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Shengxian Ji[1, a], Guisheng Jie[1, b], Shan Gao[1, c], Hengli Wang[1, d], Ruitian Wang[1, e] and Xiaohu Liu[2, *]

[1]National key Laboratory of Science and Technology on Vessel Integrated Power System, Naval University of Engineering, Wuhan 430033, China
[2]College of Electrical Engineering, Naval University of Engineering, Wuhan 430033, China

*Corresponding author e-mail: 2847403138@qq.com, [a]1210144127@qq.com, [b]zhenyujie@sina.com, [c]highershan@163.com, [d]wanghengli1984@126.com, [e]wangrt4321@163.com

Abstract. In the phase-shifted full-bridge circuit, the voltage spike caused by the hard turn-off of the switch tube increases the voltage stress of the switching device. Due to the existence of energy-consuming components such as resistance in the traditional absorption circuit, the efficiency is not always high. Based on the RCD snubber circuit, a low-loss absorption circuit is designed in this paper. This circuit absorbs voltage spikes through an absorption capacitor, and then slowly releases energy through an oscillating circuit consisting of current-limiting inductance, stray inductance, and absorption capacitance. The current-limiting inductance reduces the current stress of the blocking diode effectively, which can be achieved with the absorption not being affected and the power loss being reduced. Finally, the absorption effect and energy loss of the new low-loss absorption circuit and the commonly used RCD circuit were simulated and compared in PSpice software, and verified its feasibility.

1. Introduction

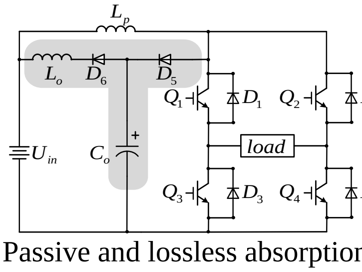
Because the switching device of the phase-shifted full-bridge (PS-FB) circuit could realize the soft switching control by designing the circuit topology and changing the component parameters, and this control can reduce the switching loss and improve the conversion efficiency. Therefore, for chain isolated DC power supply with high-power, high-conversion-efficiency and high-frequency, PS-FB soft-switching converters would become the preferred choice. However, when the switching devices were turned off, voltage spikes would occur for the stray inductance and resonance inductance in the circuit cannot change abruptly. If the voltage spikes were not absorbed, the switching device might be damaged. In order to solve the occurrence of voltage spikes, an absorption circuit was usually designed to buffer to prevent transient overvoltage, reduce switching losses, and ensure that the switching tube can be safely switched.

Absorption circuits were usually divided into active absorption and passive absorption circuits. The passive absorption circuit was widely used for its simple structure and high reliability [1]. There were three types of absorption circuits commonly used: *C* type, *RC* type, and *RCD* type [2]-[5]. Among them, the C type absorption circuit was the most common. It was suitable for small and medium capacity converters. It could suppress voltage spikes, but it was easy to resonate with stray inductance. The RC type of absorption circuit was simple and suitable for small-capacity converters, but it was still easy to cause voltage spikes when the current and stray inductance were large. There were three types of absorption circuits of RCD type: I, II and III, which could be applied to large, medium and small capacity converters, but the energy absorbed by the capacitor was released through the resistor, and most of the energy was consumed on the resistor, causing energy loss. In recent years, an improved topology of common absorption circuits had been proposed [6] [7]. The absorption circuit released the energy on the voltage spike through a resistor and consumes a lot of energy on the resistor. In addition to the power drop, it had a large capacity. More stringent requirements are placed on the power, volume and heat dissipation of the resistor.

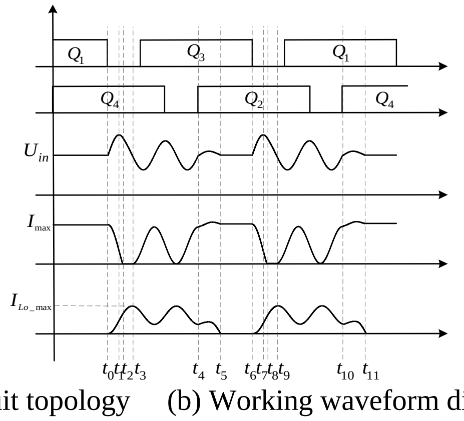
In order to overcome the shortcomings of large loss energy in the absorption resistance, the research of passive non-destructive absorption circuit was very meaningful [8]-[11]. Literature [12] proposed that in the passive lossless buffer circuit under high power, part of the energy was slowly output through partial resonance, but the current stress of some diodes were large, and the selection of devices was difficult. The absorbing circuit proposed in literature [13] had an inductance in the absorbing branch and cannot absorb a large peak current. In a large-capacity device, the absorbing effect was not obvious. Literature [14] proposed that the circuit topology was complex, and the diode's on-state loss was significant in practical applications. In view of the existing problems, a new topology was proposed in this paper, which could better realize the function of absorbing voltage spikes.

