$, the current flows through the closing coil should be exponentially decayed to zero during the holding process.

2.1.3 Closing process

During the closing process, the closing coil is energized by the rectified dc voltage source. The equivalent electrical circuit is demonstrated in Fig. 2(a). The resultant electromagnetic force is the permanent-magnet force integrated with the electromagnetic force produced by voltage source. Normally, the total closing time of the armature of ac PM actuator is shorter than that of ac EM actuator. By applying the Kirchhoff's voltage law, the dynamic behavior of the electrical system is governed by the following voltage equation:

$$u^*(t) = i_1 r_1 + \frac{d\lambda_1}{dt} = \left|\sqrt{2}U_{rms} \sin(\omega t)\right| \quad (3)$$

where
$u^*(t)$: dc voltage source, which is rectified from an ac sinusoidal voltage source,
ω : angular frequency of the $u^*(t)$, it is two times that of the ac voltage source $u(t)$,
U_{rms} : root-mean-square value of the nominal ac voltage source,
r_1 : resistance of both the closing coil and the connecting conductor,
i_1 : current flows through the closing coil,
λ_1 : flux linkage across two terminals of the closing coil.

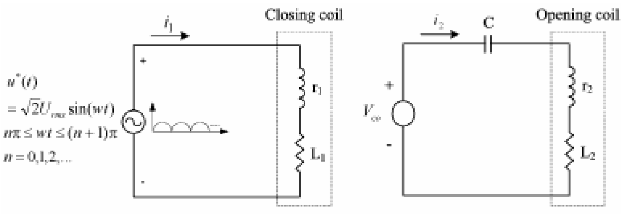
Because the flux flows in the magnetic circuit can not be changed instantaneously [10], hence, the inductance of the coil L_1 should almost be kept at a constant value at a time instant. The flux linkage can be represented as $\lambda_1 = L_1(x) i_1$ and it is substituted into (3). We obtain

$$u^*(t) = i_1 R' + L_1(x) \frac{di_1}{dt} \quad (4)$$

where the generalized resistor is defined as $R' = r_1 + (v dL_1)/dx$. Equation (4) is simply a first-order differential equation and its initial value of coil current is assumed to be zero, namely $i_1(0) = 0$. The current flows through the closing coil can be expressed as below

$$i_1(t) = -\frac{V_m}{|Z|}\sin(\theta - \phi)e^{-t/\tau} + \frac{V_m}{|Z|}\sin(\omega t + \theta - \phi) \quad (5)$$

where $V_m = \sqrt{2}U_{rms}$ is the amplitude of ac sinusoidal excitation voltage source. 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 $\sqrt{(R')^2 + \omega^2 L_1^{\ 2}}$ and the power factor angle ϕ is $\tan^{-1}(\omega L_1/R')$, respectively. It is evident that the coil current `` includes a dc offset component 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 electrical system of the actuator.`



(a) (b)

Fig. 2. Show the equivalent electrical circuit: (a) during the closing and holding processes; (b) during the opening process

2.2 Magnetic circuit analysis

The geometrical structure and the equivalent magnetic circuit of the proposed ac PM actuator are shown in Fig. 3. The magnetic circuit of the ac PM actuator is symmetrical with the central leg of E-type core. The magnetic circuit analysis can be further simplified. The permanent magnet is arranged on the central leg of E-shape armature. By applying the magnetic circuit analysis technique to the magnetic circuit shown in Fig. 3(b), the magnetic equations can be described as follows:

$$\begin{cases} (\Re_1 + \Re_{x1} + \Re_3 + \Re_{x3} + \Re_4)\phi_3 - (\Re_3 + \Re_{x3})\phi_2 \\ = N_1 i_1 + F_{mag} \\ -(\Re_3 + \Re_{x3})\phi_3 + (\Re_2 + \Re_{x2} + \Re_3 + \Re_{x3})\phi_2 \\ = i_2 \end{cases} \quad (6)$$

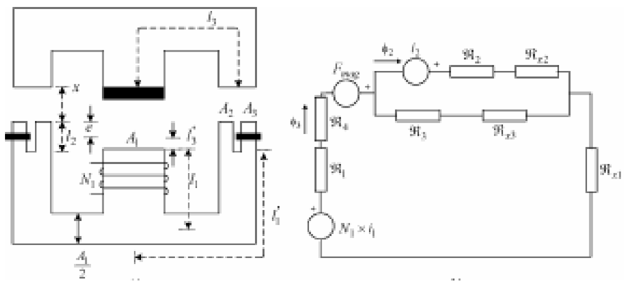
The reluctances in each of the magnetic circuit are calculated respectively by using reluctance principle and expressed as below:

$$\begin{cases} \Re_1 = \dfrac{l_1 + l_1^{'} + l_3}{u_0 u_r A_1}, \Re_2 = \dfrac{l_2}{2u_0 u_r A_2}, \\ \Re_3 = \dfrac{l_2}{2u_0 u_r A_3}, \quad \Re_{x1} = \dfrac{x+e}{u_0 A_1}, \\ \Re_{x2} = \dfrac{x}{2u_0 A_2}, \Re_{x3} = \dfrac{x}{2u_0 A_3}, \Re_4 = \dfrac{l_3^{'}}{u_0 u_r A_1} \end{cases} \quad (7)$$

As can be seen in (7), the reluctances in each of magnetic circuit shown in Fig. 3 are generally a function of the average length of individual magnetic circuit. After the total reluctance $R(x)$ is obtained, the equivalent inductance value $L(x)$ is easily derived by the following formulas:

$$L(x) = \frac{N^2}{R(x)} \quad (8)$$

where N is the number of windings of coil.



(a) (b)

Fig. 3. Show the proposed ac PM contactor: (a) the geometrical structure; (b) the equivalent magnetic circuit

2.3 Force analysis

If the armature displacement is held at a constant value, the variation of mechanical energy should be equivalent to zero. The change of the magnetic coenergy stored in the magnetic energy-conversion system can be calculated as follows [14].

$$W_c' = \int_0^{\lambda} \frac{\zeta}{L(x)} d\zeta = \frac{\lambda^2}{2L(x)} \quad (9)$$

where ζ is a dummy variable of integration. The relationship of between the coil current and the flux linkage is given by $i(\lambda, x) = \lambda/L(x)$. In addition, the electromagnetic force is determined by the derivative of the magnetic coenergy with respect to the armature displacement, that is

$$F_e = \frac{\partial W_c}{\partial x} = \frac{1}{2} i^2 \frac{\partial L(x)}{\partial x} \quad (10)$$

Equation (10) clearly shows that the electromagnetic force F_e is a function of the coil current and the armature displacement.

