To Develop a New Arcless and Power-Saving Power Relay with Hybrid Contacts

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Abstract: - When a power relay is used as a switching device to close and break the loading current by using its mechanical contacts, especially DC heavy load, high-temperature arc is often generated between their contacts due to contact bounces and heavy DC load current flowing them. Arc often leads to seriously shorten the using life and decreases the operating stability of contact and application system. Besides, the contact arc is also radiates electromagnetic interference at the same time. In this paper, the author provides a new power relay with hybrid contact. It is then able to be used as the switching device of DC heavy load. This hybrid contact is composed of power electronic devices and the original mechanical contacts of power relay in parallel. The instantaneous heavy DC load current is arranged to flow through the power electronic device. Meanwhile the stable load current flows through the mechanical contact. Both advantages of these constituting devices are included in this hybrid switching device. The arcless and power-saving purpose will be acquired. For the purpose of verifying the feasibility of this new hybrid switching device, a laboratory-scale prototype of this new power relay with hybrid contact was established in our laboratory. Several useful experiments are carried out under different load and power source conditions. The collected experimental result shows that the proposal new power relay with hybrid contact is actually feasible and valuable. There is no arc occurred during the closing and breaking the DC load current process. Much more energy can be saved if the working time is taken in the closed process.

Key-Words: - Power relay, Electromagnetic interference, Power electronic device, Hybrid contact.

1 Introduction

Power relay is one of a typical electrical to mechanical conversion and low voltage rating component. Input electrical energy and then is converted to mechanical energy for the purpose of moving the movable contacts of power relay. The load current is then switching to on or off by their moving contacts. For the external applied voltage source, the coil of power relay is belonging to an inductive load. Amount of magnetic energy will be stored in the magnetic system during each working cycle. The power relay works much like a filter component when it is supplied with a constant voltage source. Therefore, the current flows into the coil of the power relay can not be suddenly changed [1-5].

In many industrial application fields, the mechanical contacts are usually used as mainly switching device for closing or breaking the load current, especially the DC heavy load. Power-relay contact closure performed in the course of action, before contacts closure enters into a stable mechanical contacts shown in Fig. 1 often occurs between the contacts closed repeatedly phenomenon. This result for the controlled circuit or load may thus result in malfunction. If the device is used in closing or breaking the heavy DC load current, it may result in high-temperature arc between the contacts. This arc often causes to shorten the using life of a mechanical contact and to decrease the operating reliability of the applied equipment.

According to the physics theory, the contact bounce would be generated when the movable contacts or the armature of the power relay touches with the fixed contacts, and results in movable contact with excessive kinetic energy. The moving kinetic of movable contact of the power relay is a function of the average applied coil voltage value. Therefore, if the moving kinetic of the power relay would be hoped to be changed dynamically in the closing process, it can be achieved by means of switching the applied coil average voltage value of the power relay. The moving velocity of the movable contacts is then controlled. The bouncing duration after the movable contact first collides with the fixed contact during the closing process can be effectively decreased or even be removed completely [6,7].

2 Bounces Occur in Closing Process

When the movable contact touches with the fixed contact, both the collision effect and the arc with high temperature will serially decrease the using life of the contact included in power relay. Severe, probably because the contact arc with high temperature occurs and leads to erode the contacts result, the contacts therefore can no longer perform normally breaking action, cause equipment malfunction, threatening the lifespan of device and the safety of equipment operators [8,9]. The number of times and the total maintaining duration of the mechanical contact bounces after the collision of both the movable contact and the fixed contact is generally close related to the moving kinetic energy of movable contact before the collision event occurred. According to the theory in physics, the kinetic energy of the moving object and the moving speed of an object can be described by the relation as follows [10]:

$$E = \frac{1}{2} m v^2 \tag{1}$$

Equation (1) means that the kinetic energy of the movable relay contact or the armature is proportional to the square of its moving speed value before collision. So that, there is a critical conclusion can be deduced from the Eq. (1). If the moving kinetic energy of the movable contact during the closing process is hoped to be controlled for reducing the bouncing duration after the collision of both movable contact and fixed contact, the optimal controlling strategy is to effectively control the moving speed of their movable contact. In fact, the use of objects collision analysis in physics also know, the collision occurred since the movable contact first collides with the fixed contact is a kind of elastic collisions. Since the fixed contact is always stationary, the moving speed of fixed contact after the collision is kept at zero value. On the other hand, the movable contact is mechanically couple with the movable iron. After two objects are collided together by different initial velocities, these two objects would be moved toward contrary direction. After the collision, the fixed contact is still kept stationary or none of real displacement. Since the system spring provides a tension force to the movable core after the collision event generated. The moving force in the closing direction will be decreased step by step. Finally, the movable contact should be situated in stationary status due to the kinetic energy dissipated completely. Because there is excessive instantaneous kinetic energy is included in the movable core, therefore, the time is needed for dissipating the excessive kinetic energy after the contacts collision. Meanwhile, an occasionally and repeatedly contact bounce duration during the closing and breaking process generated between the mechanical movable contact and fixed contact. The reason is that the movable contact, movable core and contact frame are mechanically coupled together. The symbol m represents the mass of the power-relay armature. The motion equation of the power relay can be represented by using the moving speed of its armature or iron core as follows[11-16]:

$$v = \int \frac{F_e - F_f}{m} dt \tag{2}$$

where the meaning of the symbols shown in Eq. (2) is given respectively:

F_e, F_f : the magnetic force and spring force;

m : the mass of armature;

v : the moving speed of armature;

t : the closure duration.

Apparently, Eq. (2) shows that the moving speed of armature of the power relay depends on the magnetic force F_e. If the magnetic force F_e acting on the armature is hoped to be controlled or adjusted, it can be achieved by means of changing the coil current. Since the magnetic force F_e is function of the square of coil current. The lagging angle between the applied coil voltage and coil current is dependent on the equivalent excitation coil impedance of power relay. In addition, the equivalent inductance across the coil is function of the position of the armature and they are often a nonlinear relationship each other. For a typical power relay, the more the movable core is closing to the fixed core, the more the equivalent inductance across the coil is. So this is desirable to control the excitation coil voltage applied in the closing process. Because the instantaneous applied voltage and the equivalent impedance across the coil are different, so the coil current will also be different. Take advantage of this special feature of the power relay to control the armature mechanism velocity, as result of the kinetic energy of the contacts before collision is controlled at the same time. Indirectly, the mechanical contact bounces of power relay will be effective suppression.

3 Working Principle of Hybrid Contact

3.1 The structure of hybrid contact

The purpose of this article is to design a new power relay with pairs of hybrid contacts based on a traditional electromagnetic-type power relay and a field-effect power transistor (MOSFET), it is a kind of voltage-controlled power electronic components, voltage sensing circuit, driving circuit and an intelligent electronic controller circuit as shown in Fig. 2, are included. A power electronic component and a mechanical contact of the electromagnetic type of power relay are connected in parallel together. Power electronic device has fast transition and response characteristics. The use of the superior advantages of power electronic is to execute the precise control. It is used in a required long conduction application, the heat generated by the internal resistance loss increase due to the increase temperature of the element. In other words, it is ideal for a short period of conduction like that it conducts only in the closing or opening instantaneous stage. Relatively, the power dissipation of the mechanical relay contacts in the steady state condition is very low due to low mechanical resistance across two contact terminals. This special feature included in the mechanical contact of the conventional electromagnetic-type power relay is very fit to conduct a large stable load current for a long time, but the response speed of mechanical contact is slow and easy occurrence caused by a short arc with high temperature between the contacts. In this paper, their advantages both the power electronic device and mechanical contact are adopted to form a new hybrid contact. These two types of switching component are connected in parallel [15,16]. Figure 2 is the configuration block diagram of the new power relay with proposed hybrid contacts. In Fig. 2, the symbols U_C and U_L represents the external applied coil voltage source and load voltage source, respectively.

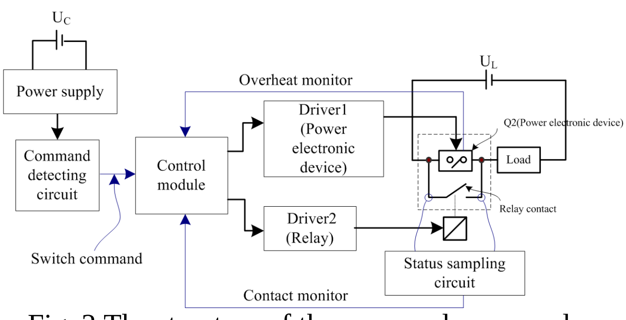

Fig. 2 The structure of the proposed power-relay hybrid contacts.

