

Research on pulse power based on saturable pulse transformer and magnetic switch

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Abstract: A method of using saturable pulse transformer (SPT) in series with a magnetic switch is adopted in research on high power pulsed power miniaturisation and high repeat frequency in this study. SPT not only plays a part in boosting, but also plays a part in pulse compression. In this case, a stage magnetic pulse compression can be omitted, and the volume and weight of the system are both reduced. First, the topology of pulse power supply is presented, and working principle of the topology is introduced in detail. At the same time, the dynamic process of de-magnetic saturation control circuit of magnetic switch is analysed. Second, the selection principle of magnetic core of SPT and magnetic switch is given, and the core used in this study is modelled in PSPICE. At last, the whole circuit is modelled and simulated in PSPICE. Simulation results show that the proposed scheme is feasible, which has a good theoretical guidance for the subsequent experimental work.

1 Introduction

The switch principle of magnetic switch is determined by the non-linear properties of the magnetic switch core [1–3]. The technology of magnetic switch pulse compression can effectively sharpen and compress pulse voltage. On the switch performance, magnetic switch can overcome the shortcomings of other high power switch, which can improve the discharge frequency due to non-contact closing action and strong repeatability. Magnetic switch can greatly improve the performance of pulse forming unit because of its long service life, high voltage and high resistance to flow [4–8]. In recent years, with pulse power technology application in the military and civilian becomes more and more widely, the research also is more and more urgent, especially in the research of miniaturisation and compactness. Owing to the magnetic switch with high repetition rate, high stability, long service life, convenient operation, small volume and so on, it has been widely used in pulse power technology [9–11]. With the development of pulsed power technology, pulse transformers are more and more widely studied, especially magnetic saturation and de-magnetic saturation of the magnetic cores [12–14]. However in terms of power pulse compression technology, saturable pulse transformer (SPT) not only plays the role of booster, but also plays the role of compressing the pulse width. At present, because SPT in the applications of pulse power technology is more and more prominent, scholars at home and abroad is paying more and more attention to researches on saturated magnetic core.

First, the topology of the high power pulse power supply based on the magnetic switch with the de-magnetic saturation control circuit is introduced in this paper. Second, the design of the SPT, the magnetic switch and the design of the de-magnetic saturation

control circuit are described in detail. The dynamic process of de-magnetic saturation control circuit is analysed and the related parameters of de-magnetic saturation control circuit are calculated. Finally, the modelling and simulation of overall system are carried out, and the results are analysed. The results of the magnetic circuit with de-magnetic saturation control circuit are compared with the results of the non-de-magnetic saturation control circuit. The final results show that the proposed scheme can not only compress the whole system in space, but also can compress the pulse width in time.

2 System design and principle analysis

2.1 Structure of the whole topology

In this paper, the SPT and magnetic switch are used, which not only can get all solid-state high-power pulse generator, but also, at a certain extent, can be conducive to the development of miniaturisation and compact pulsed power devices. The structure of the power pulse device can be divided into five parts, which are low voltage with wide pulse width power supply, SPT, de-magnetic saturation control circuit (in this paper, only the magnetic switch to be applied to the magnetic field, the SPT comes with the de-magnetic saturation function), magnetic switch compression circuit and load, as shown in Fig. 1.

Low voltage with wide pulse width power supply is easy to get. Pulse voltage is passed through pulse transformer, and not only the amplitude of low voltage pulse power supply is improved, but also the pulse width of low voltage pulse power supply is compressed, and then the pulse width is further compressed by the magnetic

