# A New Hardware-Based Actuator for Driving an AC/DC Electromagnetic Contactor

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*Abstract:* - This paper focuses on developing an interchangeable electromagnetic contactor that essentially features with high power efficiency, low electromagnetic noise, and high power resource usage. The magnetic coils of this new IC-controlled method can be excited by AC or DC voltage and the range of the operating voltage is shown to be much larger than the conventional contactor. A wide range of applications for the new contactor is obtained. According to the electric performance requirement, the proposed controlling method, the pulse width modulation (PWM), provides a suitable energy for the exciting coils under the different operating condition. This is resulted in a stable operation between closing or opening process of the contactor greatly leads to the reduction of noise and energy loss for the exciting coils. Thus, the using life of the contactor can be greatly extended. In order to prove the validity of the proposed controlling method in this paper, several experiments had been performed and the results are shown the feasibility and reliability of the new design.

*Key-Words:* - Electromagnetic contactor, Electromagnetic noise, IC-controlled, Pulse Width Modulation, Energy, Using life.

## 1 Introduction

An AC electromagnetic contactor (abbreviated as AC contactor) is a major component for using in closing/opening contacts of a load circuits. The analysis model for the contactor is a complex nonlinear system that is coupling the equations from electric and mechanical dynamics. In order to predict the performance of the conductor, designer needs to fully understand the relative theories about both fields. Recently, they are couple of commercial software appeared in the market due to the advance of the hardware of computer. Some of software can be used for the optimal design of conductor as introduced in [1-7]. During the closing phase of the conductor, the presence of the bouncing behaviour results in producing the electric arc that causes erosion damage on the conducting surface and greatly reduced the lifespan of the conductor. Some researches proposed methods on solving this problem [8,9,11,12].

During the operation of AC conductor, nearly 90% of power consumption expensed inside the electromagnetic core and short-circuit ring. If an electric DC power is used to replace the AC electromagnetic system for the conductor, the power consumption will be greatly reduced. There is the invariant magnitude and direction of the electric current during the time course for the DC system. The magnetic flux line produced by the magnet of the conductor will not change. This will result in no power consumption due to the absent of hysteresis and eddy current. And it will resolve some problems [14-22], such as noise and overheating, commonly appear in the AC system. Based on the analysis, the magnetic force produced by the electromagnetic system varies according to the operation steps of the conductor. In order to overcome the large magnetic potential drop which resulted in the large magnetic resistance of the gap between the movable magnet and static magnet, the excited coils of the conductor needs higher voltage that provides a larger current inside the coils and produce a higher magnetic force. Once the conductor entering the closing process, the less magnetic force will be required to maintain the closing process due to the no gap between the movable magnet and the static magnet. A less voltage will be imported on the excited coils to supply the suitable electromagnetic force for the closing process of the conductor. Comparison to the conventional conductor with the single source for the exciting coils, the research by Walcott [10] points out that the power consumption can be reduced by 86% if the pulse-width modulation (PWM) is implemented as the voltage control method for the exciting coils of the conductor. And, the consumption of power will save up to 30~60% due to the smaller radius of copper used for the less power consumption case.

This research will develop an electrical control board that implements PWM technology as the controlling method that provides dynamical modulation on the voltage of the exciting coils. The automatic adjustment of the electric voltage level for the exciting coils is according to the operating step of the conductor. The control board will record the fluctuating voltage level and self-adjustment of the duty cycle in order to maintain the constant voltage level for the exciting coils. The outcomes of the implementing this control method will extend the operation range of the external voltage on the exciting coils, reduce the electromagnetic noise, and lower the consumption of the power and material. Furthermore, the results of the function improvement of the conductor will project onto the performance of the design circuitry, the heat generation, complexity, the production cost of the circuitry. All leads to a prolongation of the lifespan of the conductor.

The remainder of the paper is organized as follows. A short description of the mechanism of the experimental apparatus is given in section 2. In section 3, we describe the principles of the PWM controller of our new contactor. In section 4, a systematically discussion is on the wide-pulse voltage method for the external voltage and the circuit design for PWM. Based on above mentioned control scheme, several experimental results are presented in section 5 to illustrate the application of the proposed methods. Finally, in section 6 we outline the main conclusions.

## 2 The Structure and Operation of AC Contactor

Conventional contactors are devices composed by a set of springs and magnetic circuit in which includes the moveable contact and stationary contact, as shown in Fig. 1. When a voltage is applied to the coil, an electromagnetic filed will be established around the magnet due to the exciting coils. A attractive force appears between the movable contact and the stationary contact by the electromagnetic force forces the movable contact move in the direction of the closing the gap and makes a contact with the stationary contact.

