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Research on the Method of Leakage Inductance Suppression of High Frequency Transformer of Switching Power

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***Abstract*—Switching power supply is widely used in electrical systems. Its conversion efficiency is one of the key parameters for evaluating the quality of the power supply. At present, high frequency switching power supply is highly required with possible reduced size on transformers and inductors. When the working frequency reaches 10MHz in the switching power supply, the leakage inductance of high frequency transformer is the main factor affecting the overall conversion efficiency. By analyzing the main reason and the possible damage of the leakage inductance in high frequency transformer, a novel design is proposed in the paper, in which the primary and the secondary couplings are increased by the new design of the transformer, and the influence of the leakage inductance is suppressed by the RCD(Residual Current Device) clamp circuit. The optimized design is carried out on the 5V-2A low-power switching power which is widely used. The conversion efficiency of switching power is increased from 75.8% to 85.3%, and the withstand voltage of MOSFET(Metal-Oxide-Semiconductor Field-Effect Transistor) is reduced from 640V to 500V.**

Keywords-high frequency transformer; leakage inductance; electromagnetic coupling; clamp circuit

I. INTRODUCTION

Switching power is widely used. Its working principle is to control electronic switching devices (transistors, field-effect transistors, thyristors, etc.) to turn on and off continuously at a high frequency, and pulse modulate the input voltage, so as to realize AC(Alternating Current) / DC(Direct Current), DC / AC, DC / DC and other voltage conversion, as well as the adjustable control of output voltage and current. The core technical index of switching power is conversion efficiency η, which refers to the proportion of output power to input power, and the difference between input power and output power is transformed into heat energy emission. Obviously, improving the conversion efficiency can improve energy utilization efficiency, energy conservation and emission reduction, and reduce energy consumption; on the other hand, it can reduce the heat generated by power loss, improve the working environment of switching power and delay its life.

To improve the switching power conversion efficiency η, the core method is to increase the working frequency. At present, power electronic technology has made the working frequency exceed 10MHz, so that the conversion efficiency can reach more than 95% [1].With the increase of switching power frequency, the influence of high frequency transformer leakage inductance on conversion efficiency becomes more and more prominent, which becomes the main factor to restrain the further improvement of conversion efficiency. Optimizing the design and suppressing the leakage inductance of high-frequency transformer has become an effective path to improve the switching power conversion efficiency η and reduce the failure rate [2].

II. LEAKAGE INDUCTANCE AND ITS INFLUENCE

High frequency transformer is a device for energy storage, release and conversion. It converts the input electric energy into magnetic energy and stores it in the magnetic core, and then releases the magnetic energy to the output end in the form of electric energy. In the process of transformer manufacturing, the primary and secondary coils can not achieve the ideal coupling degree, and the magnetic circuit of the magnetic core also needs to reserve a variable air gap to adjust the inductance. Therefore, the magnetic line generated by the primary coil can not be coupled to the secondary coil through the magnetic core, and a part of the magnetic flux will be leaked into the air to form a closed magnetic circuit. The leakage magnetic flux is called magnetic-flux-leakage, which produces leakage inductance.

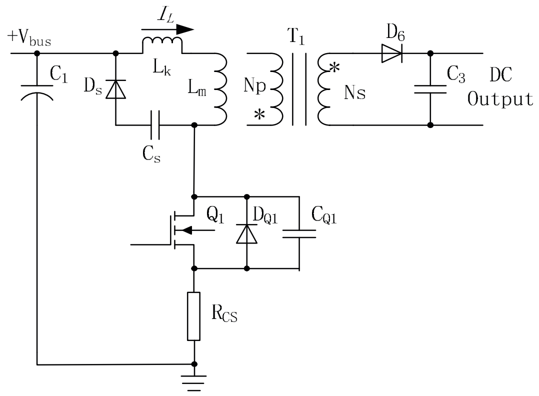

Figure 1. Diagram of main circuit of transformer

Figure 1 shows the diagram of high-frequency transformer[3-5].Transformer T_1 includes ideal transformer composed of primary winding N_p and secondary winding N_s, primary side excitation inductance L_m, leakage inductance L_k, parasitic diode D_{Q1} of Q_1, parasitic capacitance C_{Q1}, absorption capacitor C_s, absorption diode D_s, input rectified bus voltage V_{bus}, output voltage V_o.

