

Method for Suppressing Current Spike in Wide Input Flyback converter

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SUMMARY

As one of the main application topologies for medium and small power auxiliary power supplies, flyback converters are increasingly being used in flexible direct current transmission modular multilevel converters (MMCs), requiring their inputs to meet wide range and high input voltage requirements. However, due to the transformer, device distribution, and parasitic parameters of the circuit wiring, the flyback converter generates current spikes and voltage spikes when the power switch is turned on and off. Voltage spikes can cause severe electromagnetic interference, and converter losses due to current spikes can be large, especially at high input voltages, which can affect the conversion efficiency, power density, and reliability of the entire device.

Therefore, in order to analyze the causes of the current spike of the flyback converter in detail, this paper firstly divides the flyback transformer working in DCM mode into five working phases, and analyzes the principle of each phase. The results show that the distribution of the primary winding of the transformer and the discharge of the parasitic capacitance of the drain and source of the switch are result in a current spike during the turn-on of the switch. Moreover, it can be concluded from the calculation that the loss caused by the current spike is positively correlated with the square of the input voltage of the flyback converter and the distributed capacitance of the primary side of the transformer.

Then, based on the flyback converter prototype with the input voltage range of 300~3000V85W developed in this paper, the current and drain-source voltage waveform of the switch under the rated input voltage of 1600V DC are recorded. It can be seen that the current spike amplitude is close to the maximum current value of the switch conducting phase. And the current spikes under different input voltages are tested, and the influence of current spikes on the flyback converter under different input voltages is obtained: as the input voltage increases, the losses caused by the turn-on current spikes of the switches increase rapidly. In order to analyze the influence of the on-current spike of the switch on the efficiency of the flyback converter, the ratio of the loss caused by the current spike to the total loss of the converter and the ratio of the loss to the input power of the converter are calculated. It is calculated that the two ratios increase with the increase of the input voltage, and at 3000V

input voltage, the loss caused by the turn-on current spike of the switch in the total loss of the converter can be close to 40%.

Finally, the improvement measures of suppressing the opening current spike are proposed from the aspects of transformer winding layout and winding interlayer connection. The improvement of the distributed parameters of the device by interleaved layout and Z-winding connection is analyzed through calculation and experiment. The calculation results show that the two methods can obtain smaller transformer distributed capacitance. The experimental results show that the converter efficiency can be improved by 7% by improving the layout of the transformer windings, and it can be improved by 2% by changing the connection mode between the transformer windings.

KEYWORDS

flyback converter; switch tube; current spike; transformer; distributed capacitance

0 Introduction

Flyback converters are widely used in small and medium power auxiliary power supplies due to their simple circuit structure, easy control, and stable and reliable operation^[1]. Influenced by the transformer, device distribution, and parasitic parameters of the circuit wiring, the flyback converter generates current spikes and voltage spikes when the power switch is turned on and off. Current spikes can cause increased circuit losses, and voltage spikes can cause severe electromagnetic interference. Therefore, in order to suppress the influence of voltage spikes, many scholars have carried out detailed research on the turn-off voltage spike^[2-5], and proposed to introduce the absorption circuit^[3] and change the leakage inductance of the transformer^[5] to suppress voltage spikes. In terms of current spikes, the conventional flyback converter has a lower input voltage, a smaller current spike, and less loss to the converter. Therefore, most of the existing studies have only focused on the electromagnetic interference generated by the turn-on current spikes and the effects on the control loop^[6].

However, with the development of power electronics technology, flyback converters are increasingly being used in the auxiliary power supply^[7-9] of the flexible direct current transmission modular multilevel converter (MMC) submodule. This application requires that the input of the flyback converter meets a wide range of high voltages with input voltages exceeding 3kV^[10-11]. The high input voltage of the flyback converter will inevitably cause a large switch-on current spike, which not only causes serious electromagnetic interference, but also increases the turn-on loss of the switching transistor and reduces the overall efficiency of the converter^[12-14]. Therefore, it is necessary to analyze the mechanism of the phenomenon to provide a theoretical basis for the study of effective inhibition methods.