The exciting coil was used for generating the magnetic flux that controls the electromagnet of contactor operation. As the external power supply is

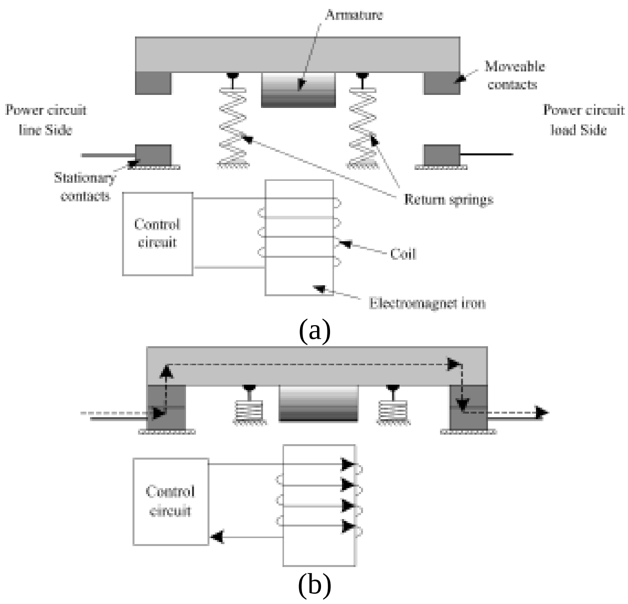



Fig. 1. Contactor configuration (a) opening position (b) closing position.

applied to the exciting coil, based on the ampere's right-hand rule, there creates an alternating magnetic flux and the magnitude of the alternating magnetic flux is proportional to the coil current. The electromagnet is made up by the low reluctance materials as in the lamination structure to reduce the eddy current.

Because of the lower reluctance feature of the electromagnet of contactor, most of the fluxes will flow and limit inside the electromagnet. According to the principle of the virtual displacement, an electromagnetic force will be generated between the movable and stationary electromagnets [5]. Two shading coils are installed on the pole surface of the stationary electromagnet that will establish a smooth electromagnetic field and make a reduction in the noise level for the closing process. They also are responsible for the development of a secondary alternating magnetic flux to stabilize the operation of contactor. The operation principle of the shading coils is described as followed:

### 2.1 One complete working cycle

Fig. 2 shows the current command profiles with the operation in the conventional ac contactor. During closing process in the conventional AC electromagnetic contactor, the transition time is shorter than the other two processes. After the movable iron core has closed with the fixed iron, the armature of the proposed AC contactor, little electric power energy is absorbed by the AC contactor within the holding process. Because the total reluctance is greatly reduced when two iron cores is closed together, therefore, the self-inductance across the coil suddenly becomes larger than in the closing process. 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. To wait the armature moves away the fixed iron core till the total reluctance in the magnetic becomes large enough. From the current command profiles of the AC contactor shown in Fig. 2, if most of continual working time of AC contactor is operated in the holding process, the outstanding energy-saving result should be obtained.

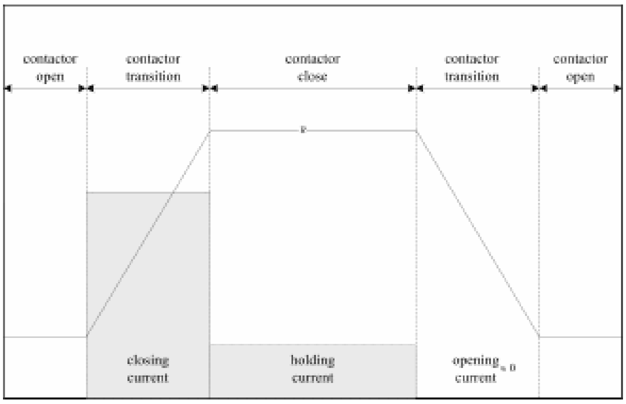



Fig. 2 Current command profiles with the operation of conventional ac electromagnetic contactor.

## 2.2 Dynamic behaviour of electrical system

When the exciting coil of contactor is supplied with an alternating current voltage, an alternating current will flows through a loop formed by the exciting coils and power source. The alternating current ($i(t)$) is assumed and given by:

$$i(t) = I_m \sin wt \tag{1}$$

where $I_m$ is the magnitude of the alternating current, $w$ denotes the frequency of the alternating current and $t$ is time. According to the ampere's rule, alternating magnetic flux will be generated and flows in the electromagnet. The intensity of the alternating magnetic flux is proportional to the magnitude of the coil current. We assume that magnetic flux is a sinusoidal function and lagging the coil current. According to (1), the magnetic flux ($\phi_s$) can be expressed by the following equation:

$$\phi_s = \phi_{mp} \sin \omega t \tag{2}$$

where $\phi_{mp}$ is the magnitude of the magnetic flux of the exciting coils. Since the magnetic flux is function of the time, and assume the magnetic flux passing through the shading coils is $\phi_{mps} \sin \omega t$, $\phi_{mps}$ is the magnitude of the magnetic flux of the shading coils. The induced voltage ($e_s$) by the shading coils is given as:

$$\begin{aligned} e_s &= -L \frac{di}{dt} \\ &= -e_{ms} \omega \cos \omega t \end{aligned} \tag{3}$$

where $L$ is inductance and $e_{ms} = \phi_{mps} \omega$. For the single one turn of the shading coil is setup, that is $L = 1$.

In general case, the radius of the shading coil is larger than the exciting coils and will need less turn of coil. And, the impedance is dominant by the resistance. The current of the shading coils is:

$$I_s = -\phi_{ms} \cos \omega t \tag{4}$$

where the $\phi_{ms}$ is defined as $\omega \phi_{mps} / R_s$. And, $\phi_{ms} >> \phi_{mps}$ due to the small value of $R_s$. The magnetic flux produced by $I_s$ is denoted as $K \phi_{ms} \cos \omega t$. $K$ is a constant. The relationship between the main flux and the shading coils is shown on Fig. 3. From Fig. 3, we found that the shading coils voltage must lag the exciting coil voltage by a phase angle $90^\circ$. These two kinds of magnetic fluxes can not go to zero at the same. Here, for simplicity, we assumed that both the exciting coil and shading coils have the same amplitude of the alternating magnetic flux, that is $\phi_{mp} = \phi_{mps} = \phi$.

The electromagnetic force created between the movable and stationary electromagnet is proportional to the square of the magnetic flux. The electromagnetic forces for the exciting coils and shading coils are given by:

$$f_1 = \phi^2 \sin^2 \omega t \tag{5}$$

$$f_2 = \phi^2 \cos^2 \omega t \tag{6}$$

where the $f_1$ and $f_2$ is the electromagnetic forces that are generated by the exciting coil and shading coils respectively. Total electromagnetic force, $f$, of contactor is the sum of these two electromagnetic forces and is given as:

$$f = k \phi^2 \tag{7}$$

where the constant k is the constant ratio of the electromagnetic force to square of flux. From (7), the electromagnetic force will be kept at a constant value. In other words, the function of the alternating current contactor is performed like the direct current contactor.

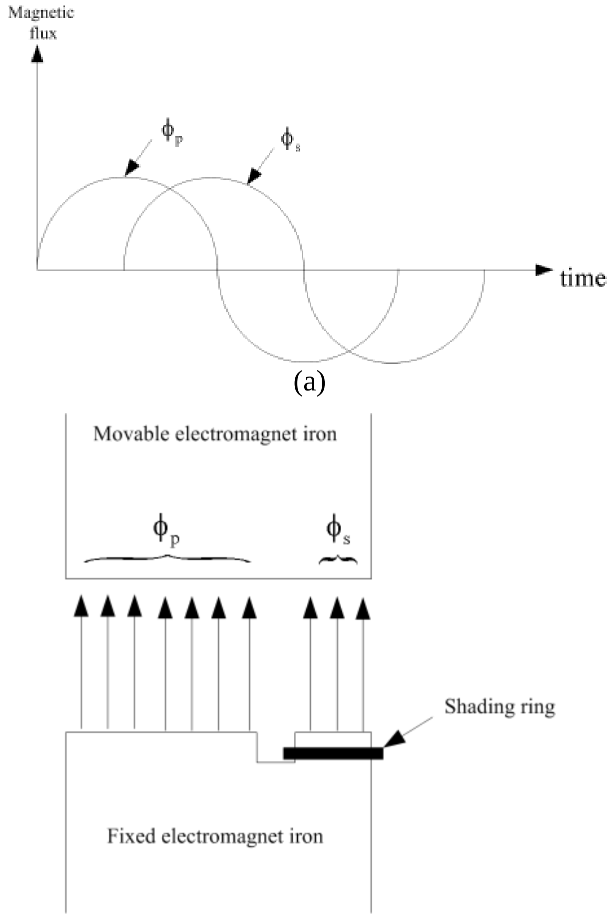



Fig. 3. Time-varying magnetic flux and shading coils.