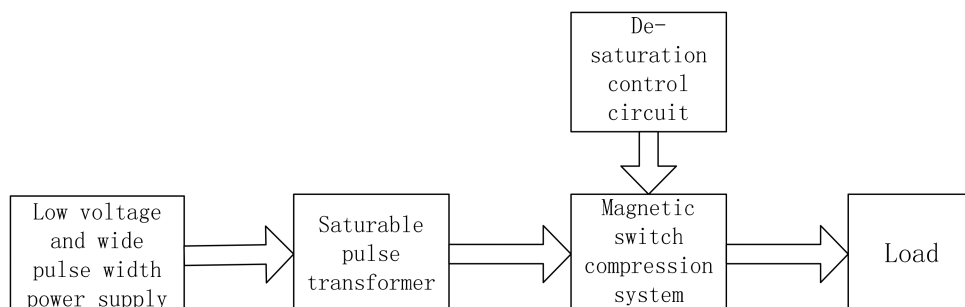


Fig. 1 Structure of pulse power generator

switch, and eventually released to the load. This is the whole process of the system running.

2.2 Working principle analysis

The design of the system topology structure is shown in Fig. 2.

The working principle of the whole topology is described as follows:

- When the capacitor C_1 is charged by the front stage power supply, the switch S is closed. Capacitor C_1 starts to discharge to capacitor C_2 through the switch S and SPT, at the same time the voltage is also applied to the two ends of the magnetic switch.
- The key point of the design is to make the magnetic core of magnetic switch (MS) be saturated before the core of SPT. When C_1 is charging to C_2 (charge is $>50\%$), MS is saturated. At this point, C_1 and C_2 begin to discharge to the load. When the SPT is saturated (up to the compression pulse width), discharge of capacitor C_1 is completed, and the C_2 continues to discharge (the remaining is very little). The remaining amount power of C_2 not only discharge to the load, but also through the saturation inductance L_2 to the transformer and negative to the magnetic field, to achieve the magnetic core de-magnetic saturation of pulse transformer.
- Since there is a reverse magnetic field around transformer, in order to protect transformer, the resistance R_s and diode D_s which can be composed of buffer circuit are connected in parallel with the primary winding.

According to its operational principle, it can be obtained that the ideal waveform changes in each stage as shown in Fig. 3. It can be seen from the figures that the pulse voltage amplitude is increased, the pulse width is compressed.

2.3 Dynamic process analysis of de-magnetic saturation control circuit

For each stage compression system, the capacitor charging circuit and the de-magnetic saturation circuit are shown in Fig. 4.

As can be seen from Fig. 4 that the compressed pulse voltage not only charges the capacitor, but also excites the winding L_m of the magnetic switch. Before the saturation of the magnetic switch, there is a very close coupling between L_m and the reset winding L_r (the coupling coefficient is close to 1). Through this inductance, a excitation voltage will be generated in the reset circuit. The amplitude of the voltage is given as (1), N_r and N_m are the number of winding turns, respectively

$$V_2(t) = \frac{N_r}{N_m} \frac{V_0}{2} (1 - \cos(\omega t)) \quad (1)$$

It is assumed that the impedance in the circuit is generated by L_r , so the current in the magnetic circuit can be calculated by (2) (relative to the impedance produced by L_r , which can be ignored produced by C_b)

$$i_2(t) = \frac{N_r}{N_m} \frac{V_0}{2L_r} \int (1 - \cos(\omega t)) dt \quad (2)$$

It is assumed that the magnetic switch is saturated (lose the function of the transformer, then the circuit is connected, and continue to charge the next capacitor) when the time $t = t_{\text{sat}}$, and the capacitance C_n is charged.

Then the peak current in the circuit can be calculated by

$$i_{pk} = \frac{N_r}{N_m} \frac{V_0 t_{\text{sat}}}{2L_r} \quad (3)$$

When the current of the reset circuit reaches the maximum value of i_{pk} , its value decreases rapidly until the external current is I_0 . In the