No matter how the permanent magnet is arranged on the moving armature or the fixed iron core of the magnetic circuit, the effect of the permanent magnet force imposed upon the armature is near to equal [13]. The resultant force imposed upon the armature is composed of the gravitational force, spring anti-force and resultant magnetic force. Since the normal line of the installation platform is always parallel with the geometrical central line of contactor mechanism, as shown in Fig. 1, so that the effect of gravitational force on the armature can almost be ignored, the forced resultant force on armature can be further simplified as below:

$$F = F_{mag} - F_f \tag{11}$$

where

F_{mag} : resultant magnetic force, which consists of the electromagnetic force and permanent magnet force,

F_f : spring anti-force.

By using Newton's law of motion, the governing equation of the armature's motion during the closing and opening processes can be directly formulated as follows:

$$F_{mag} - F_f = m\frac{d^2x}{dt^2} \tag{12}$$

where m is the mass of armature.

2.4 Work-Energy theorem

On the basis of the behavior of the magnetic energy-conversion system is conservative and lossless; the energy transferred from mechanical system to electric system or vice versa is determined by the moving direction of the armature. In addition, the work done dW_m by the mechanical system equals the variation of armature displacement times the magnetic force and the result can be further deduced as follows:

$$\begin{aligned} W_m &= -\int_x^{x_0} F_{mag}\,dx \\ &= \int_{v_0}^{v} mv\,dv \\ &= \frac{1}{2}mv^2 - \frac{1}{2}m{v_0}^2 = \Delta E_k \end{aligned} \tag{13}$$

where the initial moving velocity of the armature v_0 is assumed to be zero for convenience. The final kinetic energy of the armature $E_k = (mv^2)/2$ can be directly determined by the final moving velocity of the armature v at the moment of two contacts impact. Therefore, equation (13) means that the final kinetic energy imposed upon the armature is equivalent to the energy transferred from the magnetic coupling field to the mechanical system. Equation (13) is well-known as the work-energy theorem in physics [17].

3 Contact Bounce in Closing Phase

By employing the Newton's third law, the rate of change of the momentum of a system is proportional to the resultant force imposed upon the system and is in the direction of that force. It follows that the vector change in momentum of either particle, in any time interval, is equal in magnitude and opposite in direction to the vector change in momentum of the other. The net change in momentum of the system is therefore zero. That is,

$$\sum P_f = \sum P_i \tag{14}$$

where, P_i and P_f represent the linear momentum of movable contact before and after collision, respectively. Since the linear momentum of movable contact is conservative, it is to be held a constant value before and after the moment of impact. To assume the contact system of contactor includes two particles, such as movable contact and fixed contact. The mass of movable contact is m_1 and its initial moving velocity is v_{1x}. In contrast, the mass of fixed contact is m_2 and its initial velocity v_{2x} is zero, such that it is stationary. If the movable contact is assumed to be collided with the fixed contact along with a straight line, the final linear momentum relationship before and after two contacts impact can be written as follows:

$$m_1 v_{1x}' + m_2 v_{2x}' = m_1 v_{1x} \tag{15}$$

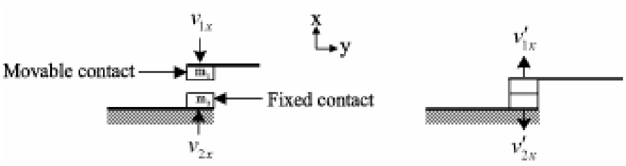
Fig. 4 shows the sketch of the movable contact and the fixed contact before and after impact. The total kinetic energy of the contact system should be maintained at a constant value due to the conservative principle. Thus, it can be given by

$$\frac{1}{2}m_1(v_{1x}')^2 + \frac{1}{2}m_2(v_{2x}')^2 = \frac{1}{2}m_1 v_{1x}^2 \tag{16}$$

From the expressions of both linear momentum and kinetic energy shown in (15) and (16), we can see that the final velocities of both movable contact and fixed contact after impact can be easily derived and shown below:

$$v_{2x}^{'} = \frac{2m_1}{m_1 + m_2} v_{1x} \tag{17}$$

$$v_{1x}^{'} = \frac{m_1 - m_2}{m_1 + m_2} v_{1x} \tag{18}$$



(a) (b)

Fig. 4. Demonstrates the colliding process of two contacts: (a) before collision; (b) after collision

Because the fixed contact is arranged on the mechanical frame of the contactor, it is reasonable to assume $m_1 << m_2$. In practical, the fixed contact is always kept on stationary state after two contacts collision, so that (18) equals zero. In contrast, the final velocity of movable contact v_{1x}' is equal in magnitude, but the moving direction is reverse to the initial velocity v_{1x}. Therefore, the contact spring system will be compressed by the linear momentum produced by the movable contact with $m_1 v_{1x}^{'}$. Thus, the stretched and compressed actions of the contact spring system may be repeated for many times before attaining stable state. That is well-known as the contact bounce.

4 Control Strategy of Contact Bounce

The bounce duration after contacts closing depends on three influencing factors, such as the dynamic behavior of the contact spring, the current value flows through the contact and the moving velocity of the movable contact prior to the impact. The former two items can not be controlled generally. On the contrarily, the last method is feasible and easy to be achieved through controlling approach.

4.1 Control strategy

During the closing process, the armature is not only forced by an uncontrollable permanent magnet force, but also forced by a controllable electromagnetic force. Therefore, the dynamic resultant magnetic force imposed upon the armature during the closing process can be controlled by changing the value of the closing coil current. Moreover, as can be seen in (3), the closing coil current is a function of the closing phase angle of the rectified dc voltage source. In other words, if we select a closing phase angle of the dc rectified voltage source on purpose, a predicted value of the coil current may be obtained. Certainly, the moving velocity or the kinetic energy of the armature prior to two contacts impact is determined as well.

4.2 Control circuit

Fig. 5 shows a schematic diagram of the microcontroller-based (PIC16F877A) ECU. As can be seen in Fig. 5, ECU only includes some simple digital and analog components. The operation of the ECU is controlled by the voltage value of ac source or the output of a coil-voltage detector. The main designing idea of this ECU underlying controls the closing contact bounce, improves robustness, and monitors the dynamic behavior of contactor contacts. The operation of the ECU, in particular, during the closing and opening processes will be addressed to the remainder of this section.

4.2.1 Rectifier circuit

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 to convert the ac sinusoidal voltage source to dc voltage $u^*(t)$ with ripples, as denoted in Fig. 2. The rectified dc voltage source $u^*(t)$ has the same amplitude as the $u(t)$. However, the frequency of the former is two times of the latter. A metal-oxide varistor (MOV) (it is not drawn in Fig. 5) is often connected with the input of the full-wave bridge rectifier in parallel. The objective is used to prevent the transient over-voltage included in ac voltage source from damaging the ECU.