The calculation formula of energy storage of high frequency transformer core is as follows:

$$J = \frac{1}{2} \times L_P \times I_{PK}^2 \qquad (1)$$

The excitation inductance L_m and leakage inductance L_k are connected in series, and the flowing current are the same:

$$i_{Lm} = i_{Lk} = \frac{V_{bus}}{L_k + L_m} \times t \qquad (2)$$

The stored energy of inductance L_m and leakage inductance L_k are obtained by substituting equation 1 and equation 2:

$$J_{Lm} = \frac{1}{2} \times L_m \times I_{Lm}^2 \qquad (3)$$

$$J_{Lk} = \frac{1}{2} \times L_k \times I_{Lk}^2 \qquad (4)$$

The energy storage of excitation inductor L_m is coupled with the secondary and can be transmitted to the secondary output. The energy storage of leakage inductance L_k can not be coupled to the secondary, and it will be consumed in the oscillation with the parasitic capacitance of the line, which will increase the loss and decrease the conversion efficiency. Excitation inductance L_m and leakage inductance L_k oscillate with parasitic capacitance C_{Q1} respectively. The V_{ds} waveform generated after MOSFET switch-off is shown in Figure 2:

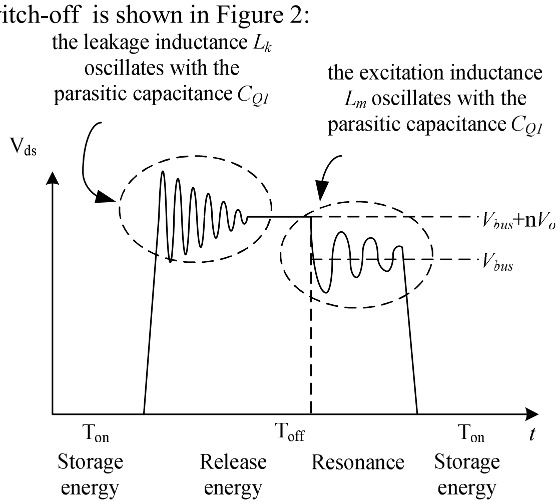

Figure 2. V_{ds} waveform after MOSFET switch-off

During the MOSFET turn-on period (T_{on}), the transformer energy storage, V_{ds} is 0V. When MOSFET is turned off (T_{off}), the transformer releases the stored energy to the secondary. At the same time, the leakage inductance L_k oscillates with the parasitic capacitance C_{Q1}. The oscillation center voltage is V_{bus}+nV_o (n = N_p / N_s). The amplitude of leakage inductance oscillation is proportional to leakage inductance L_k and parasitic capacitance C_{Q1}. It can be seen that the larger the leakage inductance L_k, the greater the oscillation energy loss, the lower the conversion efficiency, and the greater the overvoltage damage to MOSFET. When the primary energy storage is released, the excitation inductance L_m and parasitic capacitance C_{Q1} oscillate. The upper limit of the oscillation is V_{bus}+nV_o, and the energy loss and damage to MOSFET are lower than that of leakage inductance L_k.

The existence of leakage inductance L_k will affect the performance of switching power. Especially, with the increase of the converter frequency f_{sw}, the permeability of ferrite core material of transformer will decrease, and the excitation inductance L_m will decrease. However, the leakage inductance L_k is affected by the transformer process, and the leakage inductance value remains unchanged, so the relative value of the excitation inductance L_m increases, and the influence on the power converter becomes greater. At present, the working frequency of AC / DC converter can reach 10MHz, and leakage inductance is the main factor affecting conversion efficiency.

III. METHOD OF LEAKAGE INDUCTANCE SUPPRESSION

To suppress the leakage inductance and improve the switching power conversion efficiency η is mainly implemented in two aspects: optimizing the transformer design to reduce the leakage inductance [6], increasing clamp circuit to suppress the influence of leakage inductance [7].