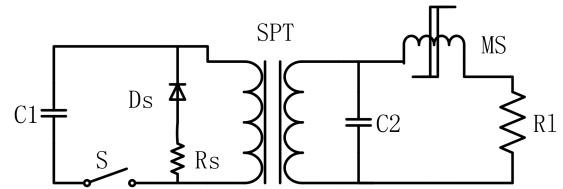


Fig. 2 Circuit topology of magnetic compression system

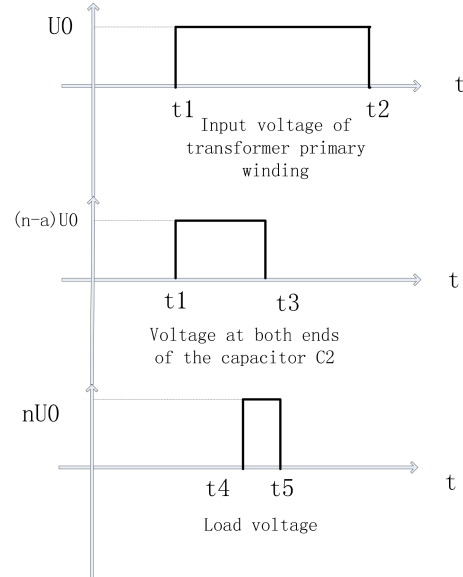


Fig. 3 Demonstration of waveform changes

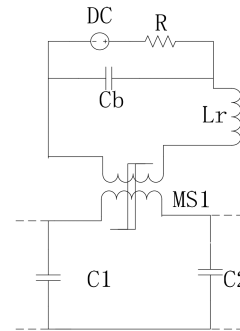


Fig. 4 Charging circuit and de-magnetic saturation control circuit

process of reducing the current, a reverse electromotive force (EMF) will be generated, which is the reset voltage of the core. The speed of the reset of the magnetic switch is affected by the generation of the reverse EMF and depends on the rate of decrease of the current. So it is important for the choice of I_0 .

For a magnetic switch, the size of the current in the de-magnetic saturation control circuit should be larger than excitation current at the saturation point, so the following formula (4) can be obtained (magnetic switch around a magnetic ring):

$$I_0 \geq \frac{2\pi H_s r_0}{N_r}, \quad H_s = \frac{N_r \times I}{l}, \quad V_{dc} = I_0 \times R \quad (4)$$

where H_s is the magnetic field strength at the negative magnetic induction saturation strength, r_0 is the average radius of the ring, N_r is number of turns of the reset winding, l is exciting current and l is average magnetic circuit length.

3 Selection of the important components of the system

The pulse generator's key parts are the pulse transformer, and magnetic switch; therefore, in this section the design of these two units will be described.

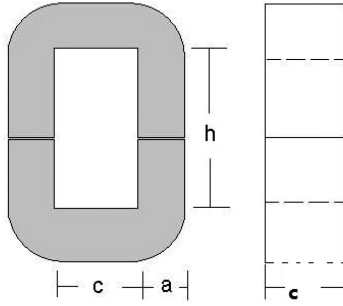


Fig. 5 Shape and size of the magnetic core of the transformer

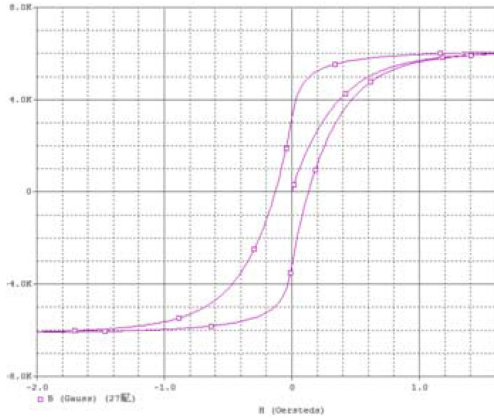


Fig. 6 Hysteresis loop of the magnetic core of the transformer

3.1 Pulse transformer

The requirement of the magnetic core for SPT is different from the general pulse transformer. In this paper, according to the literature [15–17], the request of the core to design the parameters of the magnetic core is put forward. When designing the SPT, the CD type magnetic core is selected. The details are shown in Fig. 5.