2. Working analysis of absorption circuit

As shown in Fig. **1** (a), the absorption circuit is composed of an absorption capacitor (C_o), a current limiting inductor (L_o), and a blocking diodes (D_5, D_6). The main circuit includes the input power (U_{in}), the loop stray inductance (L_p), and a phase-shifted full-bridge circuit (four switching tubes $Q_1 \sim Q_4$ and four anti-parallel diodes $D_1 \sim D_4$) and the load ($load$). The absorption circuit mainly stores energy in the absorption capacitor by absorbing the voltage spikes on the bus, and slowly releases it through the current limiting inductor to avoid causing secondary voltage and current shock to the circuit. The drive signal of Phase-shifted full-bridge, the voltage of absorption capacitor and the current of current-limiting inductor are shown in Fig. **1** (b).



(a) Passive and lossless absorption circuit topology

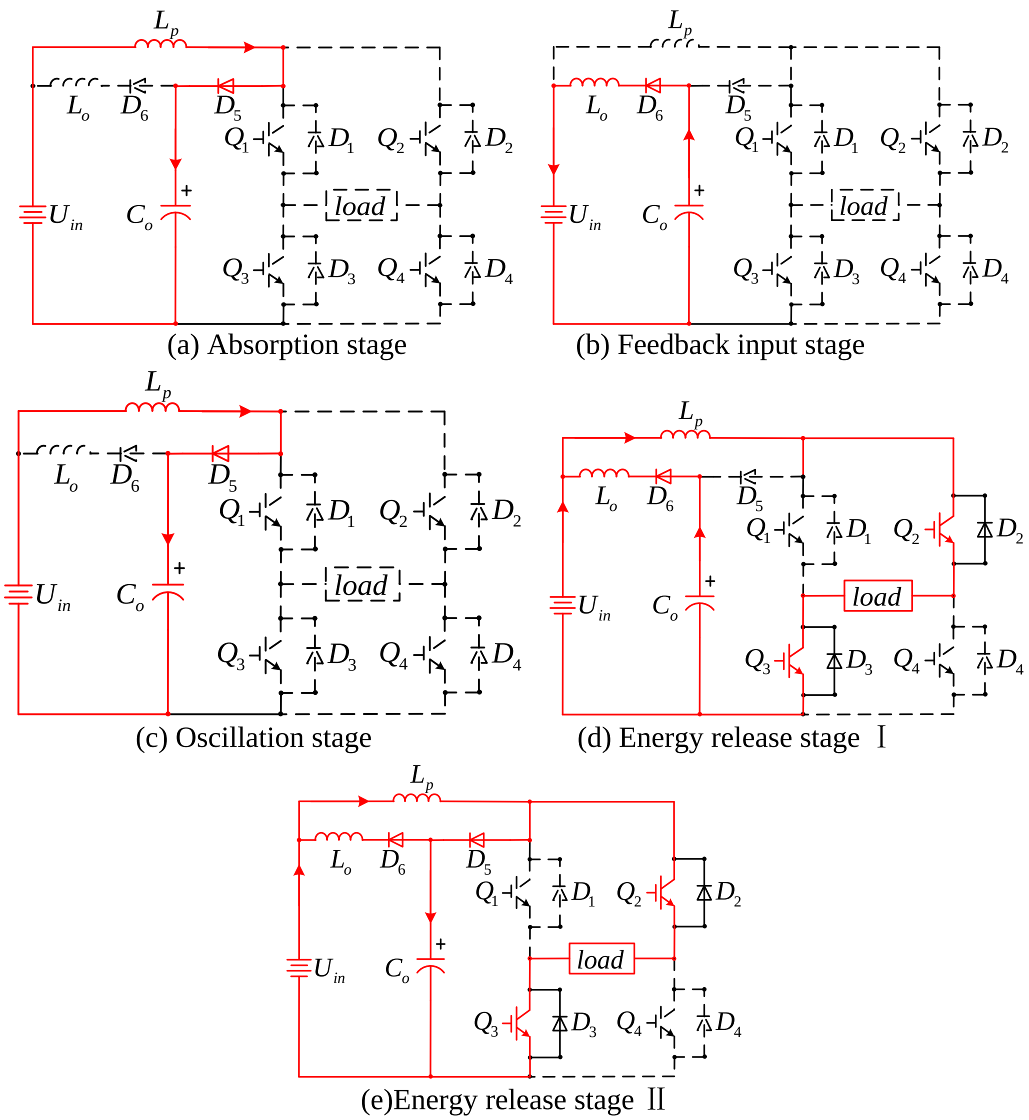


(b) Working waveform diagram

Fig. 1 Absorption circuit topology and working waveform diagram

Before analyzing the operation of the absorption circuit, make three assumptions: 1) all components are ideal components, that is what there is no on-state voltage drop and the switching action of the switching device having no delay time; 2) the reason of the peak voltage appearing on the voltage bus is the stray inductance current in the loop cannot be abruptly changed and has nothing to do with the load, and the stray inductance is smaller than the current-limiting inductance, $L_p < L_o$; 3) The load is a purely resistive load (R_{load}).

The absorption circuit absorbs surge voltage spike energy and releases it mainly including four stages of absorption: feedback input, oscillation and energy release. Due to the symmetry of the PS-FB circuit, in one switching cycle, the switching devices Q_1 and Q_3 on the leading bridge arm are basically in the same working conditions. The first half of the switching cycle is analyzed (Fig. **2**).