4.2.2 Coil-Voltage and coil-current detectors

Part G in Fig. 5 depicts that there is a coil voltage detector is composed of two resistors, R19 and R21. It is connected with the rectified dc voltage source $u^*(t)$ in parallel. Based on voltage division law, the detected coil voltage is sampled and amplified, and then fed to the input of the microcontroller. In addition, a coil-current detector, which consists of a low-value resistor R22, is connected with the coil in series. Since the voltage across R22 is proportional to the coil-current value, the current flows through the coil can be derived by first reading the voltage across the resistor R22 and then calculating based on the law of ohmic. The coil-current sampling circuit has been drawn in the part F in Fig. 5.

4.2.3 Closing signal and its driver

When the dc voltage value is stable, the coil voltage is then read and justified by microcontroller. If the sampled coil voltage lies in minimum allowable closing voltage value of the ac PM actuator, the microcontroller begins producing a closing signal based on the default setting of the closing phase angle of the ac voltage source, as shown in part J of Fig. 5. This produced closing signal will be a logical high level and maintained for a time period. In general, this closing signal should be first amplified by a voltage amplifier, as the part B shown in Fig. 5, and then used to switch the power MOSFET Q7 on. After the armature reaches its closed position, the voltage across the closing coil will be cut off right away.

4.2.4 Opening signal and its driver

Before the opening process starts, an electrolytic capacitor C8 has been charged by the maximum value of the ac voltage source, that is $\sqrt{2}U_{rms}$. In a similar manner, once the voltage across the opening coil is lower than the maximum allowable releasing voltage of ac PM actuator, this sensed signal is fed to the microcontroller. An opening signal with logical level is produced by the microcontroller. The driving capacity of this logical opening signal is too weak to drive the power MOSFET Q8 on directly, so that a driver is arranged on the output of the microcontroller for amplifying requirement.

4.2.5 Serial-Port interface

To provide with remote control in many industrial applications, a serial port communication interface

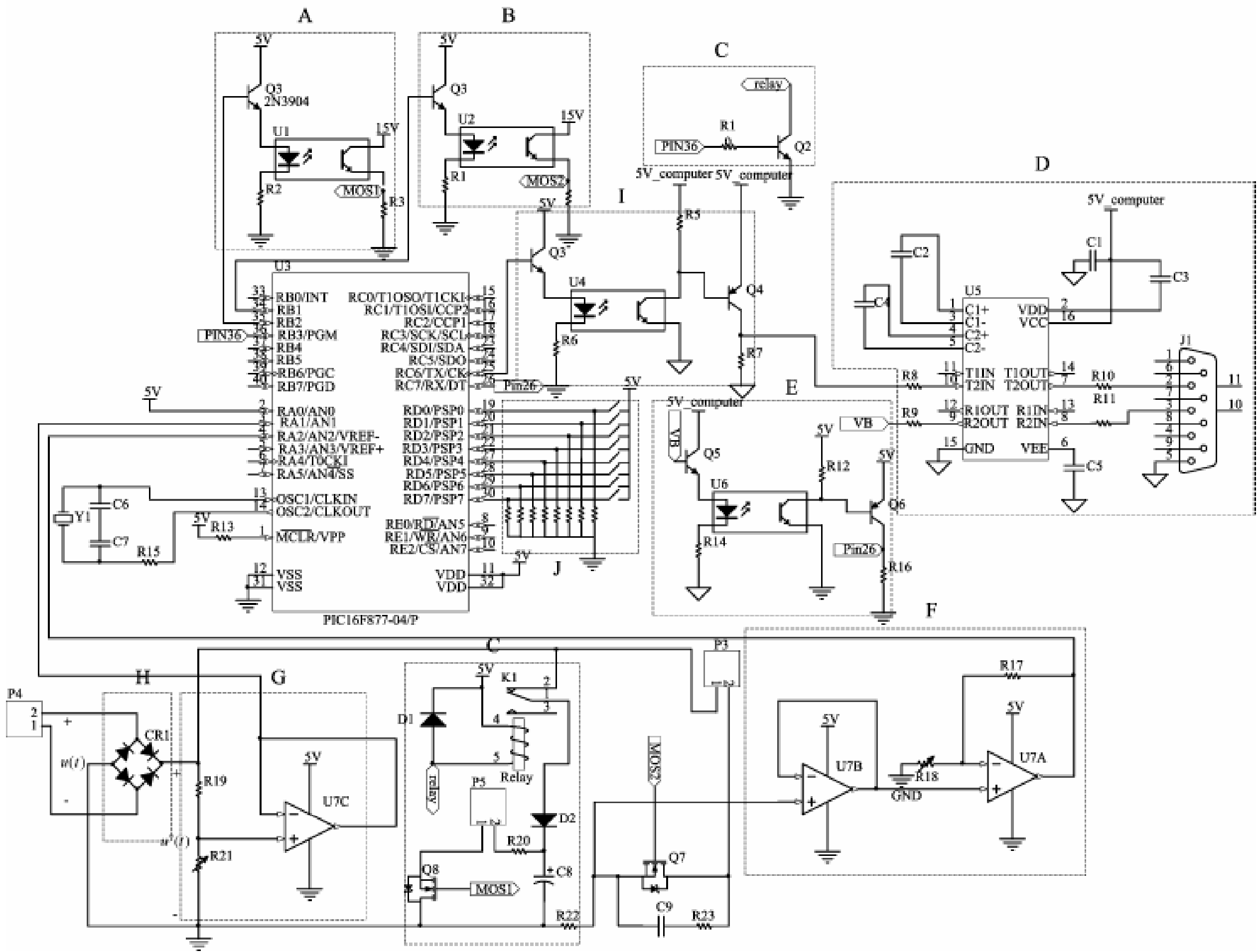


Fig. 5. Schematic diagram of electronic control module.

is designed to be built in the ECU of the actuator and diagrammed in the part D of the Fig. 5. A voltage amplifier included by U5 and the other interface circuits are used to convert those signals from TTL positive logic level to RS-232 negative logic level and vice versa. To ensure the operating safety of the serial communication interface, the microcontroller and the series-port pins are isolated by a pair of photo couplers.

5 Real-Time Monitoring Interface

The applied voltage and coil voltage of the PM contactor are dynamically measured. On one hand, the action of the contactor is relied on the dynamic value of these data, on the other hand, the single chip will real time transmit these measured valuable data to the remote personal computer by way of the serial port. As shown in Fig. 6, the monitoring contactor is directly to a server computer. The dynamic measured data is sent by some wireless equipment, GPRS is used here. Any computer which is connected to internet network at any time and place can require receiving necessary data from client computer.