## 2.3 Dynamic behaviour of mechanical system

Fig. 4 shows the equivalent mechanical mechanism of the AC contactor. Similarly, the dynamic behavior of the translational mechanical systems could be expressed by employing Newton's law of motion. Thus,

$$f = m\frac{d^2x}{dt^2} + D\frac{dx}{dt} + K(x - x_0) - F_e \tag{8}$$

The electrical energy input $W_{eo}$ can be expressed as

$$W_{eo} = \int e_l i dt \tag{9}$$

From Faraday's law, we can solve for the induced voltage $e_l$ in terms of the flux linkage $\lambda$, that is $e_l = d\lambda/dt$ [12], and substituted into (9) results in

$$W_{eo} = \int i d\lambda \tag{10}$$

An amount of energy is transferred from mechanical system to magnetic system, $W_{mo}$ is written as the work done by the magnetic force $F_e$ along with the opposite translational direction $x$.

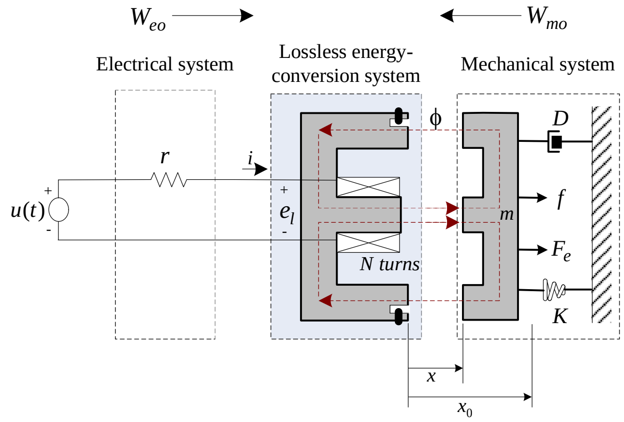



Fig. 4. Elementary contactor system.

$$W_{mo} = -\int F_e dx \tag{11}$$

Substitution of (10) and (11) into (8), we obtains

$$W_f = \int i d\lambda - \int F_e dx \tag{12}$$

## 2.4 Magnetic circuit.

The geometry and equivalent magnetic circuit of the developed ac PM contactor with colenoid actuator is shown in Fig. 5. Clearly, the considered magnetic mechanism of the ac PM contactor is symmetrical. Therefore, the magnetic circuit analysis can be simplified greatly. Compared with conventional ac EM contactor, we can see that a permanent magnet has been arranged on the fixed E-type core. By applying the magnetic circuit analysis technique, the magnetic equations can be written as shown below

$$\begin{cases} (\Re_1 + \Re_{x1} + \Re_3 + \Re_{x3} + \Re_4)\phi_3 - (\Re_3 + \Re_{x3})\phi_2 = N_1 i_1 + F_{mag} \\ -(\Re_3 + \Re_{x3})\phi_3 + (\Re_2 + \Re_{x2} + \Re_3 + \Re_{x3})\phi_2 = i_2 \end{cases} \tag{13}$$

where the reluctances in each part of the magnetic circuit are calculated respectively by using reluctance principle and expressed as follows:

$$\begin{cases} \Re_1 = \dfrac{l_1 + l_1' + l_3}{u_0 u_r A_1}, \Re_2 = \dfrac{l_2}{2u_0 u_r A_2}, \Re_3 = \dfrac{l_2}{2u_0 u_r A_3} \\ \Re_{x1} = \dfrac{x + e}{u_0 A_1}, \Re_{x2} = \dfrac{x}{2u_0 A_2}, \Re_{x3} = \dfrac{x}{2u_0 A_3}, \Re_4 = \dfrac{l_3'}{u_0 u_r A_1} \end{cases} \tag{14}$$

As can be seen in (14), the reluctance in each part of magnetic circuit is generally a function of the average length of individual magnetic circuit. After the total reluctance $R(x)$ is obtained, the equivalent inductance value $L(x)$ from the coil view point can also be derived by the following formulas:

$$L(x) = \frac{N^2}{R(x)} \tag{15}$$

where $N$ is the number of windings of coil.

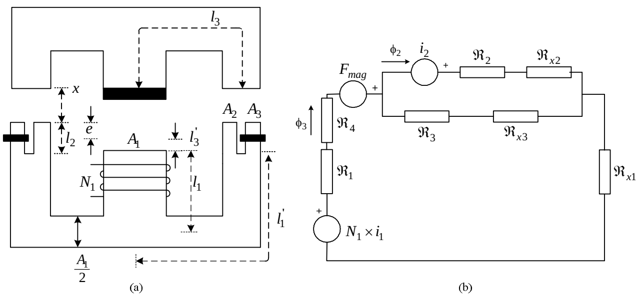


Fig.5. Developed ac PM contactor, (a) sketch of the geometry and (b) equivalent magnetic circuit