(a) Absorption stage (b) Feedback input stage

(c) Oscillation stage (d) Energy release stage Ⅰ

(e)Energy release stage Ⅱ

Fig. 2 Absorption circuit working stage

*2.1. Absorption stage ($t_0 \sim t_2$， Fig. **2**(a))*

At t_0 time, the device Q_1 is turned off. Because of the stray inductance di/dt cannot being abruptly changed, the diode D_5 is turned on at this time, and the energy on the stray inductance is transferred to the absorption capacitor. When the voltage across the capacitor is higher than the input voltage U_{in} after charging the capacitor, a current begins to flow through the current-limiting inductor. During the absorption phase, the current on the stray inductance, current-limiting inductance, and voltage across the absorption capacitor are:

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$$I_{Lo}\left(t\right)=\frac{I_{\max}L_p}{L_o+L_p}-\frac{I_{\max}L_p}{L_o+L_p}\cos\left(\omega_1\left(t-t_0\right)\right) \tag{1}$$

$$I_{Lp}\left(t\right)=\frac{I_{\max}L_p}{L_o+L_p}-\frac{I_{\max}L_o}{L_o+L_p}\cos\left(\omega_1\left(t-t_0\right)\right) \tag{2}$$

$$U_{Co}\left(t\right)=U_{in}+\frac{I_{\max}}{C_o\omega_1}\sin\left(\omega_1\left(t-t_0\right)\right) \tag{3}$$

Where, $\omega_1=\sqrt{\frac{L_o+L_p}{C_oL_oL_p}}$, $I_{\max}$ is the maximum current on the bus, U_{in} is the input voltage.

When the current on the stray inductance L_p is the same as the current on the current-limiting inductor L_o, the voltage across the absorption capacitor reaches the maximum, that is

$$I_{L_o}=I_{L_p} \tag{4}$$

Substituting equations (1) and (2) into equation(4), we get

$$t_{01}=\frac{\pi}{2\omega_1} \tag{5}$$

Substituting equation (5) into equation (3), the maximum voltage on the absorption capacitor is:

$$U_{Co\_\max}=U_{Co}\left(t_{01}\right)=U_{in}+\frac{I_{\max}}{C_o\omega_1} \tag{6}$$