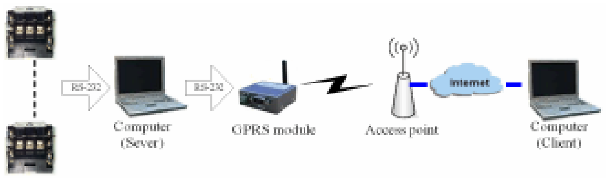


Fig. 6. A wireless network structure between client computer and controlled PM contactor.

The proposed PM contactor usually is assumed to be installed in a power or control panel. Basically, the important parameters data such that external applied voltage and coil current will be dynamically transmitted to the client computer. If the client computer has been installed a friendly human machine interface, therefore, the measured valuable data from the monitor ac PM contactor can also be displayed on the monitor. From the displayed status of monitored ac PM contactor, proper action will be done by the operator and accidental event will be then avoided as much as possible.

5.1 Peripheral circuit of single chip

Fig. 7 shows the peripheral circuits of single chip, PIC16F877. The pin 34 of the single chip will output a high logic level signal. The driving strength of this logic level is not enough. Therefore, it is amplified first by an amplifier based on a transistor and then is used as the turn on signal of MOSFET power transistor. At the same time, single chip will sense the dynamic values of applied voltage and current of coil and real time transmit them to the memory of the server computer. In case of a request command is sent from client, these stored useful data will be sent from server computer to client computer. A turning off signal is generated when the applied voltage of the PM contactor is broken, the logic level in pins 35 and 36 will be changed from low to high and sustained for time duration. Like turning on signal, these two signals are amplified and used to turn the PM contactor off. In order to ready the RS-232 or serial port communication, the definition of logical level should be converted into negative and RS-232 logical level, as can be seen in Fig. 8.

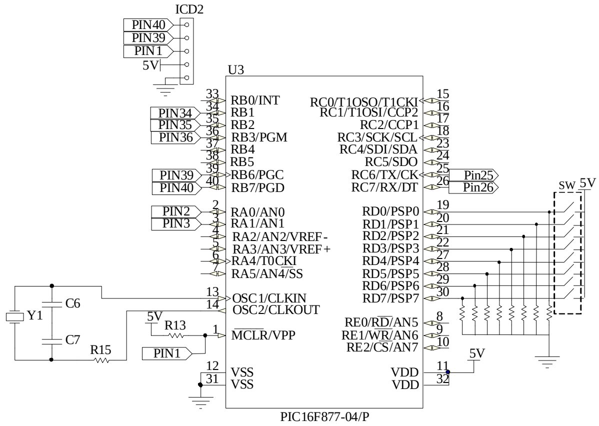


Fig. 7. Single chip and its peripheral circuit.

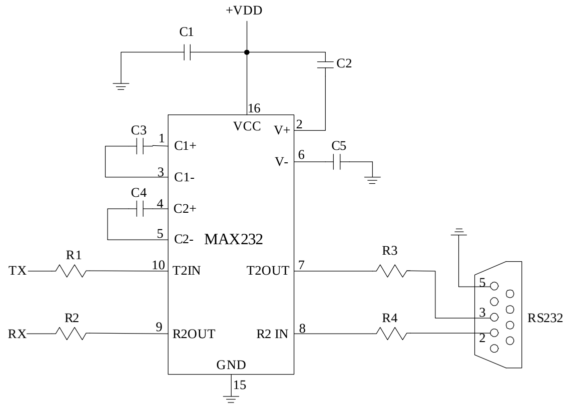
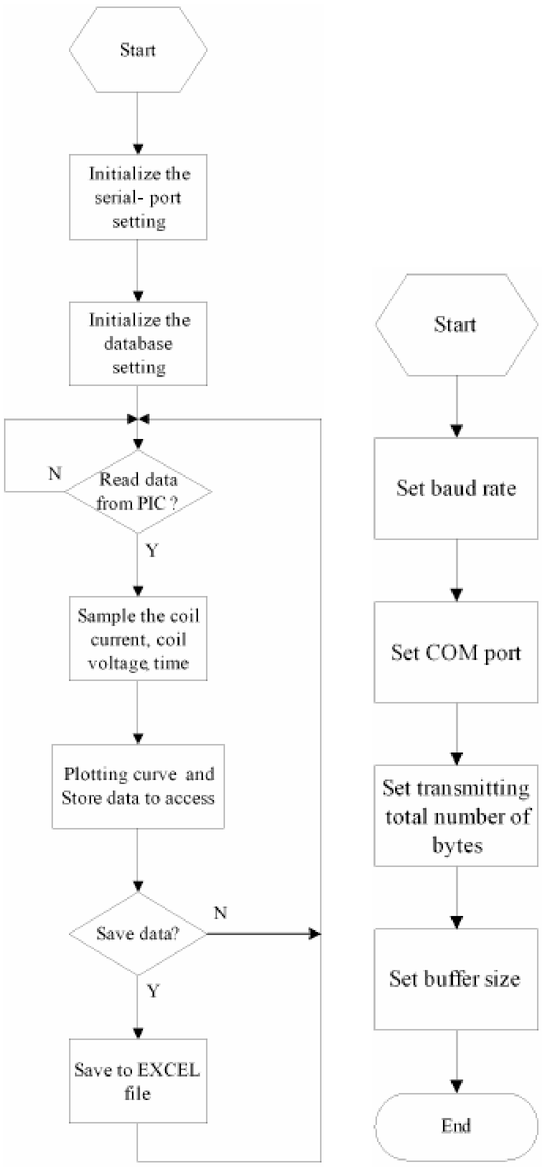


Fig. 8. Circuit for converting logic level to RS-232 level.

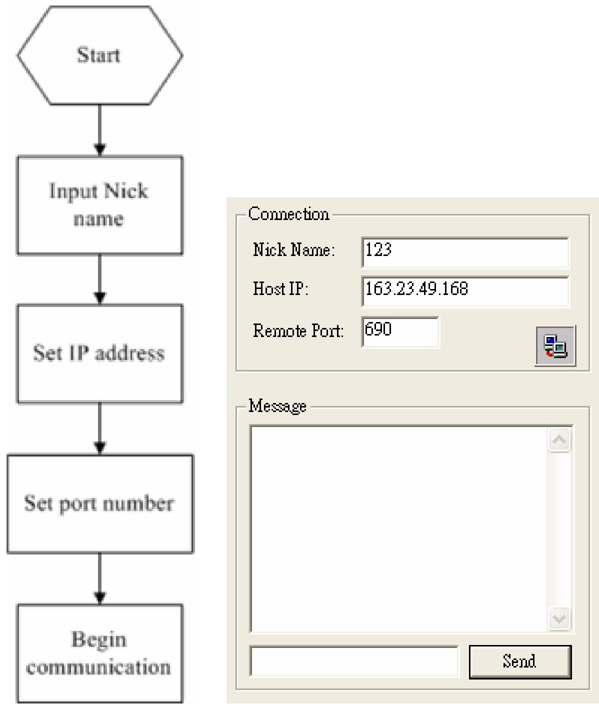
5.2 Communication between server and client computer

Fig. 9 shows the software flow chart of the human machine interface between PM contactor and server computer which is written by VB software. As mentioned earlier, the single chip is always connected to the server computer. Under the necessary circumstances, the communication between server computer and client computer can be established by employing internet network or GPRS directly. In this paper, the protocol is used to communicate between these two computers is shown in Fig. 10(a). By using a Winsock icon which is defaulted by VB software, the communication relation between server computer and client computer can be set up easily. Firstly, the property of Winsock icon in the server computer and client computer should be keyed in relative IP address and PORT number, respectively. The setting process on the software interface is shown in Fig. 10(b). Therefore, the preparing work for setting up communication between two computers by using internet network is then really ready now.