### 2.5 Work-Energy theorem.

On the basis of the behavior of magnetic energy-conversion system is conservative and lossless; the energy transfer from mechanical system to electric system or vice versa is determined by the moving direction of armature. The work done $dW_m$ by the mechanical system which equals the variation of armature displacement multiplies the magnetic force; it can be further deduced as follows[13]:

$$\begin{aligned} W_m &= -\int_x^{x_0} F_{mag}\, dx \\ &= \int_{v_0}^{v} mv dv \\ &= \frac{1}{2}mv^2 - \frac{1}{2}mv_0{}^2 = \Delta E_k \end{aligned} \tag{16}$$

where the initial velocity of armature $v_0$ is assumed to be zero, the final kinetic energy of armature $E_k = (mv^2)/2$ is determined by the final velocity of armature $v$ at the moment of two contacts impact. As we known, the final kinetic energy of armature is equivalent to the energy transfer from the magnetic field to the mechanical system. Equation (16) is well-known as work-energy theorem.

## 3 Principles of the PWM Controller

The block diagram of the proposed electromagnetic contactor is shown on Fig. 6. Both the AC and DC power input voltages are allowable in our new contactor. In order to maintain the constant voltage level in the exciting coils, PWM technology is implemented and used to modulate the variation of input voltage by dynamically adjustment of duty cycle of output pulse of controller. After analysis the operation sequence of the contactor, the less electromagnetic force is required to maintain the making process when the contactor enters the making process. The power consumption of the exciting coils is proportional to the square of the electromagnetic force. From the consideration of reducing of power consumption of the exciting coils, a lower voltage level will apply to sustain the minimum requirement for the making process. This is the reason that the application of PWM technology can achieve a longer life span of the conductor by means of low power consumption.

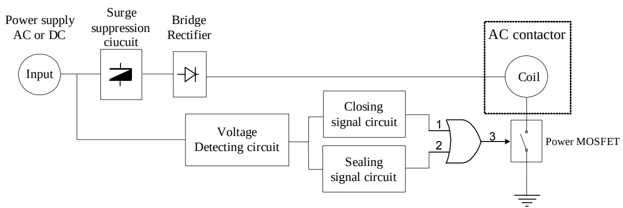



Fig. 6. The function block diagram of the proposed actuator of AC contactor.

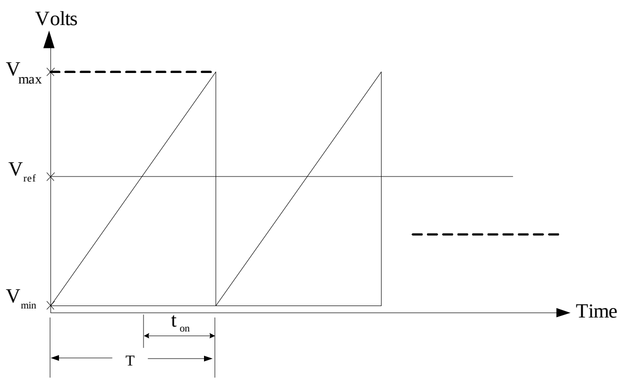



Fig. 7. Operation principle of the proposed PWM method.

The voltage level of the exciting coils in the proposed contactor is controlled by the operation sequence of the power transistor (PTR). As shown in the Fig. 6, the operation of the PTR is much look like the operation of a mechanical switch. The operation is controlled by a control board that is consisting of analogy components. The relationship between the voltage level of exciting coils and the external voltage input of the contactor is shown by the PWM waveform on the Fig. 7. Comparison of a saw-teeth wave $V_{tri}$ to a DC reference voltage $V_{ref}$, a voltage pulse $V_{coil}$ of exciting coils is obtained. As the variation of reference voltage, the time $t_{on}$ for high level voltage output will be longer and the output duty cycle of PWM will be bigger. The relationship between contactor coil and input line voltage can be calculated from the equation for the average voltage generated by a PWM waveform.

$$V_{coil} = V_{in} \frac{t_{on}}{T} = d\,V_{in} \tag{17}$$

where the parameter $d$ is defined as $t_{on}/T$, $T$ is called the period of duty cycle, $V_{coil}$ is the exciting coil of contactor driving voltage; $V_{in}$ is the output direct current voltage of the bridge rectifier which built in the electronic control module. By the geometry relationship, (17) can be approximated by:

$$V_{coil} \approx V_{in} \frac{V_{\max} - V_{ref}}{V_{\max} - V_{\min}} \tag{18}$$

$V_{\max}$ and $V_{\min}$ are the maximum and minimum voltage, respectively. For the invariant of $V_{coil}$, the ratio of $V_{\max}$ and $V_{\min}$ will be constant. Rearranging (18), we get:

$$V_{ref} \approx V_{\max} - \frac{K}{V_{in}} \tag{19}$$

where constant $K$ is defined as $V_{coil}(V_{\max} - V_{\min})$. Form (19), the raising the level of the external control voltage ($V_{in}$) will result in the increase of DC reference voltage $V_{ref}$. By the PWM operation, the time $t_{on}$ for the high level voltage reference of pulse issued by PTR will be shortened. Therefore, the average voltage level of exciting coils will be reduced. In the opposite end, the $t_{on}$ will be longer and the $V_{coil}$ will increase when the input of external voltage is lower.