3.2 The working sequence of hybrid contact

During a complete working cycle of the hybrid contact of power relay, it can be further divided into seven different sub-steps. The former four sub-steps are belongs to the contact closing process, while the remaining three sub-steps are responsible for the breaking process. All the sub-steps included in a working cycle will be introduced step by step in the following:

Phase 1($t_1 \sim t_2$): The closing command is detected y the arranged voltage sensor. A closing command is ordered by the electronic controller, both the coil and the power MOSFET of hybrid contact should be driven at the same time. Naturally, the closing speed of power MOSFET would be faster than that of the mechanical contact of power relay due to their fast response time. Within this time difference duration, the load current flows into the power MOSFET. Compared to other working phases, the load current in the starting phase is the largest. Much of the thermal pressure would occur on the power MOSFET during the starting phase, therefore, this phase is a critical phase. Meanwhile, the coil is triggered by the controlled power MOSFET. The coil current is exponentially increasing. It is necessary to take some time about tens of mili-seconds for generating sufficient electromagnetic force. The movable contact is then truly closed with the fixed contact of power relay.

Phase 2($t_2 \sim t_3$): When the movable contact of power relay first touches with the fixed contact, a series of contact bouncing phenomenon is a inevitable result. Due to the voltage difference between the movable and fixed contacts is very small, the arc occurring condition between these two colliding mechanical contacts is insufficient.

Phase 3($t_3 \sim t_4$): Once the contact bouncing phenomenon stops, the electronic controller of the proposed power relay will immediately command the power MOSFET in the hybrid contact to stop too. This represents the mechanical contact would replace the power MOSFET to flowing across the load current. The power MOSFET in hybrid contact has completed the conducting mission during the closing process.

Phase 4($t_4 \sim t_5$): When the power MOSFET has been turned off, the working status of the power relay enters into the closed process.

Phase 5: When the sensed coil applied voltage is lower than the reference voltage threshold value, this represents the power relay enters into the opening process. The electronic controller will

turned off the power MOSFET which controls the coil voltage. At the same time, it will command the power MOSFET in hybrid contact to work again for by-passing all load current.
Phase 6($t_5 \sim t_6$): After about ten mili-seconds, the mechanical contacts break. Since most of load current conducts through the power MOSFET in hybrid contact, therefore, parts of load current and small voltage difference between the mechanical contacts. Arc with high temperature will not be occurred between the contacts. The contacts erosion problem due to the high-temperature arc is completely removed.
Phase 7(t_6 ~): The power MOSFET in hybrid contact is turned off by the electronic controller.

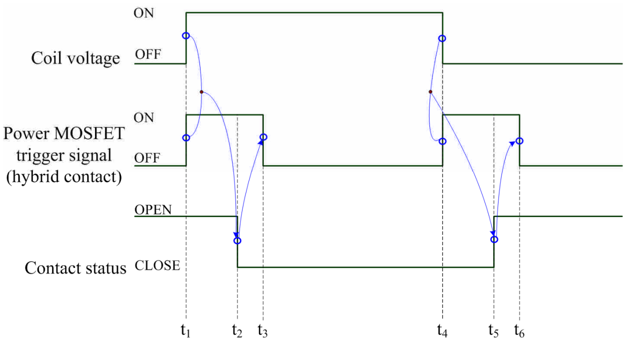

Fig. 3 The typical working sequence of the power relay with hybrid contact within a complete cycle.

The operation of this proposed power relay with hybrid contact is therefore very reliable. The mechanical contact of power relay is eroded by the high-temperature arc is very small. In other words, there is none of the using problem such as the lifespan is shortened. The contacts of the conventional electromagnetic power relay are usually affected by the high-temperature arc and the thermal pressure during the opening process. Moreover, this result can be neglected due to small occurred arc between the contacts of the proposed power relay in the opening process. The generated arc between the contacts is affected by the total inductance value across the mechanical contact or the power MOSFET in hybrid contact. In a typical electromagnetic power relay, it takes about 8 mili-seconds from triggering the coil to really closing their contact. During this operation time, the load current is conducting through the power MOSFET in hybrid contact. If the turn-on time is long enough, the temperature occurred on the power MOSFET device would be too much leads to corrupted possibly. In many practical applications, an extra dissipated heat device is generally required. Finally, the manufacturing cost and the total volume of the proposed new device becomes larger.