The formula for calculating the average magnetic circuit length of the selected magnetic core is shown in the following equation:

$$L = 2 \times (h + c) + \pi a \quad (5)$$

Calculation formula of cross-section area is shown in the following equation:

$$A = a \times c \quad (6)$$

Here $h = 8$ cm, $a = 2$ cm, $c = 5$ cm. So the calculation results are as follows: the average magnetic circuit length $L = 32.28$ cm, the cross-sectional area $A = 10$ cm². In the model establishment of PSPICE, with the calculated parameters, the magnetic hysteresis loop of the magnetic core is obtained, as shown in Fig. 6. From the resulting hysteresis loop, it can be found that the saturation magnetisation is about 0.6 T and remanence is about 0.3 T. At the same time, the initial permeability and the saturated permeability can be estimated approximately by the hysteresis loop and formula (7), they are $\mu_{ur} \approx 10000$, $\mu_{sr} \approx 100$

$$\mu = \frac{\Delta B}{\Delta H}, \quad \mu_r = \frac{\mu}{\mu_0}, \quad \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \quad (7)$$

3.2 Magnetic switch

The magnetic switch is composed of a magnetic core and windings wound around the magnetic core. The working principle of magnetic switch is based on the non-linear characteristics of magnetic materials. When the magnetic switch is not saturation, the inductance value is very large, and the applied voltage is blocked in a certain time; when the magnetic switch is saturated, the permeability of the magnetic core decreases rapidly, its value is

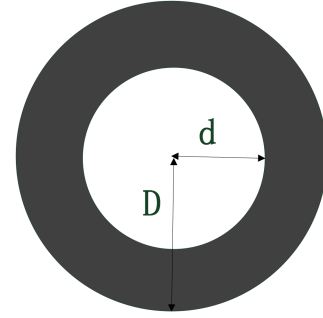


Fig. 7 Magnetic switch core model

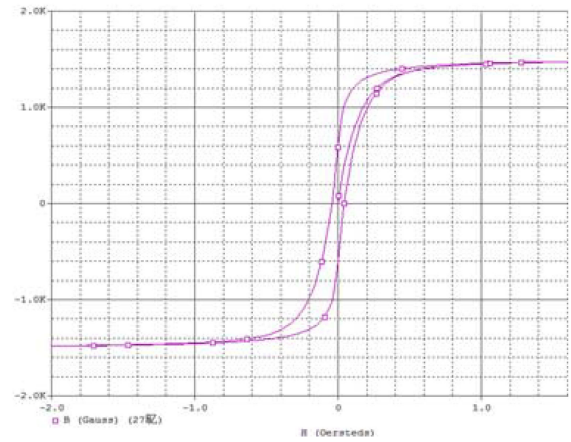


Fig. 8 Hysteresis loop of magnetic switch

close to 1, and the inductance of the magnetic switch decreases rapidly, thus reaching the goal of switching [18–21]. The key component is the saturable core.

In the design of the magnetic switch core, select the ring magnetic core (commonly known as the magnetic ring); its specific shape is as shown in Fig. 7.

We design a ring, according to the characteristic of ferrite. The relevant dimensions for magnetic ring are $D = 4$ cm, $d = 2$ cm, $h = 2$ cm. The cross-section, $A = 3.14$ cm², is calculated according to the formula $A = \pi(h/2)^2$. The average magnetic circuit length, $L = 9.56$ cm, is calculated according to the formula $L = \pi((D + d)/2)$.

In the model establishment in PSPICE, with the calculated parameters, the magnetic hysteresis loop of the magnetic core is obtained, as shown in Fig. 8. From the resulting hysteresis loop, it can be found that the saturation magnetisation is 0.15 T and remanence is about 0.05 T. At the same time, the initial permeability and the saturated permeability can be estimated approximately by the hysteresis loop and formula (7), they are $\mu_{ur} \approx 8000$, $\mu_{sr} \approx 40$.