According to the [6], the instantaneous force that tends to close the air-gap in the contactor can be expressed by:

$$f = \frac{\phi^2}{2\mu_0 S} \tag{20}$$

where $S$ is the cross sectional area of the pole of contactor and $\phi$ is the instantaneous flux that is proportional to the current of the exciting coils. In the following analysis, the coil voltage $v(t)$ is assumed to be sinusoidal with a form

$$v(t) = V \sin(wt) \tag{21}$$

where current is $90^{o}$ lagging with voltage due to the inductive load of the exciting coils. The attractive force in the making process is equal to the counterforce produced by the spring. The instantaneous force tending to close the air-gap is given as:

$$f_{\min} = \frac{\phi^2{}_{m,\min}}{2\mu_0 S} \tag{22}$$

$\phi_{n,\min}$ is the minimum flux required to keep the making process. And $\mu_0$ is the free space permeability. The minimum hold-in-voltage ($v_{hold,\min}$) is given by:

$$v_{hold,\min} = \frac{N_C\ \omega\ \phi_{m,\min}}{\sqrt{2}} \tag{22}$$

where $N_c$ is the coil turns and $\omega$ the frequency of the external power .

The physical meaning of (22) is that if the externally applied coil voltage is must higher than the minimum coil voltage $v_{hold,,\min}$, the contacts of contactor will be hold during the voltage fluctuation in terms of flux and frequency.

# 4 Interchangeable AC/DC Power Source

In addition to this innovative electronically controlled contactor can normally operate under both AC and DC power supply, it is also capable of flexibly choosing the operation voltage range in term of the power line voltage level through the switch. Normally, we assumed that the power supply voltage is V, the 2V of the power supply voltage also be compatible with our proposed power control circuits. Integration of this roughly power-supply selection method into the PWM technology, the flexibility of power supply is improved greatly and the operation voltage range of contactor is widely extended. In the following, we prepare to describe this roughly selection method and PWM technology respectively.

It is shown in the Fig. 8, no matter what the kinds of the power supply, $V_{in}$, the power source has got to go through the bridge rectifier and the bridge rectifier's output terminals produces DC voltage. According to the actually the operating voltage range of power supply, user can utilize the voltage-level-selection switch, $S_{vls}$, and properly choose the circuit configuration. The output voltage of the power voltage selection circuit, $V_{out}$, always keep at constant voltage output.

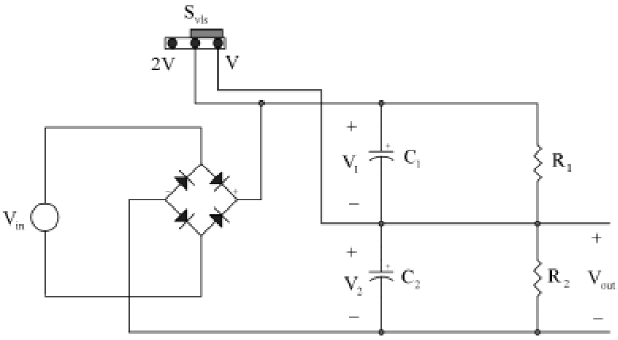



Fig. 8. The circuit structure for modulating the different input voltage levels.

Make use of the switch, $S_{vls}$, the power supply of contactor could be supplied with both AC and DC power supply. According to the operating necessities in the application fields, the switch $S_{vls}$ was responsible for the selection of the coil voltage level.As shown in the Fig. 8, we assumed that the voltage level of node A is $V_A$. The voltages across the terminals of the capacitors $C_1$ and $C_2$ was obtained by the voltage-divider law and represented as follows:

$$V_{out} = \frac{C_1}{C_1 + C_2} V_A \tag{15}$$

In order to obtain a better operating performance of contactor, the PWM technology is used to regulate the coil voltage based on the operation phase. Refer to the Fig. 9., we found that the coil current of contactor in the moving phase is larger than any other operating phases. Sufficient electromagnetic force is needed to move the movable parts of the contactor. The coil voltage should be supplied with pick-up voltage. As shown in Fig. 9, the coil voltage is supplied with a square wave or the duty cycle is 100% pulse in the moving phase. When the moving phase is completed, the operation of contactor enters the closing phase. After the movable irons have closed with the fixed irons, the needed coil current for producing electromagnetic force becomes less. Therefore, the coil voltage is supplied by a series of pulses that are generated by the PWM controller. By monitoring the power line voltage level, the output voltage of the electronic module intend to keep a constant value under self tuning the duty cycle of PWM which significantly reduces the nominal operating power dissipation of the contactor.