4 Electronic Controller Design

After trying to connect and modify the electronic controller circuit, as shown in Fig. 4, the system kernel of the electronic controller is an 8 bits single chip, the part number is PIC16F883 and is manufactured by the Microchip Corp. When the signal Vstart is changed from low logical voltage level to high logical voltage level and sent to the single chip, this represents the +5V power source of the controller has been established. As mentioned earlier, an idea working sequence of the proposed power relay has programmed. If the taken time from the coil is triggered to the mechanical contact is closed and the conducting time of the power MOSFET in hybrid contact are as short as possible, the thermal pressure occurred on the power MOSFET in hybrid contact would be decreased since the generated power loss on the power MOSFET, Q10, is reduced. Therefore, the electronic controller will trigger the power MOSFET, Q10, to turn on and maintaining about 10 mili-seconds by outputting a signal Vsw from the single chip. Since the real conducting time of the controlling power MOSFET in hybrid contact is not too much time. The temporarily load current is almost not conduct through the mechanical contact. The coil of the power relay will be changed to a smaller duty cycle driven Q9 conduction, reach the power-saving purpose.

In Fig. 4, the bottom of the controller circuit is the required DC voltage generation circuit. The required DC voltage in the system control circuit is divided into three groups: the first is the +24 V, supplying with the coil of power relay. The second is +15 V, serves as the power source of the driving circuit of the power MOSFET, including the Q9 and Q10. The third is +5 V, the main action is necessary to supply single-chip power supply.

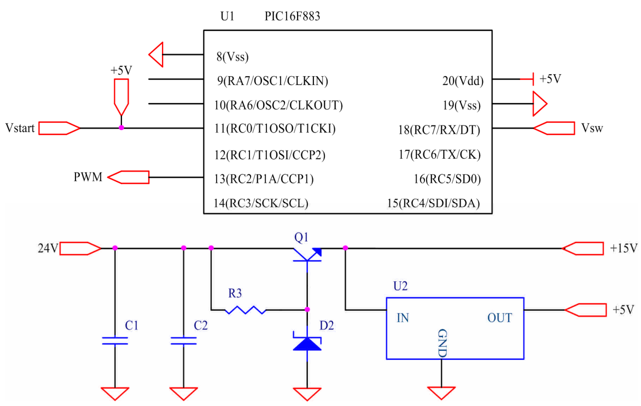

Fig. 4 The DC power generation circuit for supplying the single chip and electronic controller during the opening process.

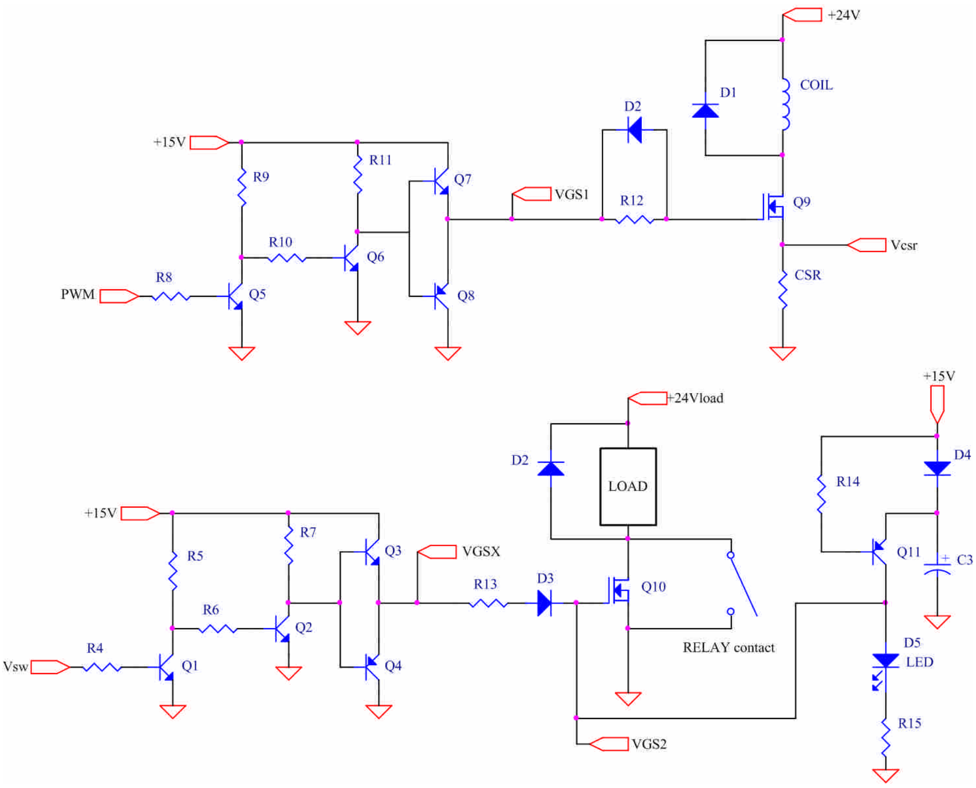

Fig. 5 The structure of the coil, hybrid contact and their driving circuits.