In the literature [15], the influence of the winding connection mode and the winding layout on the size of the distributed capacitance is analyzed by simulation and simulation. Therefore, in this paper, the equivalent circuit of the transformer parameter distribution in the flyback converter is established for the topology of the high voltage input flyback converter. According to the generation mechanism of the switching tube open current, two methods for effectively suppressing the current spike are proposed from the transformer design: 1) changing the layout of the transformer winding; 2) changing the connection mode between the winding layers. The prototype of a flyback converter with an input voltage range of 300-3000V DC, a rated input voltage of 1600V DC, an output voltage of 24VDC and a rated power of 85W was developed to verify the effectiveness of the multi-current spike suppression method.

1 Causes and effect of switch's turn-on current spike

1.1 Analysis of Causes of turn-on Current Spikes

To analyze the cause of the current spike when the switch is turned on, an equivalent circuit of the flyback converter considering the parasitic parameters of the transformer is established, as shown in figure 1. In the figure, C_s is the distributed capacitance of the primary winding of the transformer, L_s is the leakage inductance of the primary winding of the transformer, C_{oss} is the drain-source parasitic capacitance of the switching transistor, and the RCD absorption circuit is used to absorb the voltage spike caused by the leakage inductance of the transformer. For a wide range of high-voltage input conditions, the flyback converter is usually set to operate in DCM mode to ensure stable operation of the flyback converter. At

this time, each switching cycle of the flyback converter can be divided into 5 working periods as shown in Figure 2, and the working principle of the circuit in each period is as follows:

(1) Period one: $t_0 \sim t_1$, as shown in Figure 2(a)

At time $t=t_0$, the voltage on the distributed capacitor is 0, the voltage on the drain-source parasitic capacitance C_{oss} of the switch is V_{in} , and thereafter, the switch starts to turn on, and its equivalent resistance begins to decrease. When the switch is turned on, the power supply charges the capacitor C_s via the equivalent resistance of the switch. The C_{oss} is discharged through the equivalent resistance. At time $t=t_1$, the switch is completely turned on and enters the conducting state.

(2) Period two: $t_1 \sim t_2$, as shown in Figure 2(b)

During $t_1 \sim t_2$, the switch turns on, and the current of the transformer magnetizing inductance L_m rises linearly. At time t_2 , the inductor completes energy storage.

(3) Period three: $t_2 \sim t_3$, as shown in Figure 2(c)

At t_2 , the switch starts to turn off, the power supply and leakage inductance L_s are in series to charge C_{oss} together, and energy is exchanged between L_s and C_s . Therefore, the magnetizing current in L_m cannot be transmitted to the secondary side immediately. During the period from t_2 to t_3 , L_s will produce a very high back EMF, leading to a voltage spike on the switch, increasing the voltage stress on the switch, and charging and discharging between L_s and C_s to generate high-frequency ringing. After increasing the RCD clamp circuit, it absorbs the energy of L_s . At the same time, the clamp capacitor is charged in parallel with the distributed capacitance of the primary winding of the transformer, which greatly reduces the high-frequency ringing frequency and amplitude. When $t=t_3$, the energy conversion is completed, the switch is turned off, and C_s is charged to $V_{Cs} = -V_o/n$.

(4) Period four: $t_3 \sim t_4$, as shown in Figure 2(e)

From time t_3 , the secondary diode D_2 is turned on, the current in the magnetizing inductance decreases linearly, and the energy is transmitted to the secondary side. At time t_4 , the energy transfer is completed and D_2 is turned off.

(5) Period five: $t_4 \sim t_5$, as shown in Figure 2(f)

At time t_4 , the primary side magnetizing inductor energy is released and the secondary diode D_2 is turned off. The primary capacitor of the transformer and the leakage inductance of the transformer and the output capacitance of the switch form a resonant circuit in series, what's more the waveforms of V_{Cs} and V_{DS} oscillate, and the oscillation decay process is related to the degree of loop damping.