4 Modelling and simulation of pulse compression system

As shown in Fig. 9, the overall circuit of the pulse generator based on SPT and magnetic switch is built in PSPICE. In the circuit model, K_1 and K_2 are, respectively, the model of SPT and magnetic switch core, which is designed in the above section. In order to protect transformer, the resistance R_5 and diode D_1 which can be composed of buffer circuit are connected in parallel with the primary winding. C_4 is a energy storage type of pulse capacitance.

The simulation results are shown in Fig. 10. V_g is given pulse voltage with low amplitude, wide pulse width; V_{ot} is output of SPT; V_1 is load pulse voltage; B_{spt} is intensity of magnetisation curve of transformer magnetic core; B_{ms} is intensity of magnetisation curve of magnetic switch core.

From Fig. 10a, it can be seen that given pulse voltage with low amplitude, wide pulse width, after the pulse transformer and the magnetic switch, the amplitude increases, the pulse width

decreases, the results are consistent with the theoretical analysis. It can be seen from Figs. 10b and c that there is almost no output after the magnetic switch, and the output after the transformer is normal. The main reason for this result is that after the first period the magnetic switch core cannot produce large ΔB , leading to magnetic switch saturation time is greater than the width of the pulse, so the circuit is not conducted, without output. After the transformer, the output voltage is normal because the transformer comes with its own de-magnetic saturation function in the design of this paper. In order to solve the problem of rapid de-magnetic saturation of magnetic switch core (de-magnetic saturation of magnetic switch core after the complete energy transfer), a de-magnetic saturation circuit is applied. A detailed analysis of the de-magnetic saturation circuit is given in the previous section, and the basis for the selection of its circuit parameters is obtained.

The current can be obtained by calculating the magnetic hysteresis loop of the magnetic switch which is obtained from the previous chapter. After calculation and parameter selection, $I_0 \approx 4 \text{ A}$, $R = 3 \Omega$ and $V_{dc} = 12 \text{ V}$.

Simulation results of the compression system with a de-magnetic saturation circuit are shown in Fig. 11.

Pulse voltage waveform diagrams of second period, fourth period, eighth period and tenth period are given in Fig. 11. It can be seen from the results shown in the diagram that pulse voltage on load is further compressed through magnetic switch. By comparing the results of Figs. 9 and 11, it can be seen that the de-magnetic saturation control circuit designed in this paper is effective. The more ideal result is obtained by applying the de-magnetic saturation circuit, and the frequency of the power pulse device can be improved.