Figure 5 includes two sets of circuit for driving both the power relay coil and the power MOSFET in hybrid contact, respectively. In order to have the predicted controlling performance of the new proposed power relay with hybrid contact, the system hardware circuits or devices should be integrated into single-chip software. The algorithm of the software has to be carefully programmed, designed and implemented. Any of these necessary critical affecting elements is malfunction. The system function would not work well. The working sequence of the single-chip software is carefully programmed. The Fig. 6 is the working flowchart of the single-chip software. Finally, the system function will be tested by integrating with the hardware circuit and software.

5 Experimental Results and Discussions

For verifying the performance of the new proposed power relay with hybrid contacts under different testing conditions, a laboratory-scale prototype of the proposed power relay has been designed and implemented. Figure 7 shows the completed prototype picture of this new power relay.

As shown in Fig. 8, the meaning of the symbols used in the figure is explained as follows:

Ch1: the applied coil-voltage waveform, the voltage difference between the drain and the source poles;

Ch2: the voltage waveform between the gate and ground;

Ch3: the contact working status. “High” voltage level represents that the contact is broken. “Low” voltage level represents that the contact is closed;

Ch4: the coil’s triggering logical signal before the driving circuit.

The actually applied average coil’s voltage of the new power relay is controlled by the duty-cycle value of the input logical signal of the power MOSFET driving circuit. When the coil of the power relay starts powering the source voltage, this power-on signal is also sent to the single chip included electronic controller. The responding algorithm of the single-chip software is that none of action is until to ten mili-seconds later. A logical high level signal, Vsw, is transmitted from the single chip on electronic controller for commanding the power MOSFET in hybrid contact to execute the closure action. This logical signal, Vsw, should be kept on high logical level under sufficient time in order to avoid the contact bouncing duration of the mechanical contact. Here it is set about 5 mili-seconds. After the default time delay of Vsw is