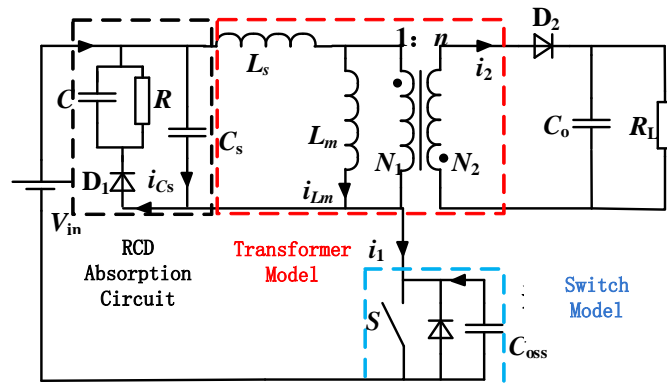


Fig 1 Equivalent circuit of flyback converter

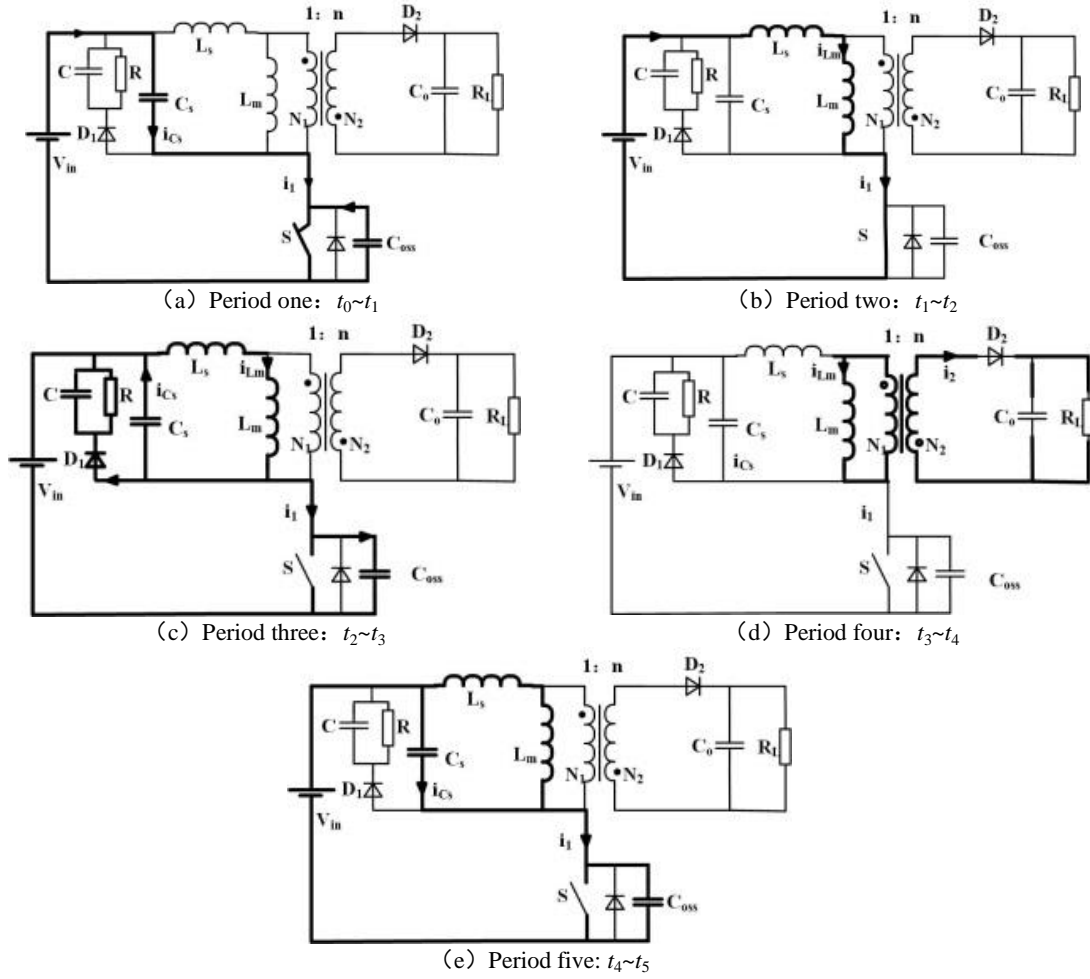


Fig 2 Analysis of Principle of Flyback Converter in DCM Mode

According to the above analysis, during the operation of the flyback converter, the charging of the distributed capacitance of the primary winding of the transformer and the discharge of the parasitic capacitance of the drain and the drain of the switch lead to the current spike in the turn-on process of the switch. However, the current generated when the distributed capacitance of the switch is discharged only flows through the drain-source equivalent resistance of the switch and does not flow through the power supply V_{in} , therefore the current actually flowing in the flyback converter circuit is the current spike generated by the distributed capacitance of the primary winding of the transformer. This article mainly analyzes the impact of this current spike and its suppression measures.