(a) (b)

Fig. 9. Human machine interface between PM contactor and server computer (a) software flow chart (b) serial port setting.



(a) (b)

Fig. 10. Computer communication setting up between server and client (a) setting flow chart (b) the properties setting of Winsock icon.

6 Simulation and Experiment Results

For convenience, the actuator of an experimental contactor and its ECU has been established in the laboratory. The actuator of the contactor prototype is allowed to be supplied with rms voltage 220 V of the nominal 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 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. A permanent magnet is arranged on the central leg of the armature[18-20].

6.1 Establishment of simulation model

A computer simulation model of the ac PM actuator is established by using those models of the electrical subsystem and the mechanical subsystem. First of all, individual simulation modules related to each subsystem are established according to their respective governing equations. Next, these modules are combined with each other.

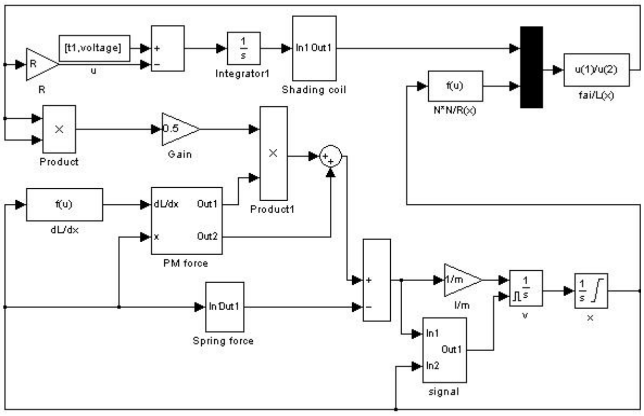
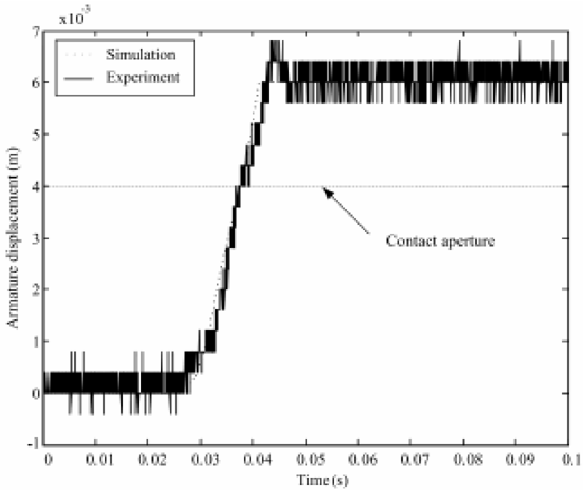
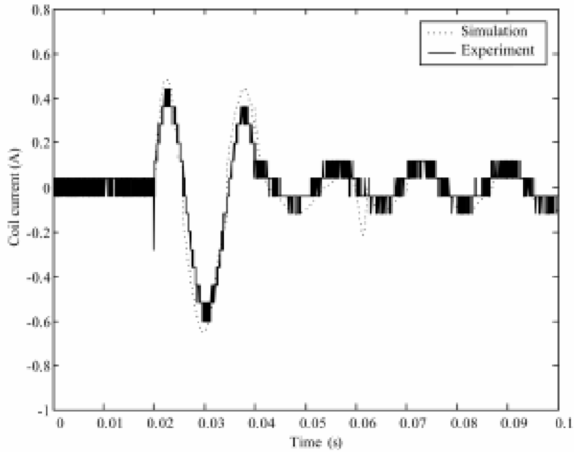


Fig. 11. Show the completed simulation model of the contactor actuator.



(a)



(b)

Fig. 12. Show the comparisons of the independent variables, which are obtained by simulation and experiment, respectively: (a) armature displacement; (b) current flowing through the closing coil.

A simulation model of the ac PM actuator is obtained, as shown in Fig.11. In order to verify the accuracy of the independent variables the proposed actuator model, such as armature displacement and coil current, are compared with experimental results.

As shown in Fig. 12, the two independent parameters of the ac PM contactor during closing process were compared between simulation and experiment case. We found that the simulated results were in good agreement with the experimental results. Those mean that the simulation results or accuracy obtained from the proposed ac PM actuator model are acceptable. For convenience, the established mathematical ac PM contactor model can be used to predict every kind of results under different assumed working conditions.

6.2 Experimental procedures and results

As mentioned above, the permanent magnet is arranged on the armature of the ac PM actuator. The action of the ac PM actuator at any time instant is determined by the ECU. The photograph of the completed ECU is shown in Fig. 13. The ECU was based on a single chip, PIC16F877. The other main components built in the ECU have also been labelled in the Fig. 13. The real closing and breaking process was controlled by means of independent power MOSFET M1 and M2, respectively. Especially, the serial port was used to dynamically communicate messages between single chip and personal computer.

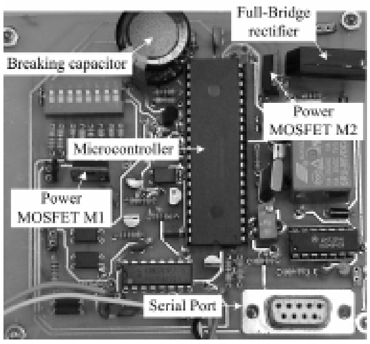


Fig. 13. Show the completed photograph of the ECU

As can be seen in Fig. 14(a), the external applied voltage of contactor coil is detected represents that the closing phase starts. After $t1$ delayed time, the coil would be triggered by ECU actuator at a special initial phase angle of ac voltage source. Therefore, the bounce phenomenon is then reduced due to the smallest closing kinetic energy of the movable contacts. Fig. 14(b) shows the entire operating sequences controlled by the microcontroller-based ECU, while the actuator is operated in the opening process. An electromagnetic force will be generated and added to the spring anti-force, the coil will be triggered by a voltage source reserved in breaking capacitor with default setting. In addition, Fig. 14(c) demonstrates the flowing chart of ECU controlled by microcontroller software. When one wants to switch the ac PM contactor on, the ac PM actuator is energized. If the closing coil is turned on at different closing phase angles, of course, the starting on-line current flows through the closing coil is then various too. The magnetic force imposed upon the armature is different from each other, as shown in (12). The time-varying curves of the magnetic force imposed upon armature under each closing phase angle are diagrammed in Fig. 15(a). We can see that when the closing phase angle of the actuator is near 30 degrees, the resultant magnetic force is generated and larger than those produced by the other closing phase angles.