A. *Optimization of transformer design*

The transformer in this design is shown in T_1 in Figure 1. The parameters of the transformer are calculated as follows: primary winding N_p is 96 turns, secondary winding N_s is 5 turns, auxiliary winding N_a is 11 turns, excitation inductance L_m is 2mH, EE13 vertical 5+5 pins skeleton and PC40 magnetic core are selected.

The conventional winding method is shown in Figure 3, with the core and framework as the core, winding outwards in turn: primary winding N_p (96 turns, wire diameter 0.2mm), secondary winding N_s (5 turns, twisted pair, wire diameter 0.45mm), auxiliary winding N_a (11 turns, wire diameter 0.2mm). The star is homonymous end, and the arrow is the in and out direction of enameled wire.

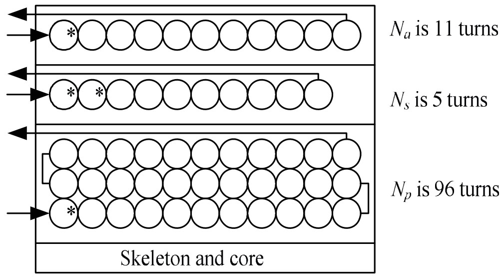

Figure 3. Conventional winding method of transformer

After testing, the transformer primary leakage inductance L_k is 220uH, accounting for 11% of the excitation inductance L_m is 2mH, and the conversion efficiency η is 75.8%. In order to suppress the leakage inductance and improve the conversion efficiency, the transformer is improved as follows:

- Sandwich winding method is adopted, that is, each winding is interleaved to strengthen coupling.
- Each group of windings should be wound tightly and evenly distributed with no gap.
- The outgoing line should be at right angle as far as possible and close to the skeleton wall.
- If the last layer can't be wrapped with one layer, it will be evenly wrapped.
- The thickness of the insulation layer should be as thin as possible to meet the withstand voltage without leaving gaps.

The improved winding method is shown in Figure4. After testing, the transformer primary leakage inductance L_k is 16uH, accounting for 0.8% of the excitation inductance L_m is 2mH, and the conversion efficiency η is 79.2%, which is 3.4% higher than the conventional winding method.

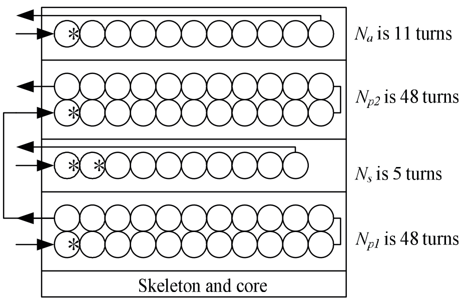

Figure 4. Low leakage inductance winding method of transformer

B. *Add RCD clamp circuit*

The leakage inductance L_k oscillates with the parasitic capacitance C_{Q1}, and the energy can not be coupled to the secondary winding N_s, which needs to be consumed gradually in the oscillation. Obviously, the larger the amplitude of oscillation is, the more energy is consumed, and the lower the conversion efficiency η. Clamp circuit can be used to suppress the oscillation caused by leakage inductance.

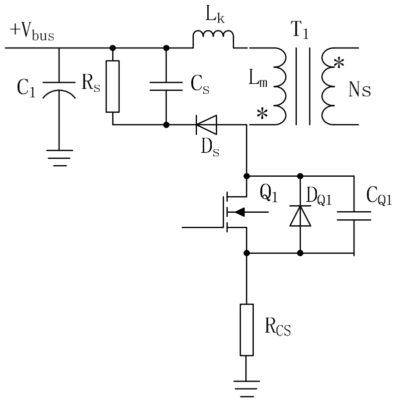

Figure 5. RCD clamp circuit

As shown in Fig.5, R_s, C_s and D_s constitute the RCD clamp circuit, which is used to absorb the oscillation generated by leakage inductance L_k and parasitic capacitance C_{Q1}. Diode D_s controls the working current direction of RCD. When Q_1 is on, D_s is cut off and RCD is not working. When Q_1 is off, leakage inductance L_k oscillates with parasitic capacitance C_{Q1}, and D_s is on to provide free wheeling channel to charge C_s, so that C_s can absorb the oscillation generated and limit the amplitude of oscillation voltage. When Q_1 is on and RCD is not working, the absorption resistance R_s releases the energy absorbed by C_s, which is ready for the next RCD cycle.