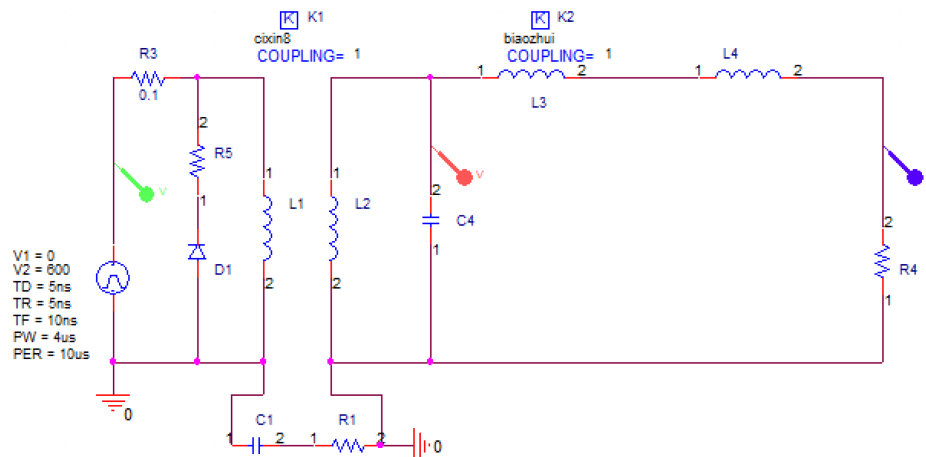


Fig. 9 Whole simulation system

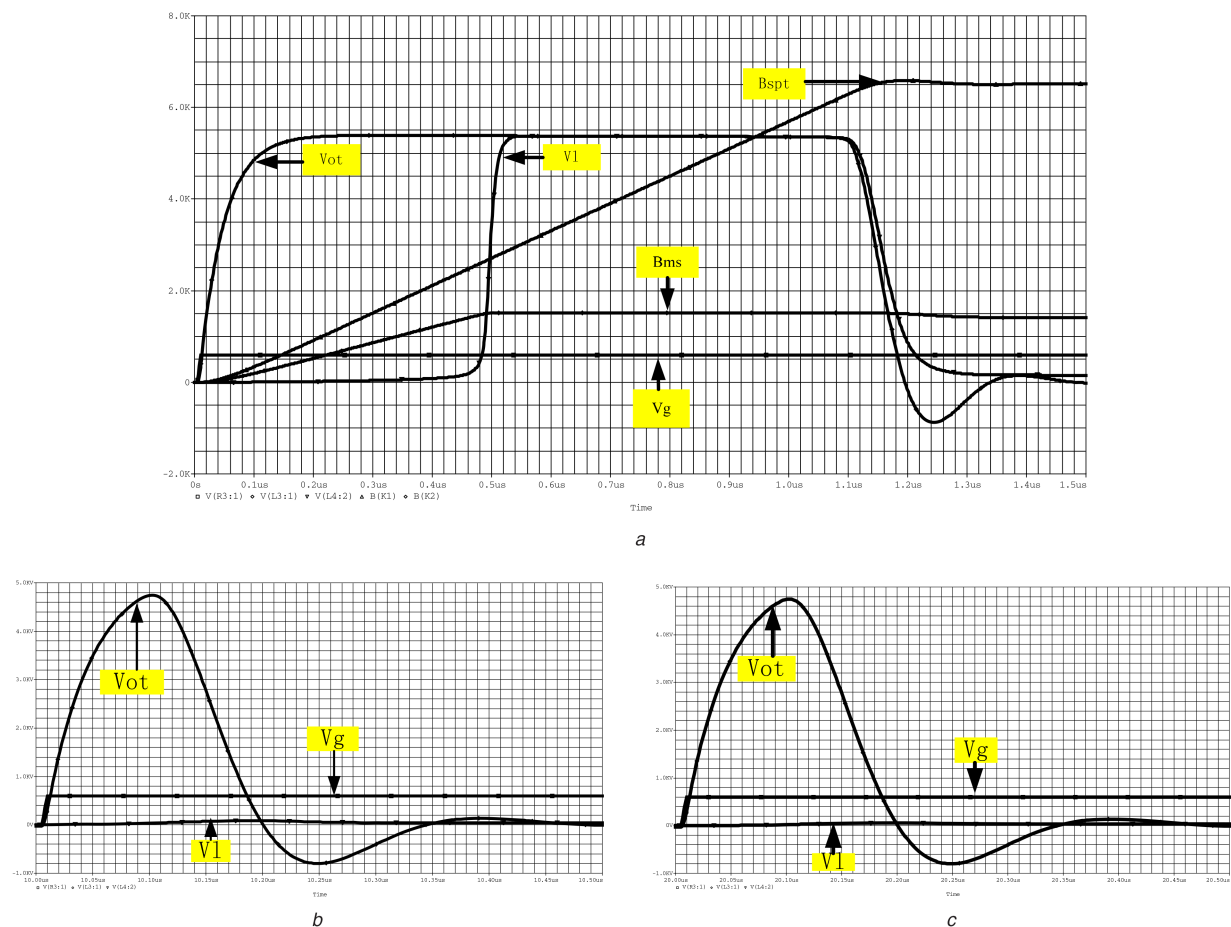


Fig. 10 Simulation results of the whole system of magnetic switch without de-magnetic saturation circuit

(a) Simulation results of the first period, (b) Simulation results of the second period, (c) Simulation results of the third period

