# *The Performance Comparison of Different Suppression Reverse-peak Circuits for Electromagnetic Relay*

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***Abstract:*** Electromagnetic relay is one of the major elements of national defense and aerospace electronic systems, its proper use has a very important significance[1]. The relay coils will generate a reverse peak voltage of a kilovolt when the relay control signal disappears, which will cause damage to other connected paths. In the past, the analysis method of the reverse peaks voltage of the electromagnetic relay and its suppression circuit was mostly based on test method without a theoretical model[2] and there is almost no research to analyze the reverse peak voltage from the physics viewpoint. Therefore, this paper would analyze the causes of reverse peak voltage based on the physics theory, then establish the mathematical model of the principle of reverse peak voltage generation of the relay and various transient suppress. After that use Matlab to get the response from those circuits of various conditions. It provides a theoretical reference for selecting a suitable eliminates reverse peak voltage circuit.

## 1. Introduction

Electromagnetic relay is an electronic component of reaction and transfer signal. It has many advantages, such as high sensitivity, low power consumption, small volume, light weight and large conversion depth. It is widely used in the fields of aerospace, weaponry and industrial control[3]. It is an important component in power electronics, information communication and remote sensing monitoring system. The relay generates a reverse peak voltage from the connection state to the break. If the reverse peak voltage was not being eliminated, it will not only interfere with the normal operation of the circuit, but also damage the components. The design of a suitable transient suppresses needs to consider the principle of generation of the relay coil reverse peak voltage, and the principle of the peak inverse suppression circuit. Therefore, this paper uses the mathematical model to analyze the circuit response.

## 2. The Necessity of the Relay Reversal Peak Circuit

A typical electromagnetic relay structure is shown in Fig. 1. When the coil is energized, a magnetic field would be generated. The magnetic flux in the magnetic circuit composed of iron core, armature and air gap changes. Increasing the current of the coil will increase the flux. When the magnetic flux increases to a certain extent, the armature is sucked into the iron core to drive the contacts to change. When the coil current is cut off or reduced to a certain degree,the magnetic flux in the magnetic circuit will disappear or reduce to a certain extent. The armature returns to the spring back to the initial position (the magnetic retaining relay needs reverse excitation to reset).

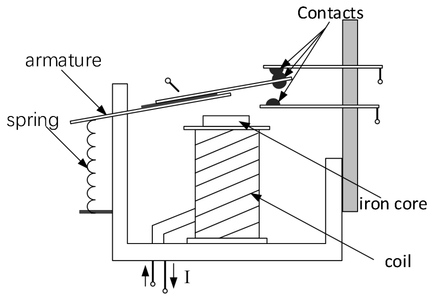



Figure 1: Structure diagram of electromagnetic relay.

According to the Biot-Savart Law, the magnetic induction intensity of the loop circuit formed by the change of magnetic field on the relay coil. Here is the relational expression:

$$\oint_l B \cdot dl = \mu \sum I_i \tag{1}$$

$$H = \frac{B}{\mu} \tag{2}$$

*B*: magnetic induction; *l:* The length of the conductor in the magnetic field; *Ii:* One of the currents surrounded by the coil; *H:* magnetic field intensity.

According to Faraday's law of electromagnetic induction:

$$e = -W\frac{d\Phi}{dt} \tag{3}$$

e: Induction electromotive force ; W: Coil turn ; dϕ : Flux variation of the W coil turns (Wb) ; dt: The time requires for magnetic flux changing to dϕ (s) .

The middle negative sign indicates that the direction of induced electromotive force is always opposite to the direction of flux change.