When the current on the stray inductance L_p is zero, the absorption stage ends, and the duration of this stage is:

$$t_{02}=\frac{1}{\omega_1}\arccos\left(-\frac{L_p}{L_o}\right) \tag{7}$$

2.2. Feedback input stage ($t_2 \sim t_3$, Fig. 2(b))

At t_2 time, the current of the stray inductance L_p is zero, the voltage across the absorption capacitor is higher than the bus voltage, the diode D_5 is turned off, and the energy of the absorption capacitor is released through the current-limiting inductor L_o and the input power U_{in}. At this time, the energy is fed back to the input power. The current on the stray inductance, the current-limiting inductance, and the voltage across the absorption capacitor are:

$$\begin{gathered}I_{Lo}\left(t\right)=I_{Lo}\left(t_2\right)\cos\left(\omega_2\left(t-t_2\right)\right)+\\ C_o\omega_2\Delta U_{Co}\sin\left(\omega_2\left(t-t_2\right)\right)\end{gathered} \quad I_{Lp}\left(t\right)=0 \tag{8}$$

$$U_{Co}(t)=U_{in}+\Delta U_{Co}\cos\left(\omega_2\left(t-t_2\right)\right)-L_o\omega_2 I_{L_o}\left(t_2\right)\sin\left(\omega_2\left(t-t_2\right)\right) \tag{9}$$

Where, $I_{Lo}\left(t_2\right)=\frac{I_{\max}L_p}{L_0}$, $\Delta U_{Co}=\frac{I_{\max}}{C_o\omega_1}$.

When the voltage on the capacitor drops to the same as the input voltage, the feedback input stage ends and the duration is:

$$t_{23}=\frac{1}{\omega_2}\arctan\frac{\Delta U_{C_o}}{L_o\omega_1 I_{L_o}\left(t_2\right)} \tag{10}$$

At the end of this stage, the current on the current-limiting inductor reaches its maximum value is shown as:

$$I_{Lo\_\max}=I_{L_o}\left(t_3\right)=\frac{\sqrt{L_p}\left(C_oL_o+L_pL_o-C_oL_p\right)}{L_o\sqrt{C_o^2L_o-C_o^2L_p+L_p^2L_o}}I_{\max} \tag{11}$$

*2.3. Oscillation stage ($t_3\sim t_4$, Fig. **2**(c))*

At t_3 time, the voltage across the absorption capacitor is the same as the voltage on the bus, and the diode is turned on. The current-limiting inductance, stray inductance, and absorption capacitor form an oscillating circuit. At this time, energy is transferred back and forth between the stray inductance, the current-limiting inductance, and the absorption capacitor, and the maximum current limit and the maximum voltage are not changed. The current on the stray inductance, the current-limiting inductance, and the voltage across the absorption capacitor are shown as:

$$I_{Lo}\left(t\right)=\frac{I_{Lo}\left(t_3\right)L_o}{L_o+L_p}+\frac{I_{Lo}\left(t_3\right)L_p}{L_o+L_p}\cos\left(\omega_1\left(t-t_3\right)\right) \tag{12}$$

$$I_{Lp}\left(t\right)=\frac{I_{Lo}\left(t_3\right)L_o}{L_o+L_p}-\frac{I_{Lo}\left(t_3\right)L_p}{L_o+L_p}\cos\left(\omega_1\left(t-t_3\right)\right) \tag{13}$$

$$U_{Co}(t)=U_{in}-\frac{I_{L_o}\left(t_3\right)}{C_o\omega_1}\sin\left(\omega_1\left(t-t_3\right)\right) \tag{14}$$

When the switch devices Q_2,Q_3 are turned on and the input connects to the load, the oscillation stage ends.

*2.4. Energy release stage ($t_4\sim t_5$, Fig. **2** (d、e))*

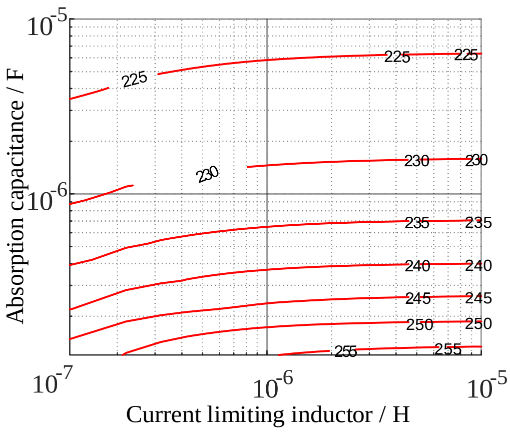
At t_4 time, the switch device Q_2,Q_3 are turned on. The energy stored in the current-limiting inductor and the absorption capacitor begins to be released to the main circuit. At time, the voltage across the absorption capacitor is higher than the voltage across the load, and the diode D_5 is turned off at the time, and the energy on the absorption capacitor and current-limiting inductor is released to the main circuit through the stray inductance (Fig. **2** (d)). The voltage across the absorption capacitor is lower than the voltage across the load at time t_4, the diode D_5 is turned on at this time, the energy on the current-limiting inductor is released to the main circuit through the stray inductance, and the power in and out is used to charge the absorption capacitor through the stray inductance (Fig. **2**(f)).