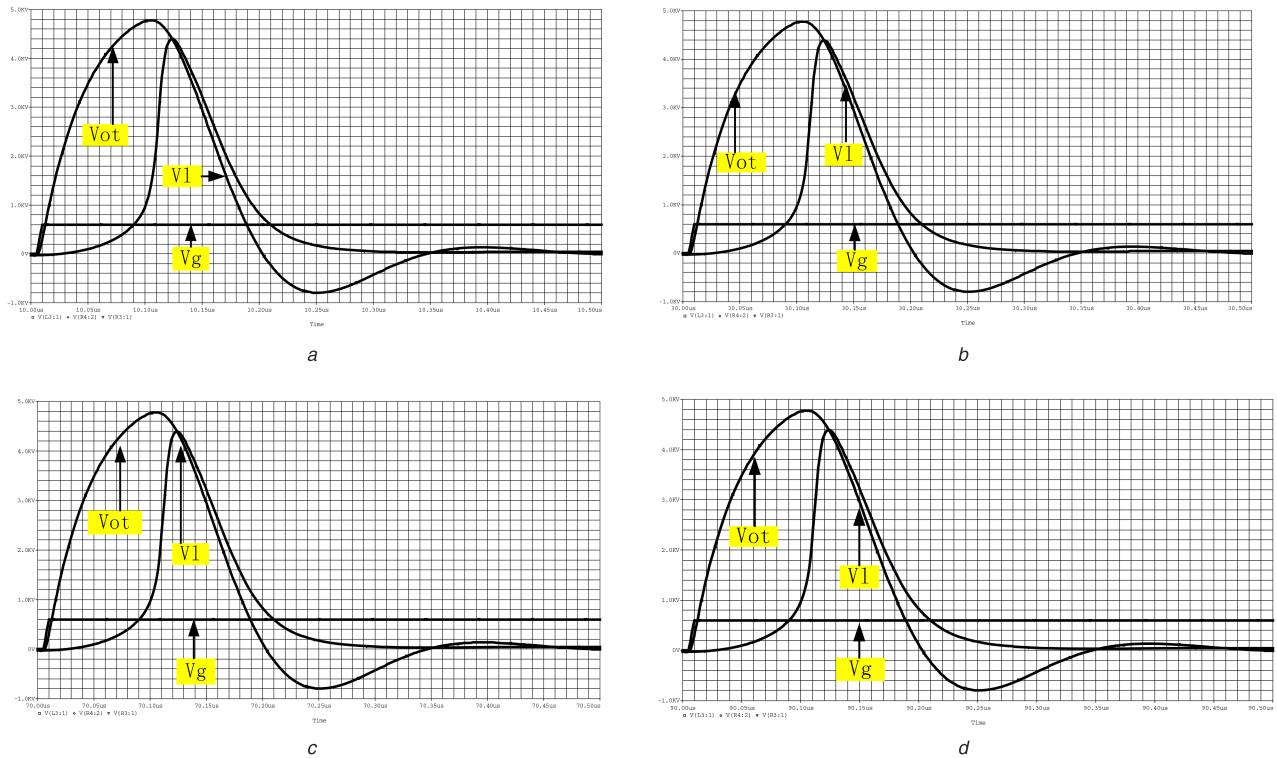


Fig. 11 Simulation results with de-magnetic saturation control circuit

(a) Simulation results of the second period, (b) Simulation results of the fourth period, (c) Simulation results of the eighth period, (d) Simulation results of the tenth period

5 Conclusions

Through the research of pulse power technique based on SPT and magnetic switch, it has been verified that the design idea and method of this technique are reasonable and can be implemented. At the same time, the automatic de-magnetic saturation function was realized for SPT without de-magnetic saturation circuit. There is a great significance to carry out the research of pulsed power technology on the scheme designed in this paper, which has an important reference for the development of high power pulse power supply to the compact, small size and high repetition rate.

6 References

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