According to the Kirchoff's second law:

$$\oint_l H \cdot dl = \sum I_i = WI \tag{4}$$

When the system is no magnetic leakage, we will have this formula $Hl = WI$ . According to literature 1, the derivation of the relationship between the magnetic field intensity and magnetic potential of solenoid Center, we can get this formula:

$$H = \frac{\beta}{\mu} = \frac{\Phi}{\mu s} \tag{5}$$

We can obtained by and :

$$\Phi = \frac{WI}{l/\mu s} \tag{6}$$

*s*: The section area of the wire, *β*: Fill factor

According to the above analysis, from, we know that the parameters of I、l、μ、s are fixed value. So, when the relay coil is de-energized, only the current passing through the coil changes. Since the coil can be equivalent to a circuit model with a series of the inductor and the resistor, so the voltage of the coil can be abrupt to zero when the power is broken, and the current in the coil will be reduced to zero from the initial value of a short time. According to Literature 2, the time of coil current changing from initial value of zero is the order for tens of microseconds. In the industry, relays with a supply voltage of 28V and a coil resistor of several hundred ohms are often used. The stable current in coil will be several tens of amperes when the relay is energized. Therefore, the relay coil will generate transient voltages above 1000 V while if there is no transient suppresses.

Let us calculate the transient voltage by using the circuit method. The mathematical model is:

$$E=\sum e=-\left(L\frac{\mathrm{d}I}{\mathrm{d}t}+I\frac{\mathrm{d}L}{\mathrm{d}t}\right) \tag{7}$$

$E$: Transient voltage $L$: Coil inductance $I$: The steady-state current in the coil dt : Turn-off time

Since the inductance value of the relay coil is generally not given in the relay manual, the inductance value of the relay coil needs to be calculated. From GJB65、MIL-R-39016, we can get the way how to calculate it: *L=RL*63%*Tmax*. RL is the resistor of the coil, *Tmax* is the maximum time for the relay coil to reach a stable current. For the model 4JRXM-2 type relay, $L=570\times0.63\times5\times10^{-3}=1.7955\mathrm{H}$, $I_0=\frac{V}{R_L}=\frac{28}{570}=49.12\mathrm{mA}$ The time for the current on the coil to change from the initial value to zero is approximately 60 μs.

Because of the inductance of the coil remains unchanged when the power of the coil cut off. So, dL is zero, and this formula has only the first item left, that is: $E=-L\frac{\mathrm{d}I}{\mathrm{d}t}=1479\mathrm{V}$ .This conclusion is consistent with the magnitude of the instantaneous voltage amplitude of about 1200V, which is mentioned in GJB1461-92 "General Specification for Electromagnetic Relays with Reliability Indicators"[4]. This high voltage is the reverse peak voltage of the relay. Therefore, in order to protect the control circuit of the relay coil it is necessary to add a transient suppress to form an anti-peak voltage path at the moment when the relay coil is powered off.

## 3. The Necessity of the Relay Reversal Peak Circuit

The research would be start from establish the suppress reverse peak circuit model of the relay, as shown in Figure 2:

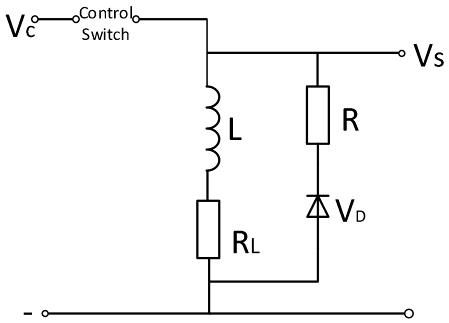



Figure 2: The suppress reverse peak circuit model of the relay.

The circuit shown in figure 2 is the most commonly used circuit[5][6], we can write the general formula of this model, that's:

$$L\frac{\mathrm{d}I}{\mathrm{d}t}+(R+R_L)\mathrm{i}(t)+V_D=0 \tag{8}$$

According to the analysis in chapter one, there would generate a high reverse voltage in the relay coil because of the electro-magnetic induction when the relay is power off. This high reverse voltage would be effectively clamp down to a safe value if we design a loop circuit for the relay coil. In this way, the voltage across the relay coil can be calculated as this:

$$V_S=R\cdot\mathrm{i}(t)+V_D \tag{9}$$

The value of VD and R are constant. Therefore, the research corn on the comparison of the suppress reverse peak circuit of the relay is located at the response of the current in the coil loop circuit. Vs is the suffered voltage to the related circuits.