For the sake of improving the operating efficiency of a contactor, we intended to develop a new electronically controlled contactor based on the power and materials saving necessities. The electronic control circuit is designed and composed of some analogue devices. The circuit is compacted in a printed circuit board that is conveniently plugged in the conventional contactor.

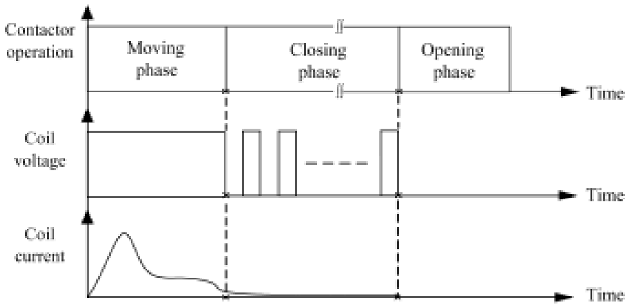
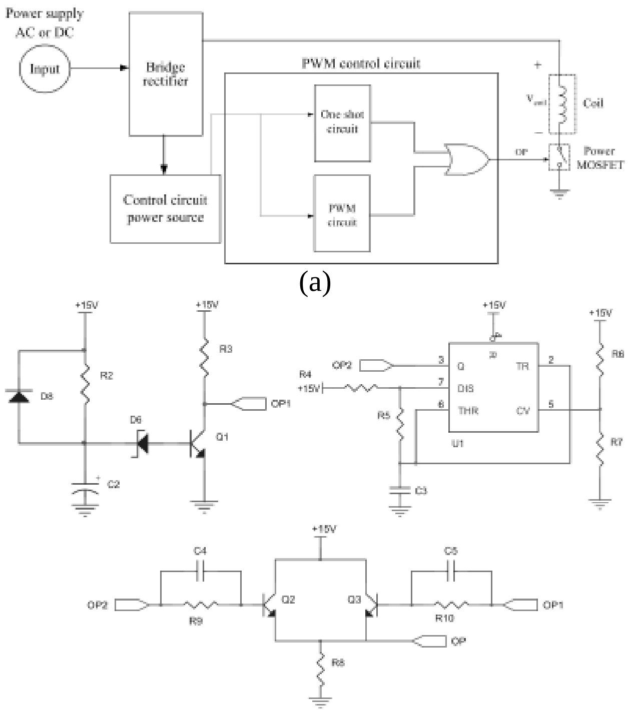



Fig. 9. The typical coil voltage, and coil current of AC contactor under one completed operating cycle.




(a)

(b)

Fig. 7. Electronic controlled AC contactor: (a) functional block diagram (b) PWM control circuit.

Fig. 10(a) shows the functional block diagram of electronically controlled contactor. The coil voltage of contactor is regulated by the power MOSFET. During the operation of the contactor, both the one-shot circuit and PWM circuit begins to generate signal at the same time. These two signals are combined together with logical OR gate. The resulting signals of the OR-gate output are utilized to trigger the power MOSFET for obtaining the pulse-type coil voltage. PWM control circuit, which is part of the control circuit, is presented in the Fig. 10(b). Based on the different operating characteristics of contactor, the high-level sustaining time of the one-shot generator is regulated by a lowpass filter which is consists of a resistor and capacitor.

## 5 Experimental Results

The new electronically controlled contactor prototype was constructed at our laboratory. Fig. 11 is a picture showing the new electronic control contactor that includes a conventional contactor and electronic control board. Due to the addition of the electronic control board, AC or DC power supply could be used as the coil voltage.

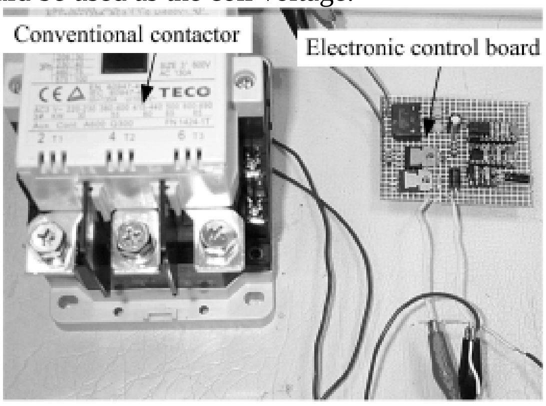



Fig. 11. The photograph of a completed electronically controlled AC contactor.