IV. VERIFICATION AND TESTING

This design chooses to implement improvement measures on the scheme of low power switching power with input of 220V and output of 5V-2A. This kind of switching power is commonly used in small household appliances, such as adapter, charger and so on. It has the most extensive use and the largest demand. Therefore, it is of great significance to improve its conversion efficiency. Due to the small power, the conversion efficiency of this kind of switching power is relatively low, and the conversion efficiency η is about 80%. The sample of switching power is shown in Figure 6 below:

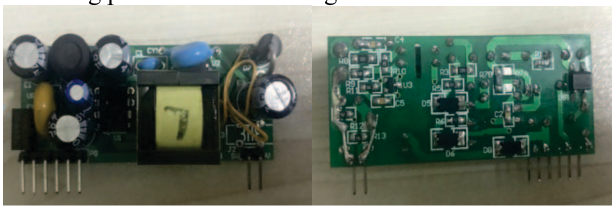

Figure 6. Photo of sample static display

The improvement is carried out on the sample, and the comparison test is carried out to verify the implementation effect of the improved transformer process to reduce the leakage inductance L_k and increase RCD clamping circuit to suppress the leakage inductance hazard.

A. *High leakage inductance and non clamping circuit*

The transformer scheme without improvement is shown in Fig.3, the leakage inductance of primary side L_k is 220uH, without RCD clamp circuit. Input 220V, output 5V-2V, D-S(Drain-Source) waveform V_{ds} of Q_1 in oscilloscope is shown in Figure 7 below. The results show that the peak value of V_{ds} is 640V, the oscillation amplitude is 360V, and the conversion efficiency of converter is 75.8%.

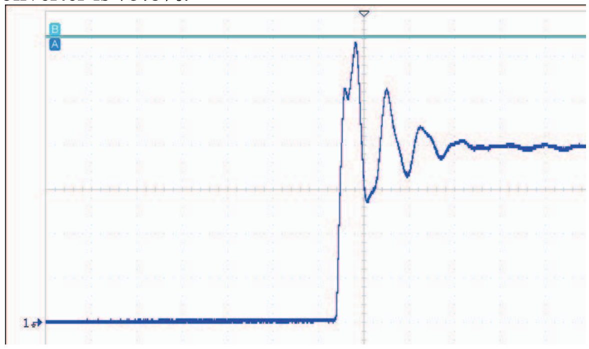

Figure 7. V_{ds} waveform of high L_k and non clamping circuit

B. *Low leakage inductance and non clamping circuit*

The improved transformer scheme as shown in Fig. 4 is adopted, the leakage inductance of primary side L_k is 16uH, without RCD clamp circuit. Input 220V, output 5V-2A, D-S waveform V_{ds} of Q_1 in oscilloscope is shown in Figure 8. The peak value of V_{ds} is 560V, and the oscillation amplitude is 240V. After calculation, the conversion efficiency η of converter is 79.2%.

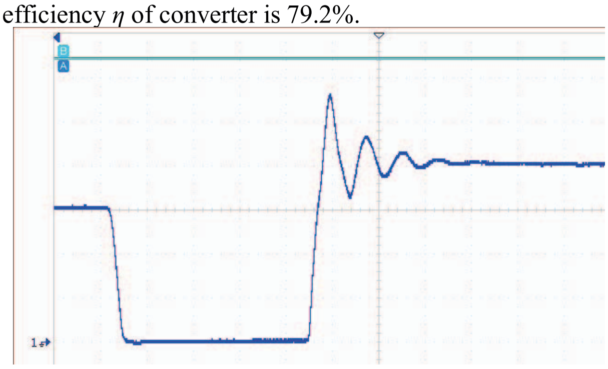

Figure 8. V_{ds} waveform of low L_k and non clamping circuit

C. High leakage inductance and clamping circuit

The scheme of no improved transformer as shown in Fig. 3 is adopted, the leakage inductance L_k of primary side is 220uH, and RCD clamp circuit is added. Input 220V, output 5V-2A, D-S waveform V_{ds} of Q_1 in oscilloscope is shown in Figure 9. The results show that the peak value of V_{ds} is 540V, the oscillation amplitude is 220 V, and the conversion efficiency of converter is 80.2%.