When the charging process of the distributed capacitor of the primary winding of the transformer causes the current spike on the switch, the switch is not completely turned on, and its forward impedance and voltage are high, which will increase the loss of the switch and affect the power supply efficiency. Analysis of Figure 7(a) shows that the power loss caused by turning on the current spike by the switch can be calculated by the following equation, ignoring the internal resistance of the power supply.

$$P_{C_s} = \frac{1}{2} C_s V_{in}^2 f_s \quad (1)$$

In the formula, f_s is the switching frequency. According to formula (1), the loss caused by the turn-on current spike of the switch is proportional to the square of the input voltage of the flyback converter. For a wide range of high input voltage flyback converter, the loss cannot be ignored at high input voltage. In addition, if the input voltage is the same, the turn-on current peak loss is only related to the size of the transformer's primary winding distributed capacitance.

1.2 Effect of turn-on current spike

The flyback converter proposed in this paper adopts the peak current detection control method, and the working mode is DCM mode, and the switching frequency is 20 kHz. The waveform of the switching tube current and the drain-source voltage in the prototype of the measured flyback converter are shown in Figure 3. It can be seen from Figure 3 that there is a significant current spike in the turn-on phase of the switch. Under the rated input voltage of 1600V DC, the current spike amplitude is close to the maximum current value of the turn-on phase of the switch. The input voltages of Figures 4(a)-(d) are 500V, 1000V, 1500V and 2000V, respectively. Comparing the current spikes at different input voltages, it can be seen that the input voltage is positively correlated with the current spike.

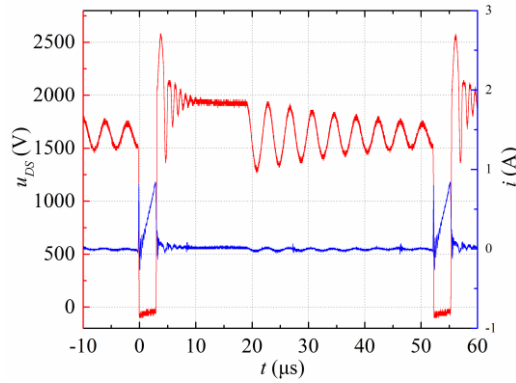


Fig3 Switch current and drain-source voltage waveform

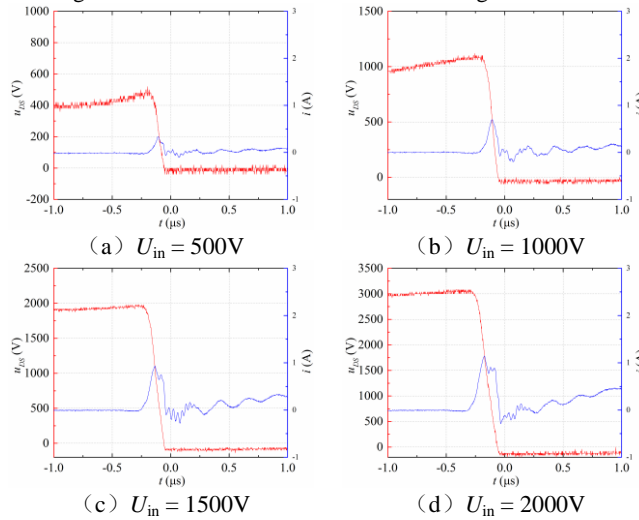


Fig 4 Current spikes at different input voltages

The integration of the product of the current and voltage of the switch in the opening phase versus time is the loss caused by the turn-on current spike, denoted by P_{ip} . The loss caused by the measured turn-on current spike of the switch is shown in Figure 5. As the input voltage rises, the loss caused by the turn-on current spike of the switch increases rapidly. In order to analyze the influence of current spikes on the efficiency of the flyback converter, the ratio of the loss caused by the current spike to the total loss of the converter P and the ratio of the loss to the input power P_{in} of the converter are calculated, as shown in Figure 6 and Figure 7 shows. As it can be seen from the figure, the two ratios increase with increasing input voltage. With a 3000V input voltage, the loss caused by the turn-on current spike of the switch in the total loss of the converter can be close to 40%. Based on the above research

results, for a wide range of high-voltage input flyback converters, the losses caused by the turn-on current spikes of the switches cannot be ignored.