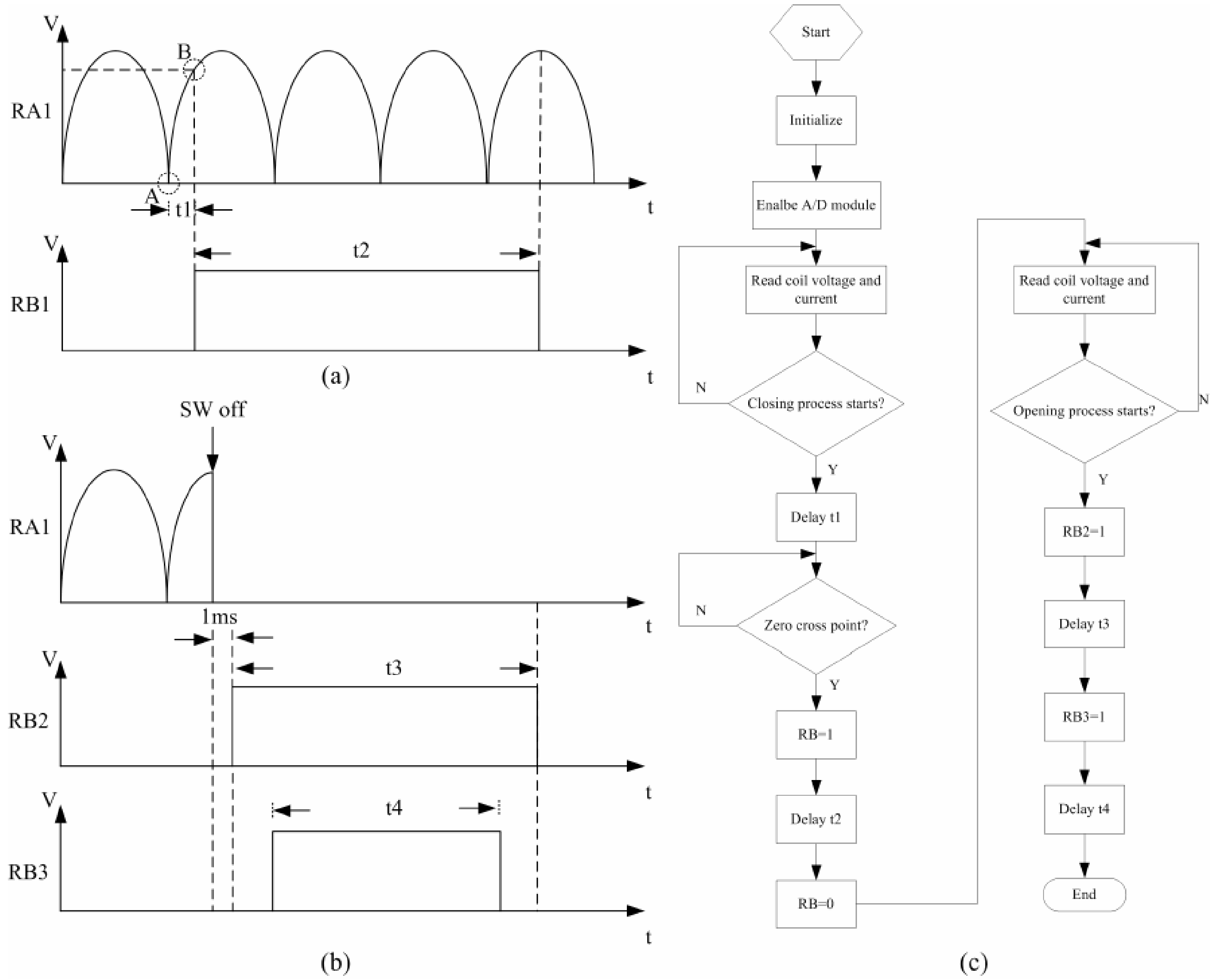


Fig. 14. Show (a) operating sequences during the closing process; (b) operating sequences during the opening process; (c) flow chart of microcontroller software.

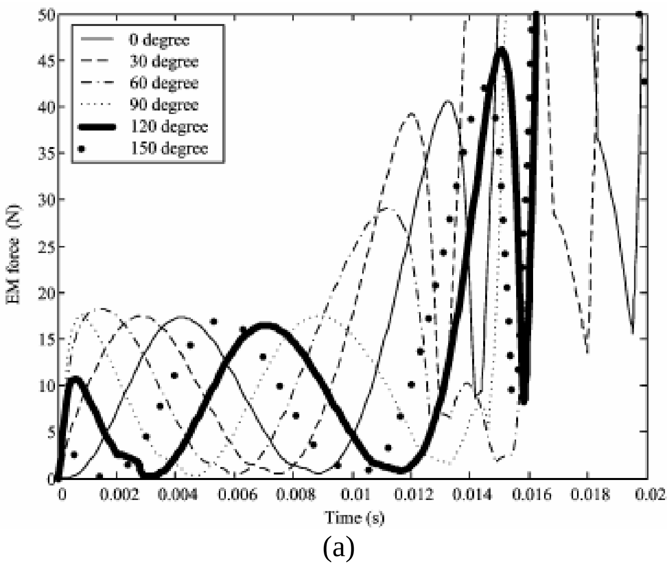
Therefore, the closing time of contacts is also shorter than that produced by the other cases, as shown in Fig. 15(b). The time-varying curves of armature displacement show that the closing process of the ac PM actuator will be completed from $t = 0.01$ sec to $t = 0.012$ sec finally. Fig. 15(c) depicts that the moving velocities of the armature before two contacts impact are concentrated on near 0.7 m/s if the coil is triggered near 30 degrees. However, if the ac PM actuator is switched on at a purposely selected closing phase angle, the moving velocity of the movable contact should be controlled. This result represents that the linear momentum of the movable contact after contacts closing will be reduced by different rate. This is also the reason why the bounce duration of the proposed ac PM contactor is often fewer than that of the ac EM contactor.