It can be lot of model to the R and VD, such as diode part of the circuit can be a single-channel Zener diode, Zener diode and normal diode in series, transient suppression diode, bidirectional transient suppression diode in series, etc. Shown in Figure 3.

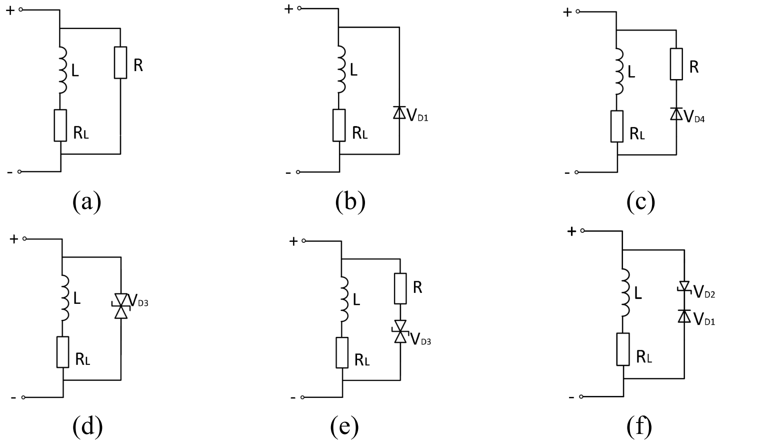



Figure 3: Different kinds of the suppress reverse peak circuit of the relay.

In Figure 3, the expressions of different kinds of relays in the general formula are different according to their composition. They are：

$$\begin{cases} R=R,\ V_{\mathrm{D}}=0 & (\mathrm{a}) \\ R=0,\ V_{\mathrm{D}}=V_{\mathrm{D1}} & (\mathrm{b}) \\ R=0,\ V_{\mathrm{D}}=V_{\mathrm{D4}} & (\mathrm{c}) \\ R=0,\ V_{\mathrm{D}}=V_{\mathrm{D3}} & (\mathrm{d}) \\ R=R,\ V_{\mathrm{D}}=V_{\mathrm{D3}} & (\mathrm{e}) \\ R=0,\ V_{\mathrm{D}}=V_{\mathrm{D1}}+V_{\mathrm{D2}} & (\mathrm{f}) \end{cases} \tag{10}$$

The form of equation is a standard first-order differential equation. Its general solution is:

$$\mathrm{i}(t)=e^{-\frac{R+R_{\mathrm{L}}}{L}t}\left[C_1-\frac{V_{\mathrm{D}}}{L}\left(\frac{L}{R+R_{\mathrm{L}}}e^{\frac{R+R_{\mathrm{L}}}{L}t}+C_2\right)\right] \tag{11}$$