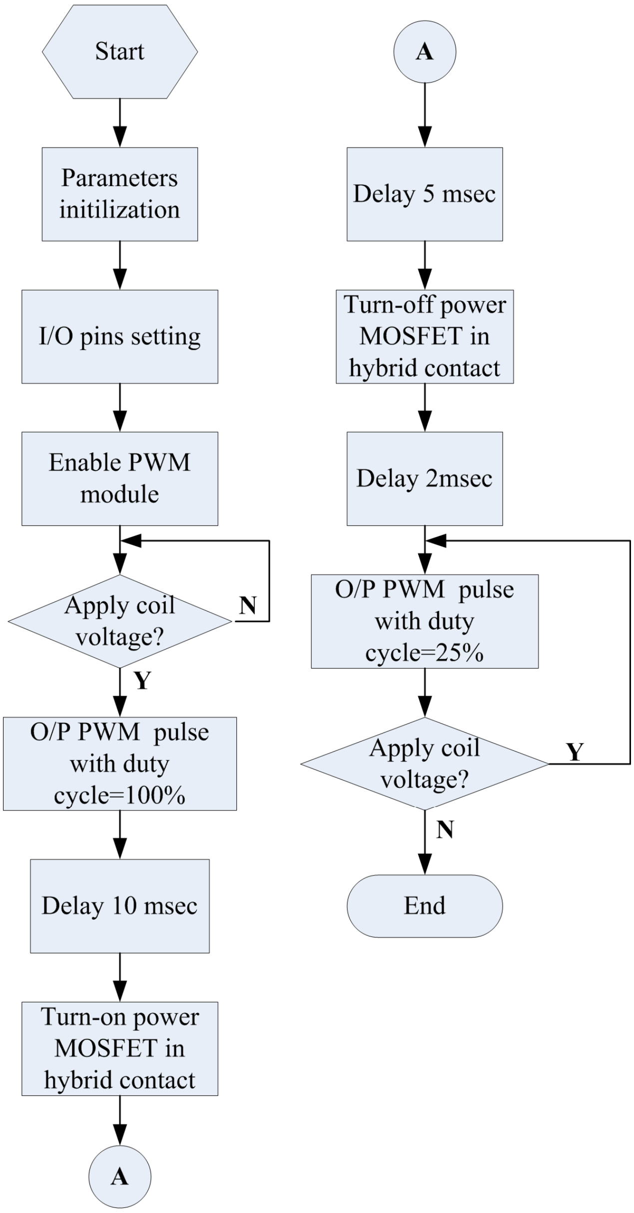

Fig. 6 The working flowchart of the controller

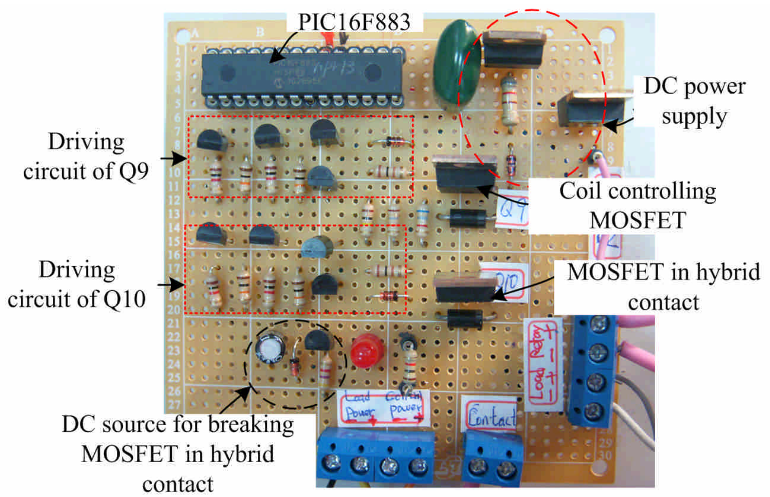

Fig. 7 The picture of the completed laboratory-scale electronic controller prototype.

reached, the power MOSFET in hybrid contact is turned off right away. Once the power MOSFET in hybrid contact has carried out the by-passing inrush and unstable load current mission, the applied coil voltage of the power relay will immediately be changed to a lower coil voltage by adjusting the duty cycle. However, the triggering signal of coil voltage commanded by the single chip would be always kept working at 20KHz. The opening process is time duration from the coil's voltage is removed to their mechanical contact is actually broken. A number of the contact bounces is usually occurred between their mechanical contacts. The arc with high temperature also appears between the movable contact and the fixed contact and leads to shorten the contacts lifespan. Finally, the using life and operating reliability of the contact of the power relay is then decreased. During the opening process, the external voltage source has been removed. There is no any DC voltage exists in the electronic controller circuit. For reducing or removing the high-temperature arc between the two contacts, a DC voltage source must be stored in the circuit in before the external applied power source is removed. Once the open process starts, the stored DC voltage will be supply the power to the electronic controller circuit for automatically generating a trigger signal for turning on the power MOSFET in hybrid contact. Therefore, the occurred arc with high temperature between the two contacts during opening process would be avoided effectively. Of course, the lifespan and operating reliability of the mechanical contacts of the power relay is prolonged.

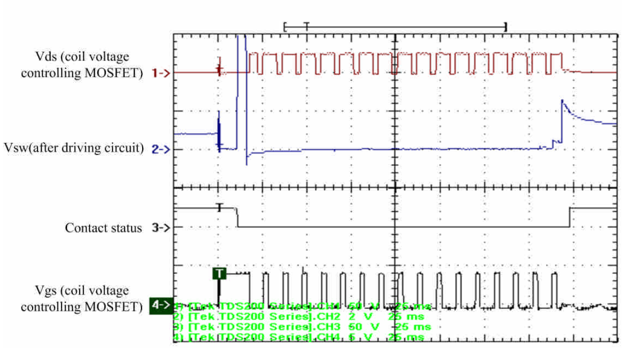

Fig. 8 Measurement waveform: ch1: Vds of MOSFET, Q9；ch2: Vgs of MOSFET, Q10；ch3: contact status；ch4: Vgs of MOSFET, Q9.

To observe the waveform of Vgs of the MOSFET, Q9, in channel 4, the applied coil's voltage value of the power relay is full voltage since the duty-cycle of trigger signal of MOSFET is 100%. In generally, the mechanical contact of the power relay executes the closing process from the coil is applied a voltage to their mechanical contact is closed. When the turn-on duration power MOSFET in hybrid contact within closing process ends, this triggering signal is usually kept on high logical level for 2 mili-seconds. Next, the coil voltage controlling MOSFET of the power relay will be changed to another pulse signal with lower duty-cycle value. The duty cycle is kept on 25% and the contact of power relay maintains closing. In other words, when the working status of power relay enters into closed process, the coil applied voltage is changed to a value which is one-fourth of the full applied voltage for the purpose of the energy saving. From the contact status waveform shown on the channel 3, there is no contact bounces is generated among one complete working cycle of the power re lay. Therefore, none of arc occurred on the contacts during closing and opening would be sufficient to the anticipated goal of the new proposed power relay with hybrid contact. In the following subsections, some different types of device such as resistive load, capacitive load and inductive load will alternately be served as the load of the proposed new power relay with hybrid contact. Through these valuable experiments and their experimental results, the effectiveness and the performance of the power relay and its electronic controller will be verified.