As shown in Fig. 15(d), the time-vary curves of armature velocity produced by the ac PM actuator is always larger than that by the ac EM actuator. This result is resulted from the resultant magnetic force is produced by both the electromagnetic force and the inherent holding force. No matter how the type of actuator, the time-varying curves of armature velocity demonstrated in Fig. 15(d) is a periodic function of the closing phase angle of ac voltage source. As can be seen in simulated results, the cyclic period of the proposed ac PM actuator is 180 degrees. If the closing phase angle equals 55 degrees, a minimum kinetic energy imposed upon armature will be obtained due to a minimum coil current. In contrast, the closing phase angle of the ac EM actuator, where the minimum kinetic energy before contacts closing is produced, appears at near 0 degree.

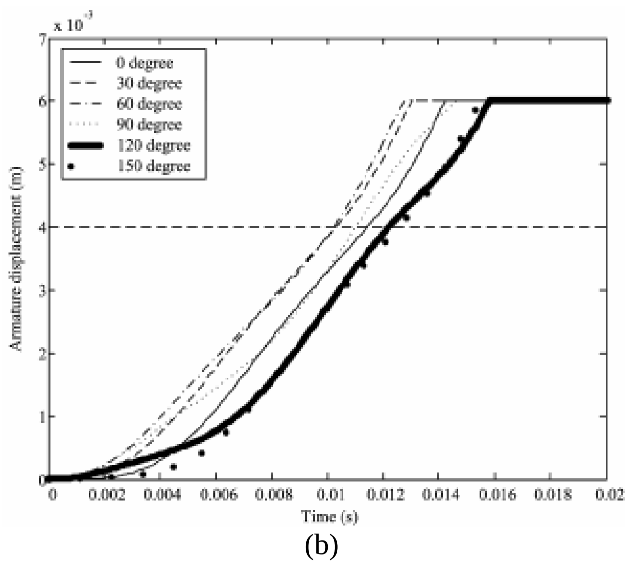
6.3 Assessment of contact bounce

As mentioned earlier, those data are completely obtained by simulation approach through a mathematical model of the ac PM contactor. For realizing the possible results while the proposed method is used in a real ac PM contactor. Some experiments will be conducted on an ac PM contactor prototype which was established in our laboratory. The effects of the proposed ac PM contactor upon the bounce duration after contacts closing are provided through several experiments and shown as follows. The testing rig designed and shown in Fig. 16(a), one of three pairs of contacts is connected with a simple electrical circuit, including a constant dc voltage source E and a fixed-value resistor R_C which acted as the measuring device of the contact bounce. When the movable contact is engaged with the fixed contact, the voltage across the R_C will be set to E; otherwise, the voltage across the R_C will be set to zero voltage. There are three types of voltage level, such as 85%, 100%, and 110% of rated voltage source, are served as the typical testing voltages. For each testing voltage level, not only both ac PM actuator and ac EM actuator are tested, but also ten times of the closing sequences of contactor are made and recorded. For each testing condition, the average of the ten bounce durations are calculated and together listed in Table 1. On the basis of those testing results, some significant conclusions are provided and shown as follows [15]:

(1) Generally speaking, the bounce duration of ac PM contactor is usually lower than that of the ac EM contactor at different external applied rms values ac voltage.
(2) Bounce duration produced in a higher applied voltage source value is generally longer than that of lower applied voltage source value.
(3) The average bounce duration produced in ac PM contactor is only 38% that in ac EM contactor.



(a)



(b)

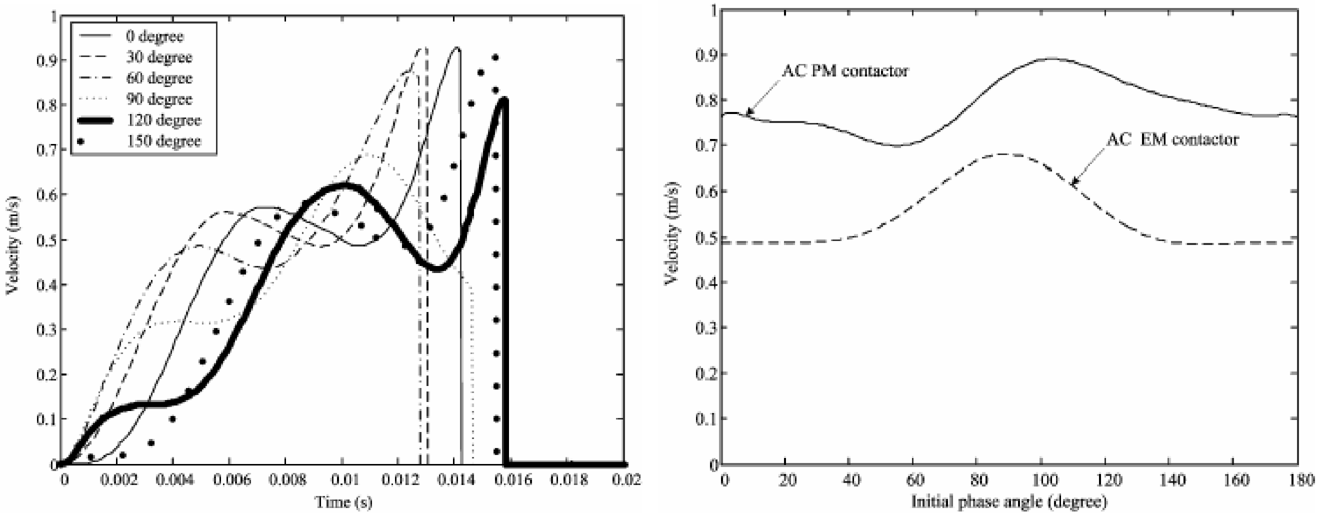


Fig. 15. Plot (a) time-varying curves of magnetic force; (b) time-varying curves of armature displacement; (c) time-varying curves of moving velocity; (d) moving velocity at various closing phase angles.