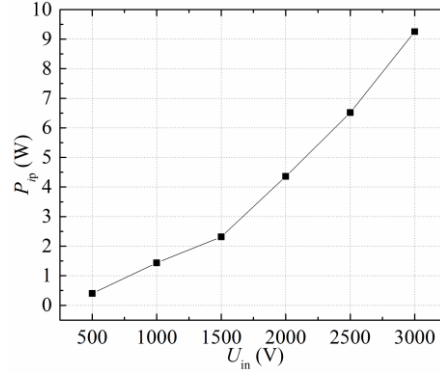


Fig 5 Loss Caused by turn-on Current Spike of Switch

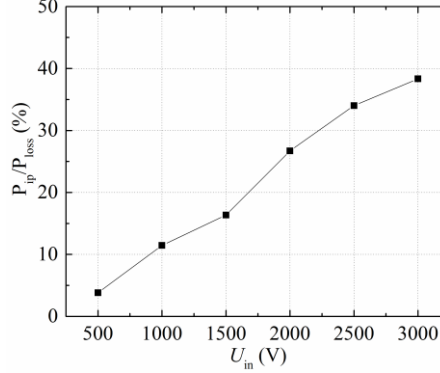


Fig 6 The proportion of the loss caused by current spikes to the total loss of the converter

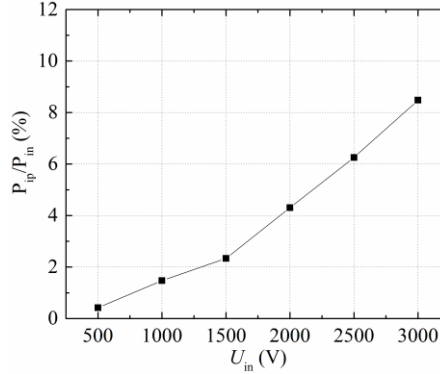


Fig.7 Proportion of loss due to current spikes to input power

2 Suppression of current spikes in switches

Without changing the input voltage of the flyback converter, the current spike of the switch can be reduced by reducing the primary side distributed capacitance of the transformer. The main factors affecting the size of the transformer's primary side distributed capacitance include transformer winding layout and winding connection methods [15-17].

2.1 Winding layout

The wide-range high-input-voltage flyback converter has many primary winding turns, which are generally divided into multiple layers. The primary distributed capacitance of the transformer mainly includes the inter-turn capacitance of the same layer winding and the inter-layer capacitance of different layer windings. Since the former is a capacitor connected in series and the potential difference between adjacent turns is small, the capacitance is negligible and the inter-layer capacitance is mainly considered. This capacitance can be expressed as:

$$C = \frac{\pi \varepsilon l}{\ln \frac{d-a}{a}} \quad (2)$$

In this formula, l is the average length of adjacent turns of different layer windings, ε is the dielectric constant of the winding insulation material, d is the center-to-center distance of the adjacent turns, and a is the radius of each turn of the winding conductor. Transformer winding layout is mainly divided into traditional layout and interleaved layout. The former first winds the primary winding and then winds the secondary winding. The interleaved layout uses the alternate winding of the primary and secondary windings, as shown in Figure 8. It can be seen from the figure that the difference in the primary side distributed capacitance of transformers with different winding layouts is mainly manifested by the different center distances of adjacent turns of the upper and lower windings. Compared with the traditional layout, the primary side windings in the interleaved layout are surrounded by secondary windings, and the spacing between the two primary windings is larger, and smaller distributed capacitance between the winding layers can be obtained, thereby reducing the turn-on current spikes.



Fig 1 Sketch of different winding layouts

2.2 Winding connection

In the case of the same transformer winding layout, the connection between the winding layer and the layer is different, and the distribution of the potential difference between the layers will change, and the distributed capacitance between the windings will be affected. Generally, the inter-layer connection method of the transformer winding includes a C-type connection method and a Z-type connection method. Taking two layers of the primary winding of the transformer as an example, the input voltage of the primary winding of the transformer is U . The two connection methods and the winding turn-to-turn potential difference distribution are shown in Figures 9(a) and (b). Let the static capacitance between the two layers of windings be C_0 , and the width of each layer of windings is w . Since the leakage flux of the high-frequency transformer is much smaller than the main magnetic flux of the excitation, it can be considered that the primary winding voltage of the transformer is evenly distributed along the coil. Figure 9 is available:

(1) The potential difference at any position x of the two-layer winding of the C-type connection is:

$$\Delta U_C(x) = U - \frac{U}{w}x \quad (2)$$

(2) The voltage difference at any position x at the two-layer winding of the Z-type connection is:

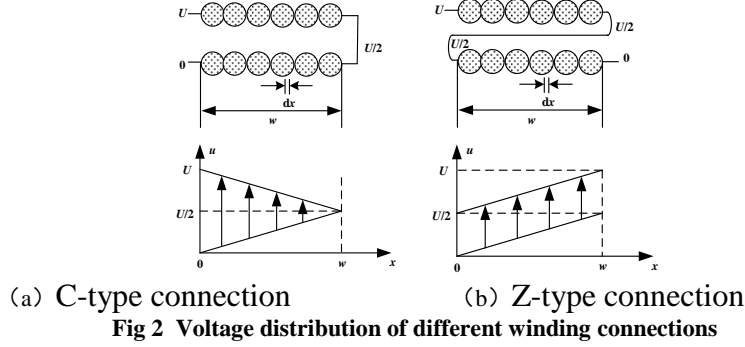
$$\Delta U_Z(x) = \frac{U}{2} \quad (3)$$

The electric energy stored in the static capacitance C_0 of the primary winding under the C-type connection and the Z-type connection can be calculated by the following formula:

$$W_C = \int_0^w \frac{C_0}{w} (\Delta U_C(x))^2 dx = \frac{1}{3} C_0 U^2 \quad (4)$$

$$W_Z = \int_0^w \frac{C_0}{w} (\Delta U_Z(x))^2 dx = \frac{1}{4} C_0 U^2 \quad (5)$$

Combining equations (4) to (5), it can be seen that, under the same input voltage, the electric energy stored in the distributed capacitance of the primary winding of the transformer wound with the Z-type connection is only 3/4 of that of the C-type connection. The turn-on spike current of the switch is proportional to the energy of the distributed capacitor electric field of the primary winding of the transformer. Therefore, winding the transformer by the Z-type connection method can reduce the turn-on current spike of the switch.



3 Experimental results

As in the wide-range high-input flyback converter described in Section 1.1, the transformer core uses EER42/20, the primary winding turns 166 turns, is divided into 4 layers, and the secondary winding has 64 turns, which is divided into two layers. In order to verify the actual working effect of the current spike suppression measures of the switch, the transformer is wound with different winding layouts and interlayer connections, and the corresponding current spikes and losses are tested.

Two transformers T1 and T2 are wound using the two winding configurations shown in Figure.8 to discuss the effect of improving the suppression of the transformer winding layout on the current spike of the flyback converter switch. T1 adopts the traditional layout, first winding the primary winding, and then the secondary winding; T2 adopts an interleaved layout, first winding two primary windings, two secondary windings in the middle, and two primary windings outside. The two transformer winding layers are connected by C-type connection. Both the primary and secondary sides are made of enameled wire. The diameter of the wires is 0.45mm and 0.6mm respectively, and the thickness of the interlayer insulation material is the same. Figure 10 shows the measured current waveforms flowing through the switch when the flyback converters of the rated input voltage adopt T1 and T2 transformers respectively. The experimental results show that the switch current spike of the transformer with traditional layout winding is 1.18A, and it of the transformer with interleaved layout is only 0.76A.



Figure 11 shows the turn-on losses of the switch caused by the current spikes when two transformers, T1 and T2, are used at different input voltages. It can be seen from the figure that as the input voltage increases, the loss increases rapidly. Besides when under the same input voltage, the switch's turn-on loss using the conventional layout transformer is higher

than it using the interleaved layout transformer, and the gap between the two increases gradually as the input voltage increases. Figure 12 shows the comparison of the overall efficiency of the converter when T1 and T2 are used respectively. It can be seen from the figure that changing the transformer from the traditional layout to the interleaved layout can effectively improve the efficiency of the converter, and the effect of this improvement becomes more and more obvious with the rising of converter's input voltage. At 3000V input voltage, the overall efficiency of the converter using staggered layout transformer increases by 7%.