5.1 Resistive load

Case A. The load DC power voltage source is 12V and the load is a cement resistor with six ohm

As the ch1 and the ch4 shown in Fig. 9, the coil's current of the power relay and the Vgs voltage waveform of the power MOSFET in hybrid contact, the coil's current and the coil's applied voltage controlled MOSFET are exponentially decreased during the opening process. Since there is a plastic capacitor is added across between +24V and ground, its capacitance is 0.47uf. In addition, the theoretical load current should be about 2A, none of high-temperature arc and contact bounces between the two mechanical contacts is occurred when the power relay with hybrid contact executes the opening process.

Observing the contact status shown in Fig. 9, there is no mechanical contact bounces occurred however the hybrid contact is situated in the closing or opening process. In fact, the reason why no contact bounces generated between the two colliding contacts during the closing and opening is that a power MOSFET is integrated into the original mechanical contact of the power relay in parallel. Especially, this special power MOSFET is only turned on in the beginning stage of the closing and opening process. The other time within a complete working cycle of the power relay does not work. On the one hand, the total mechanism volume does not increase too much because none of dissipating heatsink is required in most application fields; in the other hand, the manufacturing cost is reduced as much as possible since the basic working rating of the device is low.

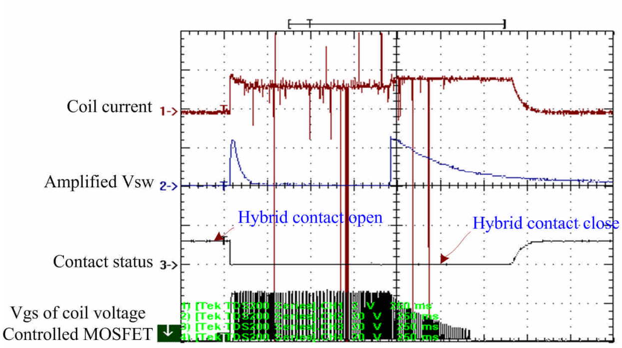

Fig. 9 The important node voltage and coil current waveforms when the load DC voltage source is 12 V and the load is a cement resistor with six ohm.

Case B. The load DC power voltage source is 24 V and the load is a cement resistor with six ohm

Figure 10 show that the measuring waveform of the same electrical parameters likes that of Fig. 9. The theoretical load current is about 4A. It is worthy that the contact status does not appear any contact bounce during the closing and opening process. In other words, there is no high-temperature occurred on the mechanical contacts and leads to the contact erosion result.

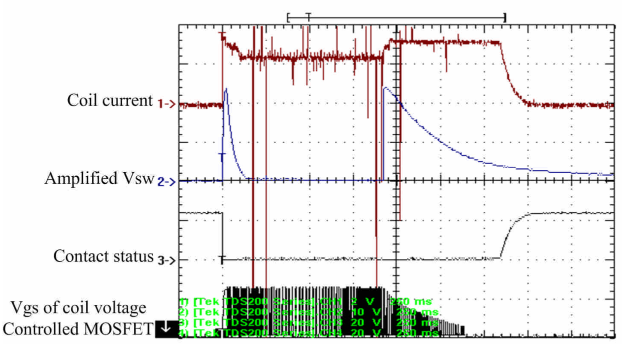

Fig. 10 The important node voltage and coil current waveforms when the load DC voltage source is 24 V and the load is a cement resistor with six ohm.

Compared to the mentioned-stated above, the coil's current becomes larger since the load applied DC voltage source is increased from 12V to 24V. It is worthy notice that the same result such as no arc occurred is achieved.

5.2 Capacitive load, $1\Omega + 1000uF$

If the DC load is a capacitive load, it is very low resistance or even no resistance across the load when it is suddenly applied a DC voltage source. The DC load is applied a 24V DC voltage source. The load is a cement resistor with six ohm and an electrolytic capacitor with capacitance 4700uf in series connection. To observe the channel 4 shown in Fig. 11, we can find that the coil's voltage is exponentially decreased when the applied DC voltage source of the power relay is removed. At the same time, the channel 2 shown in Fig. 11 shows that the voltage trigger signal, Vgs, of the power MOSFET in hybrid contact is also reduced gradually during the opening process. Certainly, the mechanical contact in hybrid contact also conducted contact broken action. Therefore, these better switching results can be explored from the contact working status shown in Fig. 11.