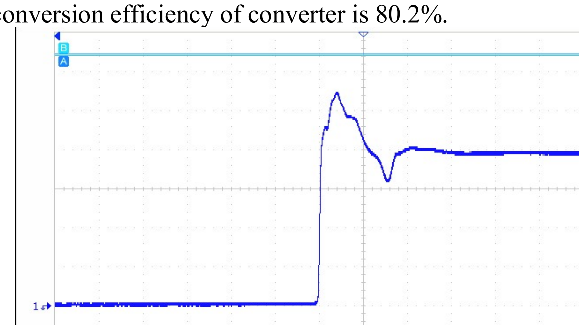

Figure 9. V_{ds} waveform of high L_k and clamping circuit

D. Low leakage inductance and clamping circuit

The improved transformer scheme as shown in Fig. 4 is adopted, the leakage inductance L_k is 16uH and RCD clamp circuit is added. Input 220V, output 5V-2A, D-S waveform V_{ds} of Q_1 in oscilloscope is shown in Figure 10. The results show that the peak value of V_{ds} is 500V, the oscillation amplitude is 120V, and the conversion efficiency of converter is 85.3%.

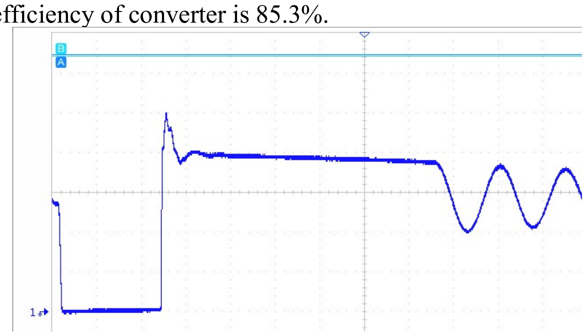

Figure 10. V_{ds} waveform of low L_k and clamping circuit

Table 1 is obtained by summarizing the data of Figure 7 to figure 10. The influence of leakage inductance and RCD clamp circuit on AC / DC converter is given.

TABLE I. COMPARISON OF EXPERIMENTAL RESULTS

leakage inductance L_k (uH)	clamp circuit	V_{ds} peak value (V)	oscillation amplitude (V)	conversion efficiency η
220	No	640	360	75.8%
16	No	560	240	79.2%
220	Yes	540	220	80.2%
16	Yes	500	120	85.3%

It can be seen from table 1 that by improving the transformer process to reduce the leakage inductance L_k and increasing the RCD clamp circuit can effectively reduce the withstand voltage of MOSFET V_{ds} and improve the converter conversion efficiency η. The RCD clamp circuit can also reduce the oscillation times and periods. In comparison, the influence of RCD clamp circuit is slightly greater than that of leakage inductance. In practical application, it is necessary to reduce leakage inductance L_k and increase RCD clamp circuit at the same time.

V. CONCLUSIONS

This paper analyzes the cause and influence of leakage inductance of high frequency transformer. Under the condition that the working frequency of AC / DC converter has reached 10MHz, leakage inductance has become the main factor affecting conversion efficiency. In this paper, two improvement methods are adopted. One is to optimize the transformer design, such as sandwich winding method, reducing winding gap, winding evenly distributed winding, reducing the thickness of insulation layer and so on, so as to increase the coupling of primary and secondary transformer and reduce the generation of leakage inductance. The second is to add RCD clamping circuit to suppress the influence of leakage inductance. The conversion efficiency is gradually increased from 75.8%, 79.2%, 80.2% and 85.3%, and the V_{ds} withstand voltage of MOSFET is gradually reduced from 640V, 560V, 540V and 500V, which shows that the improved method is effective.

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