At t_6 time, the device Q_3 is turned off and starts to work in the second half of the cycle, which is similar to the first half of the cycle.

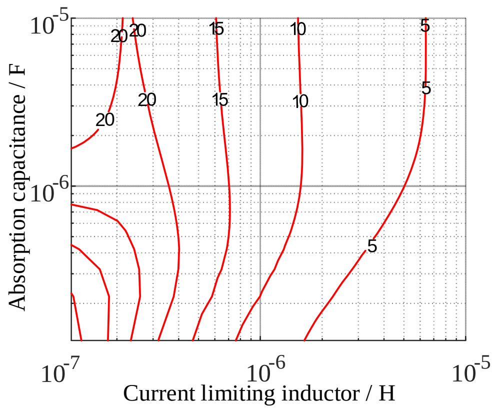
Through analysis of the absorption circuit, it can be found that the absorption circuit does not depend on the low level for the release of energy. Even in the working area, the energy can be released normally. If the dead zone is too small, the voltage on the absorption capacitor has not reached The maximum value does not affect continuous absorption.

3. Parameter design of absorption circuit

According to equations (6) and (11) and the parameters of the absorption capacitor and the current-limiting inductance, the maximum voltage on the bus and the maximum current of the blocking diode can be obtained. The previous relationship can be obtained as shown in Fig.3.



(a)Bus maximum voltage



(b) Current limit inductor current

Fig.3 Effect of Absorption Capacitance and Current Limiting Inductance Parameters on Bus Voltage and Maximum Release Current

It can be seen from Fig.3 that the maximum voltage of the bus and the capacitance of the absorption capacitor are inversely proportional and have a small relationship with the inductance of the current-limiting inductor; while the maximum current has a greater correlation with the absorption capacitor and the current-limiting inductor. It is not possible to solve the capacitance value of the capacitor simply according to the maximum voltage and the inductance value of the inductor according to the maximum current.

According to the actual circuit design requirements, it is required to design the input power $U_{in} = 220V$, the load impedance $Z_{load} = 5\Omega$, the peak current on the bus $I_{\max} = 40A$, and the stray inductance $L_p = 100nH$. According to the principle that voltage does not exceed 10%, the current is not greater than the maximum input current of 40A, take the maximum voltage of 240V, and the maximum current on the current-limiting inductor is 30A. Combining with the formula (6)(11), we get $C_o = 0.25\mu\text{F}$, $L_o = 0.17\mu H$ by MATLAB, and we take $C_o = 0.5\mu F$, $L_o = 0.2\mu H$ actually.

4. Simulation

The component parameters are designed according to the rated load of the circuit, and a simulation model is built in PSpice for comparative analysis. The specific parameters of the circuit are shown in Tab.1,

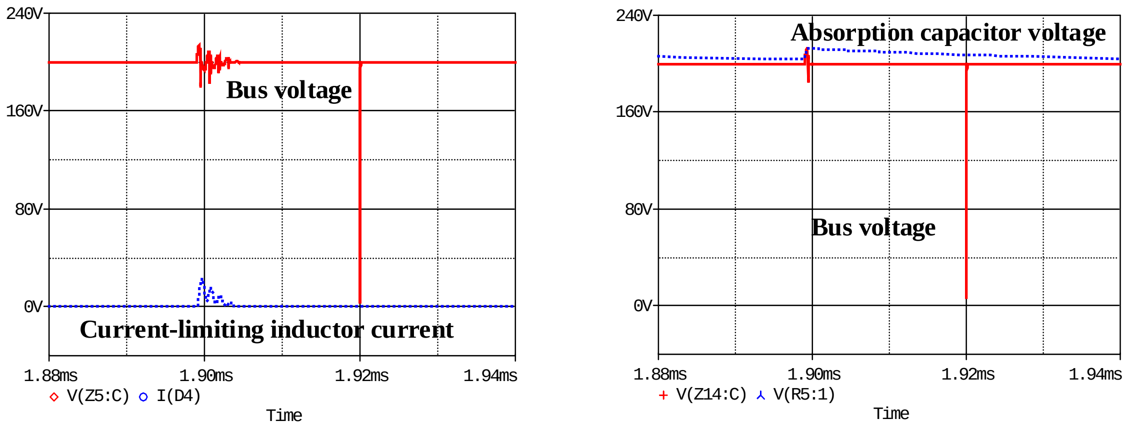
Tab.1 Parameter design of simulation main circuit components