That is：

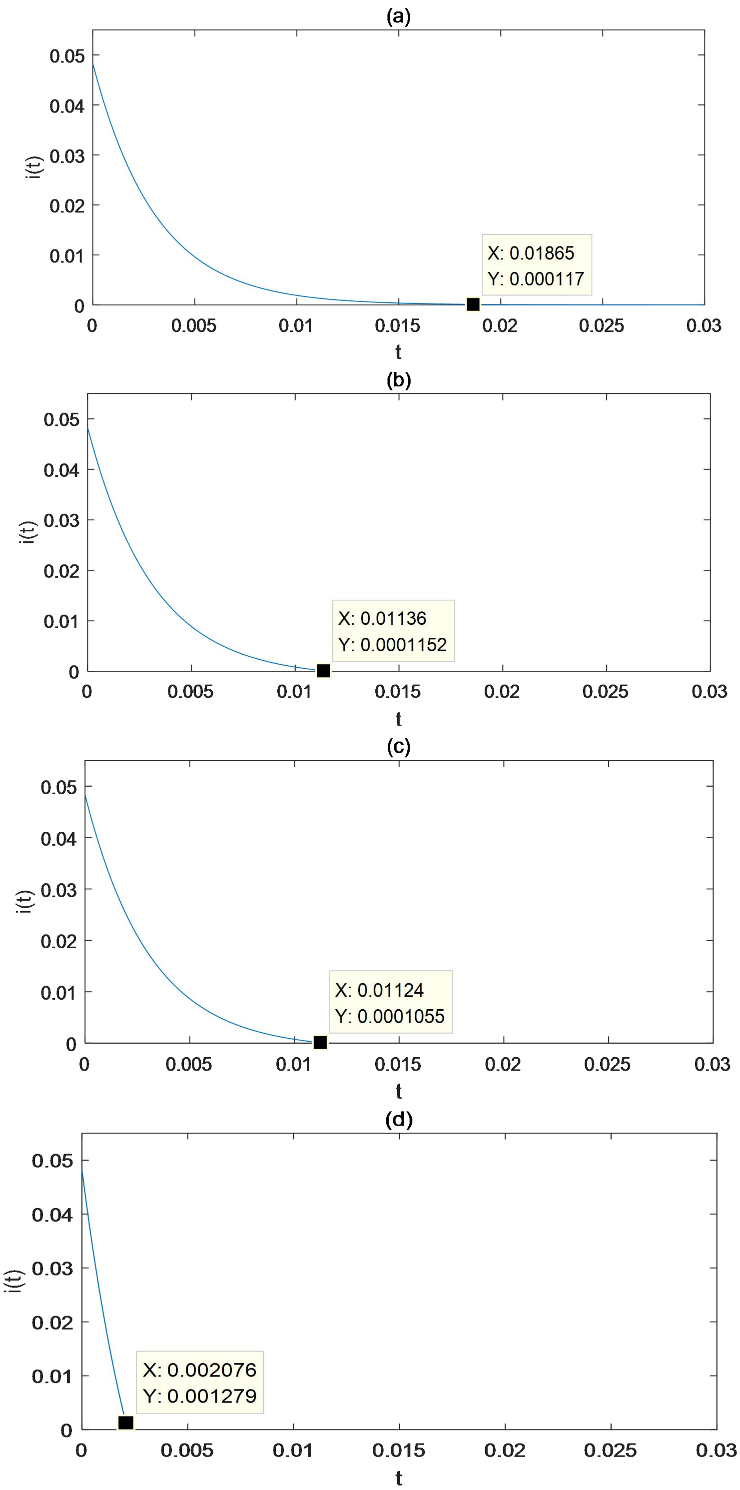
$$\mathrm{i}(t)=e^{-\frac{R+R_{\mathrm{L}}}{L}t}\left(C_3-\frac{V_{\mathrm{D}}}{R+R_{\mathrm{L}}}e^{\frac{R+R_{\mathrm{L}}}{L}t}\right) \tag{12}$$

$$C_3=C_1-\frac{V_{\mathrm{D}}}{L}\cdot C_2$$

When the relay coil is cutting off, the voltage of the coil can be abrupt to zero, but the current can't be mutated, it can only be gradually decreased to zero. So, the initial value of the current can be calculated as $\mathrm{i}(t)=\frac{V_{\mathrm{c}}}{R_{\mathrm{L}}}$ The clamp voltage of the transient voltage suppressor VQ is varied from a few volts to dozens of volts. In this paper, we chose the value of 10V. For relays of type 4JRXM-2， $\mathrm{i}(t_0)=49.12\mathrm{mA}$ . Substitute it into,we can get：

$$C_3=49.12\times10^{-3}+\frac{V_{\mathrm{D}}}{R+R_{\mathrm{L}}} \tag{13}$$

As for R=10Ω，RL=570Ω，VD=10V， we can use MATLAB to draw current response for each of the transient suppress circuit.