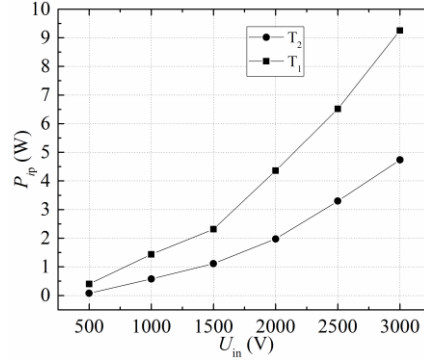


Fig 11 Comparison of Turn-on Current Spike Loss for T1 and T2

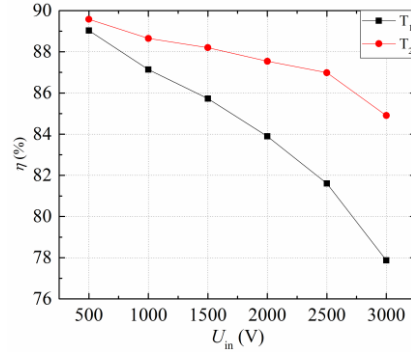


Fig 12 Flyback converter efficiency when using Ta and Tb

In order to study at the inhibitory effect of improving the connection mode between transformer windings on the turn-on current of the switch, the two transformers of Ta and Tb were wound by C-connection and Z-connection respectively, and both transformers adopt an interlaced layout. The measured turn-on current of the flyback converter with two transformers of Ta and Tb is shown in Figure 13. It can be seen that, compared with the C-type connection, the transformer wound by the Z-type connection has a smaller turn-on current spike value corresponding to the switch.



Fig 13 Current waveform of the transformer's primary with different windings

Figure 14 shows the turn-on losses caused by the turn-on current spike of the switch when the flyback converters with different input voltages use two transformers, Ta and Tb, respectively. The results show that when inter-layer windings of the transformer are connected by Z-type connection, the losses caused by the turn-on current spikes of the switch can be significantly reduced.

Figure 15 shows the comparison of the overall efficiency of the converter using two transformers, Ta and Tb, respectively. The results show that the Z-connected connection of

the inter-layer windings of the transformer reduces the turn-on current spike of the switch and the loss caused by it, and improves the efficiency of the converter. And the difference in efficiency of the converters using the two transformers increases as the input voltage increasing. With a 3000V input voltage, the transformer with a Z-type connection increases the overall efficiency of the converter by 2%.

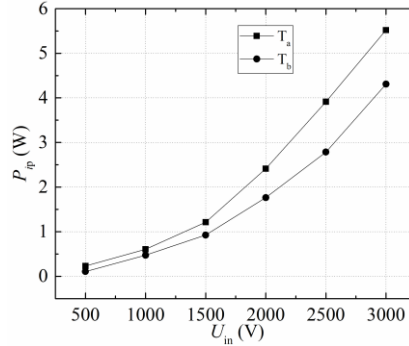


Fig 4 Comparison of Turn-on Current Spike Loss for Ta and Tb

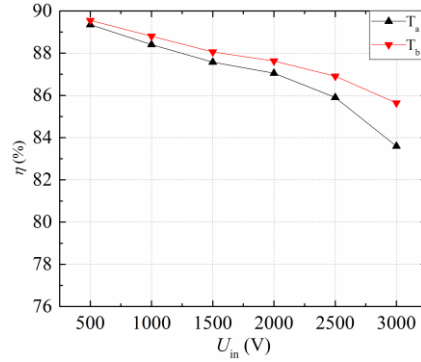


Fig 5 Flyback converter efficiency when using Ta and Tb

4 Conclusion

Flyback converters are widely used in small and medium power auxiliary power supplies. For a wide range of high voltage input flyback converters, the losses caused by the turn-on current spikes of the switches during operation are not negligible. In this paper, the causes, the influence, and the suppression measures of the turn-on current spike of the switch are studied. The conclusions are as follows:

- (1) The measured working waveform of the flyback converter with a rated power of 85W under the input of 300~3000V indicates that, at high input voltage, the loss caused by the turn-on current spike of the switch accounts for up to 40% of the total loss of the converter.
- (2) Transformers wound in a staggered layout reduce the distribution of the primary winding by increasing the center distance between the transformer winding layers, which can reduce the current spike amplitude and loss caused by the switch.
- (3) When the other conditions unchanged, the electric energy stored by the distributed capacitance of the transformer primary winding with the Z-type connection is only 3/4 of the C-type connection, thereby having a smaller turn-on current spike and loss.
- (4) The experimental results show that the efficiency of the converter can be increased by 7% by improving the transformer winding layout for this wide-range, high-voltage input flyback converter. The efficiency of the converter can be improved by 2% by improving the connection method of the transformer inter-layer windings.

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