Circuit parameters	Parameters
Input power U_{in}	$220V$
Load impedance Z_{load}	5Ω
Stray inductance L_p	$100nH$
Switch devices $Q_1 \sim Q_4$	IXGT28N120BD1
Antiparallel diodes $D_1 \sim D_4$	

Tab.2 Absorption circuit parameter setting

Devices	New Absorption Circuit	RCD Absorption Circuit
Absorption capacitance	$0.5\mu F$	$0.79\mu F$
Blocking diode	**DSEP29-12A**	**DSEP29-12A**
Current limiting inductor	$0.2\mu H$	-------------
Discharge resistance	-------------	550Ω

The characteristic waveforms of the new-type absorption circuit and RCD absorption current in one switching cycle can be obtained through simulation (Fig.4).



(a)New absorption circuit (b) RCD absorption circuit

Fig.4 Characteristic waveform diagram of new absorption circuit and RCD absorption circuit

When the load changes from heavy to light, the energy consumption of the new absorption circuit and RCD absorption circuit are compared at different output powers (Fig. **5**). In the figure, the abscissa is the energy on the stray inductance, and the ordinate is the percentage of energy loss of the absorption circuit. It can be seen that the energy consumption of the new absorption circuit is less than 1 (less than the energy of the voltage pulse). Its main energy consumption is the on-state loss of the diode, and it is lower than that of the RCD absorption circuit. The RCD absorption circuit can effectively buffer the circuit under heavy load, but because the component parameters are designed according to the rated load (if the parameter design is performed according to the light load, the design requirements cannot be met under heavy load), After the RC circuit is discharged, the bus voltage is lower than the input. During operation, the input power source charges the capacitor through a resistor, which increases the energy consumption of the resistor on the absorption circuit.

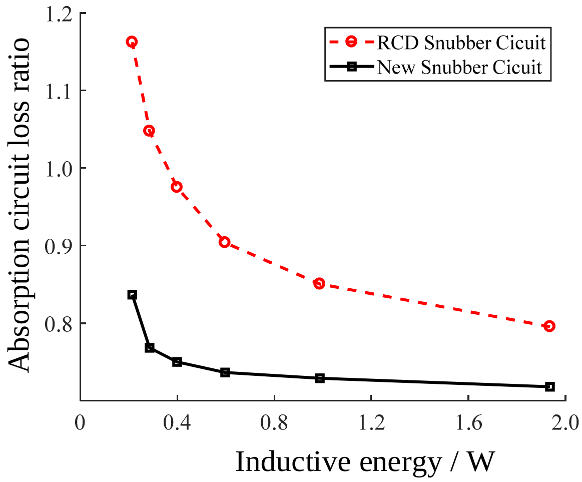


Fig. 5 Comparison of energy consumption between new absorption circuit and RCD absorption circuit

5. Conclusion

Based on the analysis of the existing absorption circuit, a new type of passive and non-destructive absorption circuit is proposed, and the working principle of the absorption circuit is analyzed. Each working condition is calculated, and the parameters of each component are obtained through analysis. the design of. The absorption circuit has the following three advantages:

1. The absorption circuit absorbs voltage spikes in the circuit in a passive and non-destructive manner. The circuit is simple and reliable, and it can return energy to the network to improve the conversion efficiency of the converter.

2. The absorption circuit absorbs the energy of the voltage spike through the absorption capacitor and then releases it through the current-limiting inductor. The absorption process and the release process are performed synchronously, and a smaller absorption capacitor element value can be achieved to suppress a larger voltage spike.

3. At light load, the loss is significantly lower than the RCD absorption circuit, which can adapt to a wide range of load (input voltage) conditions, and has good dynamic performance.

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