(a)
X: 0.01865
Y: 0.000117
(b)
X: 0.01136
Y: 0.0001152
(c)
X: 0.01124
Y: 0.0001055
(d)
X: 0.002076
Y: 0.001279
i(t)
t

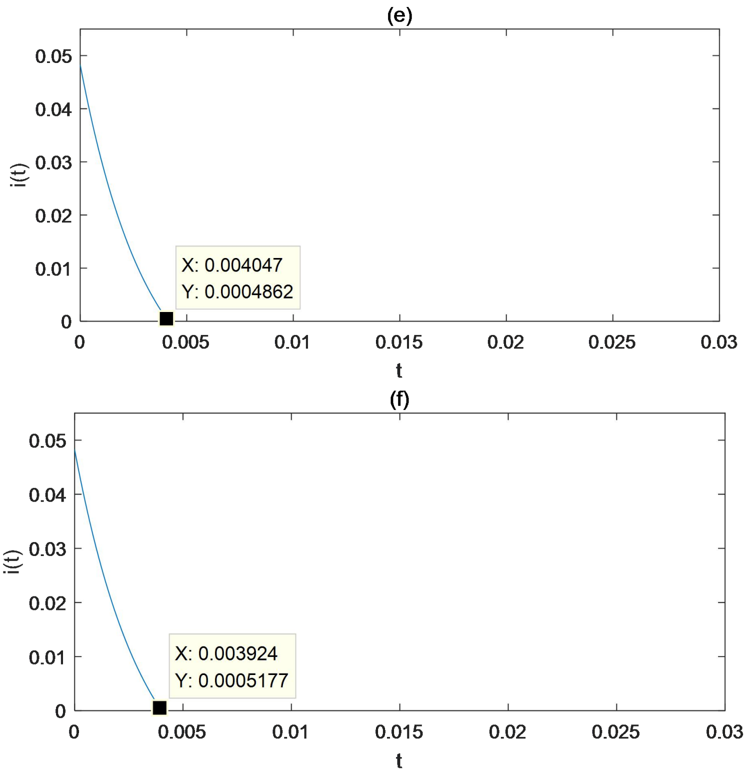



Figure 4: Current response of transient suppress circuit.

By analyzing the trend of current reduction, when there is only resistor in the transient suppress circuit, the current drops slowly. In the condition of R=10Ω， according to , the maximum of the reverse voltage is 491.2mV, the time when the current drops to zero is 18.65ms.

If there is only have a diode in the transient suppress circuit loop, the maximum of the reverse voltage will be the turn-on voltage of the diode that is 0.7V. The time when the current drops to zero is 11.36ms, it’s a little shorter than circuit (a).

For the circuit of (c) in figure 2, Vsmax=491.2mV+0.7V=1.1912V. The time when the current drops to zero is 11.24ms.

For the circuit of (d) in figure 2, Vsmax could be the clamp voltage of the transient voltage suppressor VQ. This time we chose 28V which is the relay’s working voltage as the value of VQ. The time when the current drops to zero is 2ms.

For the circuit of (e) in figure 2, Vsmax could be the sum of the clamp voltage of the transient voltage suppressor VQ and the voltage across the resistor, that’s 10.49V. The time when the current drops to zero is 4ms. Comparing the little gap to (e), add to a resistor can speed up the consumption of electrical energy. Moreover, when the transient suppression diode breaks down, the circuit can be protected by resistor, so that the reliability of the circuit can be improved.

For the circuit of (f) in figure 2, Vsmax could be the sum of the clamp voltage of the transient voltage suppressor VQ and he turn-on voltage of the diode, that’s 10.7V. The time when the current drops to zero is 3.9ms， and that is the shortest time in all of those circuit.

The resistor in (a) can be replaced to varistor. A suitable type of varistor can be selected according to the actual parameters of the circuit. Designed in this way it’s clear that when the relay coil is energized, the transient suppress circuit is also turn on. The resistor R is always keep working, so there is a higher power requirement for the control signal of the relay coil.

In addition, there is another form of transient suppress circuit, as shown in Figure 5.

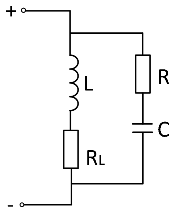



Figure 5: The suppress reverse peak circuit of the relay formed by resistor and capacitor in series.