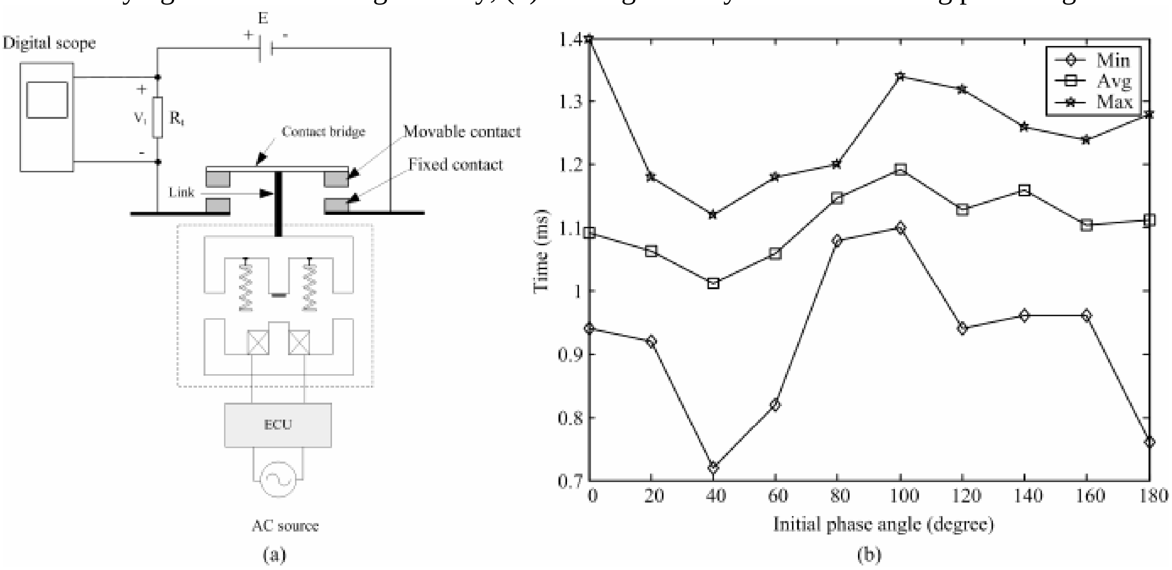


Fig. 16. Show (a) the testing rig designed for measuring the bounce duration after contacts closing; (b) the average, maximum, and minimum bounce-duration curves at various closing phase angles .

Table 1. Average bouncing time comparisons between ac PM contactor and ac EM contactor.

Applied ac voltage source (Nominal value equals 220V)	Average bouncing time (ms)	
	EM contactor	PM contactor
85%	1.556	0.832
100%	1.568	1.012
110%	1.620	1.088
Percentage of bounce-reduction	38.19%	

In general, the bounce-reduction performance of the ac PM contactor controlled by the ECU is often superior to that of the ac EM contactor. Fig. 16(b) demonstrates the bounce duration produced at various closing phase angles of the ac voltage source. If we focus our attention on the average bounce-duration curve at various closing phase angle, there actually exists a better closing phase angles of the ac voltage source will result in a minimum moving-velocity value of the armature after contacts closing. As can be seen in Fig. 16(b), the minimum moving-velocity value of the armature appears at near 40 degrees. In fact, the experimental results shown in Fig. 16(b) are in good agreement with the theoretical analyzing result shown in Fig. 10(d). Compared to the previous researching results [1-3,5], the proposed de-bounce method is not only the ac EM contactor, but also is suitable to a hybrid contactor.

6.4 Communication between server and client computer

According to the developing software flow chart of human machine interface of the personal computer shown in Fig. 9, the personal computer should first initialize the parameter setting of serial port and database of the single chip used on the electronic control module of PM contactor. Of course, the communication parameters setting related to single chip should be the same as those of the personal computer. When the ac PM contactor is triggered on, the single chip will immediately dynamically measure or detect the values of the coil voltage and current and transmit to the personal computer, namely server computer. After the server computer has completed the data receiving work, the received data will be real time shown on the screen, like the displayed results, as shown in Fig. 17, as well as stored in the database in order to be post-process by the operator of ac PM contactor. Therefore, the implemented system not only satisfies the operator to realize the dynamic status of ac PM contactor real time, but also supply some valuable information with management. Whenever, the client personal computer connected with the server personal computer can communicates with the local server computer and place by using internet network method. Fig. 18 shows a reality case. The human machine interface of a remote client personal computer has received data which transmitted from the local server personal computer. Those data will be displayed on the computer screen by real time as soon as possible. Regardless of client or server personal computer, not only can receive data from local single chip or remote personal computer, but also can allow the user to command the physical interface circuit on line. After all the operating procedures are completed, users can start the post-processing to the data recorded in the database of client or server personal computer. This is a very typical monitoring application. In addition, it is innovative that the closing and opening processes are controlled and the dynamic operations are on-line monitored for an ac PM contactor.

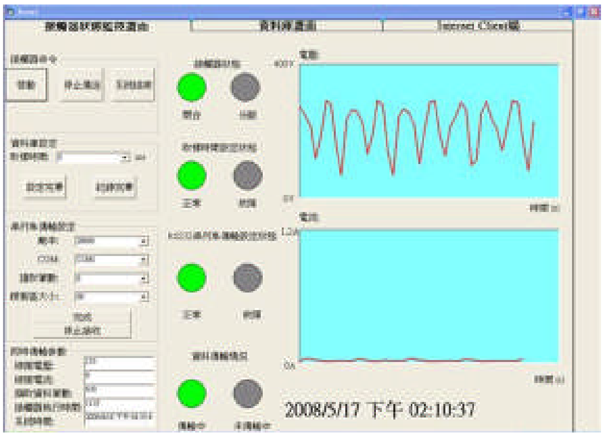


Fig. 17. Displayed appearance of the server computer.

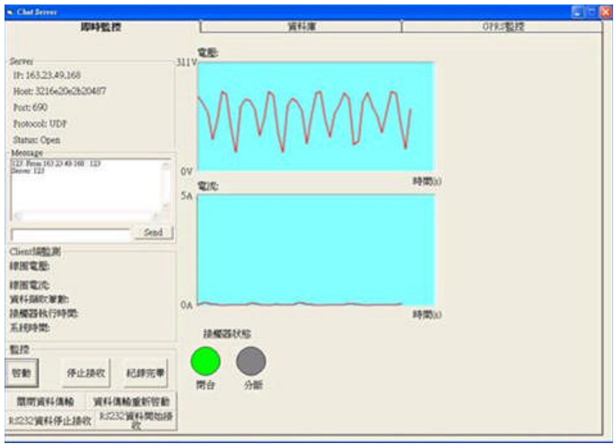


Fig. 18. Displayed appearance of the client computer.

7 Conclusion

A new type of an ac permanent magnet (PM) actuator and its electronic control circuit (ECU) based on a microcontroller will be presented in this paper. When one wants to switch the ac PM contactor on or off, a power on or off signal is then first sensed by the ECU. Shortly, the ECU immediately commands the actuator to execute the making or breaking courses at a purposely selected closing phase angle of the ac voltage source and then the actuator drives contactor closed or opened. In particular, the ac voltage source applied to the actuator is completely cut off once when the contactor has entered into the holding process. Significant improvements, such as little energy dissipation, noise-free pollution and no voltage-sag events, are achieved. The feasibility of the actuator was validated by comparing the simulation results with the experimental results. The function and its benefits offered by the proposed ac PM actuator were verified and illustrated through simulation and experimental tests as well. In this paper, we succeed to implementing a real time human machine interface for server computer and remote human machine interface for client computer as well.

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