When the contactor is situated at moving phase, a higher current is absorbed by the coil in order to create an electromagnetic force high enough to overcome the spring counterforce and move the movable electromagnet gradually toward the fixed electromagnet. As shown in the Fig. 12, the channel 1 is the coil current waveform when the contactor works on the moving phase. After the moving phase, we observed the Fig. 13 that the coil current waveform in the closing phase, the coil absorbs less current for creating an electromagnetic force so as to keep the mechanical contacts from tripping. From lots of practical applications, we known that most of the time the contactors are kept in the closing phase. If we can moderately regulate the coil voltage, the power dissipation of coil should be reduced greatly. Meanwhile, the utilization of the electrical and mechanical materials will be significantly decreased as well.

In order to extended the operating voltage range of the coil, the coil voltage can be supplied with both AC and DC power supply, and the voltage level, $V$ and $2V$, is allowable to used in our new electronically controlled contactor, as shown in Fig. 14. Regardless of the kinds of the power supply, once that the input voltage of contactor is, $V$ and $2V$, the output voltage always keep in a nominal coil voltage, $V$.

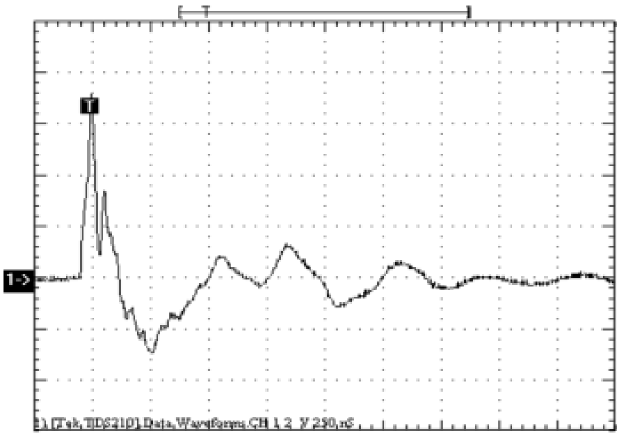



Fig. 12. The coil current waveform of contactor in the moving phase.

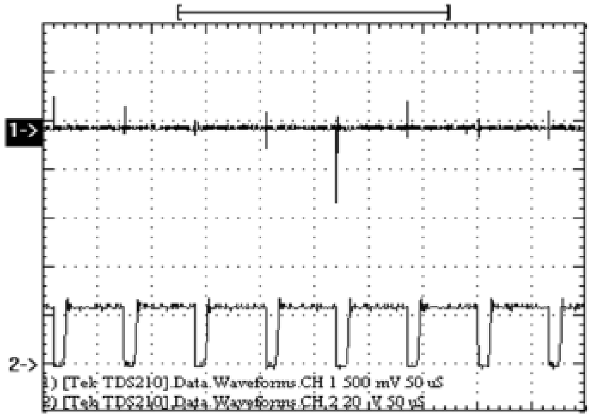



Fig. 13. Channel 1 and 2 are the coil current and drain-to-source voltage of the power MOSFET.

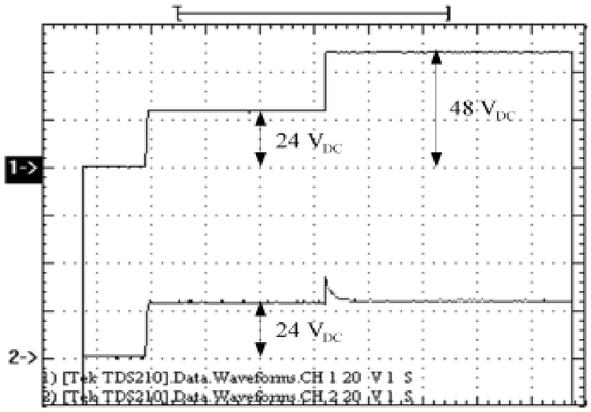



Fig. 14. Channle1 shows that the input voltage of the external power is at the rating voltage (V) or double the rating voltage (2V). Channel 2 shows that the voltage imported on the exciting coils remains on the rating voltage level.

## 6 Conclusion

A new contactor that consisted by an innovative electronically controller is designed and presented here. An electronic control board is built that incorporated the functions such that, regulating the voltage fluctuation, accommodate both DC and AC power supply used, and achieving the goal of power and material saving. For the experimental results, the newly designed controller is validated and feasible in the practical operation.

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