The mathematical model of this circuit is:

$$L\frac{\mathrm{d}I}{\mathrm{d}t}+\left(R+R_{\mathrm{L}}\right)\mathrm{i}\left(t\right)+\frac{1}{C}\int\mathrm{i}\left(t\right)\mathrm{d}t=0 \quad (14)$$

It can be written as:

$$\frac{\mathrm{d}^2 I}{\mathrm{d}t^2}+\frac{R+R_{\mathrm{L}}}{L}\frac{\mathrm{d}I}{\mathrm{d}t}+\frac{1}{LC}\mathrm{i}\left(t\right)=0 \quad (15)$$

In the condition of $R > 2\sqrt{\frac{L}{C}}$, the circuit is in overdamped state.

In the condition of $R=2\sqrt{\frac{L}{C}}$, the circuit is in critically damped state.

In the condition of $R < 2\sqrt{\frac{L}{C}}$, the circuit is in underdamped state.

According to the initial value of the current in the inductor and the initial value of the voltage across the capacitor, we can solve by Runge-Kutta method with MATLAB.

In the state of overdamped and critically damped, the current would spend more time to drop down to zero. Such as, this circuit is in critically damped state when C=22uF.And the current response is shown in Figure 6:

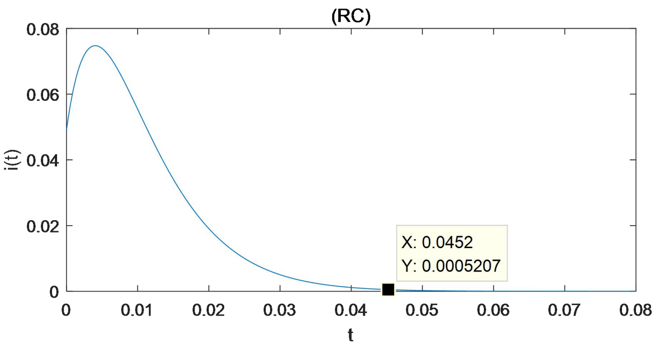



Figure 6: Current response while the circuit is in critically damped state.

It cost about 45ms to drop the current to zero. This way not only spent too much time than other ways referred in this paper, but also show that the current have an uplift tend at start. So, this method is not recommended.

The circuit would be in underdamped state in the condition of C=100uF. The current response is:

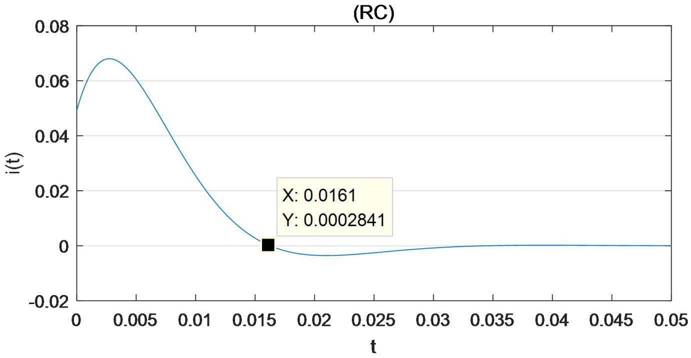



Figure 7: Current response while the circuit is in underdamped state

It's cost about 16ms to drop the loop current to zero. We also can adjust the value of the resistor and capacitor to adjust the response time of the current drop to zero.

The reverse suppression circuit constitute by resistor in series with and capacitor will cause a large change due to the value of the resistor and the inductance. During the use of the relay, the resistance of the coil may have large change due to the external environment and service life. Thereby, the reverse peak circuit would be changed from an underdamped state to an overdamped state. This method is suitable for circuits with stable component parameters. It would not be recommended in transient suppress circuits design.

## 4. Conclusions

In this paper, obtained the necessity of designing the circuit to suppress reverse peak voltage by analyzing the generating principle of the reverse peak voltage to the relay coil. And then, used the mathematical model resolved the output response of different kinds of relay reversal peak circuit. Based on the research, we can know that any one of these transient suppress circuits can realize the purpose of suppress the reverse peak voltage of relay. The key is to according the different control circuit of relay coil to choose the corresponding transient suppress circuit and its parameters. Considering the higher reliability and the shorter response time of the transient suppress circuits, the way of resistor in series with the bidirectional transient voltage suppressor would be recommend in this paper.

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