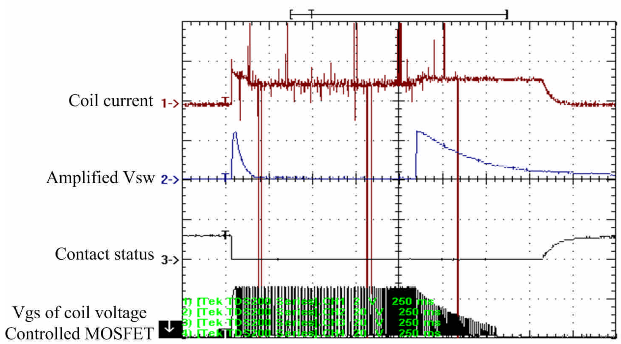

Fig. 11 The important node voltage and coil current waveform when the load is a cement resistor with one ohm and a capacitor with 4700uf in series connection.

5.3 Inductive load, $1\Omega + 10mH$

In order to verify the contact arcless performance under the inductive load condition, the load is applied a DC voltage source 24V and the load is the secondary side across two terminals of the transformer PT-15S. The resistance of the tested inductive load across two terminals is 28 ohm. The inductance value of this type of transformer is equivalent to 3.68 mH. In general, a self-induced voltage will be generated across the two terminals of the tested transformer coil. Possibly, the mechanical contact arc is generally easy occurred between the two contacts due to this high self-induced voltage. Figure 12 shows the working status of the hybrid contact (shown in channel 3) that the contact bouncing phenomenon has been completely removed regardless of during the closing or opening process. By visually observing the working status as mentioned above between the two mechanical contact during the closing and opening process, there is no any high-temperature arc is generated between the two colliding mechanical contact under the tested inductive load condition because the new hybrid contact configuration is introduced.

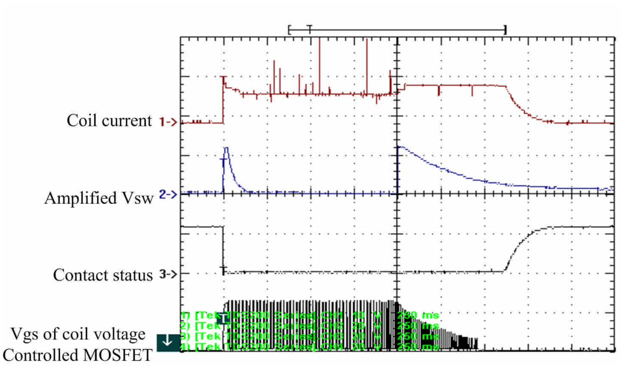

Fig. 11 The important node voltage and coil current waveforms when the load DC voltage source is 24V and the load is the secondary side of transformer (PT-15S).

6 Conclusion

For a typical conventional electromagnetic-type power relay, its contact is a pair of mechanical contact. In the closing process, the more the coil voltage is applied, the more the moving kinetic occurred on the moving contact is generated. The contact bouncing duration after the contacts collision is also increasing. In many practical applications, the load current is almost 6~10 times of the rated load current. These larger load current flows through the bouncing contact. Generally, more or less arc would be generated across the two collision contacts. Finally, the lifespan and operating reliability is shortened very much. In addition, there is a self-induced inductive voltage is generated between the inductive load during the opening process. Because this self-induced voltage is very larger, the arc with high temperature is easy occurred on the mechanical contact. The harmful effect for the mechanical contact of the conventional electromagnetic-type power relay is seemed to be inevitable result when it executes turn on or off work. In this paper, a new power relay with hybrid contact which a power MOSFET is integrated with a mechanical contact in parallel is proposed. The unstable larger DC load current flows through the power MOSFET in hybrid contact. While the DC load current is stable and lower within remaining time in one complete working cycle flows into the mechanical contact in hybrid contact. In addition, the coil is applied a full DC voltage except parts of voltage is applied during the closing and opening stage. Therefore, the purpose of the energy saving is achieved here. Comparing the bouncing duration and energy-saving performance of the proposed power relay with hybrid contact with the conventional power relay with only mechanical contact have been validated through some experimental tests under different testing conditions. The bounce duration after two contacts collision during the closing process is then reduced significantly or even completely removed. The amount of dissipated electrical energy by the proposed power relay is reduced obviously. In addition, the lifespan of contactor contacts is prolonged and their operating reliability as well.

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