

A Magnetic Integration Half-turn Planar Transformer for LLC Resonant DC-DC Converters

Enguo Rong, Siqu Li, Rui Zhang, Xiao Du, Qingyun Min, Sizhao Lu

Department of Electrical Engineering,
Kunming University of Science and Technology
Kunming, China
lusz10@kmust.edu.cn

Abstract—This paper presents a new half-turn planar transformer with integrated leakage inductance for LLC resonant DC-DC converters. A simple EILP32 ferrite core is adopted in the proposed transformer. The primary side windings are placed at both the center and side legs of the ferrite core. By adjusting the distribution of the windings on the center and side legs, the leakage inductance of the transformer can be changed. In order to balance the core loss and the copper loss, the turn number of the secondary side winding is designed to 0.5. Two configurations of secondary winding and circuit structure are given and compared. The characteristics of the proposed transformer are simulated using Maxwell and Simplorer. Finally, a 380V / 12V, 500 kHz, 750W LLC converter was built to evaluate the performance of the proposed transformer. The converter can reach 12V stable output when the input voltage range is from 360V to 400V, and realize the highest efficiency of 97% at half load condition.

Keywords—Magnetic integration; Planar Transformer; Half-turn transformer; LLC converter

I. INTRODUCTION

Modern power electronic converters are developing toward the direction of high efficiency and high power density. The miniaturization of switching power supply will inevitably lead to the rising of switching frequency. The emergence of new switching devices and topologies solves the efficiency issue of increased frequency. As an excellent topology, LLC can achieve zero-voltage turn-on of the primary switch and zero-current turn-off of the secondary switch [1]. The new generation of wideband gap power semiconductors, like silicon carbide (SiC) power MOSFET and gallium nitride (GaN) high-electron mobility transistors (HEMTs), can further reduce the switching losses, and push the power density and efficiency higher [2-3]. However, the development of passive devices is relatively backward, and the size of the magnetic components becomes the biggest bottleneck that limits higher power density. Compared to a conventional transformer building with helical windings, a planar transformer, which has been widely used in high frequency DC-DC applications, exhibits excellent thermal characteristic, extreme low leakage inductance and higher power efficiency and density [4]. The planar transformers have already been adopted in many high power efficiency and power density LLC resonant converters [5-8]. As it is difficult to integrate the resonant inductor into a planar

transformer, some of the LLC converter are unregulated ones with fixed voltage ratio [5-6], otherwise a standalone resonant inductor [7] or an auxiliary circuit is necessary for the output voltage regulation [8]. Integrating the leakage inductance into the planar transformer is of great importance for a regulated LLC converter.

In this paper, a planar transformer with integrated leakage inductance is proposed. In addition, to achieve 750W output power with a single core and to balance the iron loss and copper loss, a half-turn secondary winding configuration demonstrated in the final test of the 2017 IEEE International Future Energy Challenge was used [9]. Similar ideas was also found published recently by Dr. Ranjram [10]. In the second section, the structure and working principle of the transformer are introduced; in the third section, the simulation results of the transformer as well as the LLC resonant converter circuit are given; in the fourth section, the proposed transformer was experimentally verified by a 750W, 360~400V input, 12V output LLC resonant converter.

II. PROPOSED INTERAGATION TRANSFORMER AND OPERATION PRINCIPLES

A LLC converter with the magnetic integration half-turn planar transformer is shown in Fig. 1. V_{in} is the DC input voltage. Q_1 and Q_2 are two power MOSFETs in the primary half-bridge. C_s and L_r are the resonant capacitor and inductor. L_m is the magnetizing inductor of the transformer. W_1 ~ W_4 are the windings of the transformer secondary side. R_L is the resistive load.

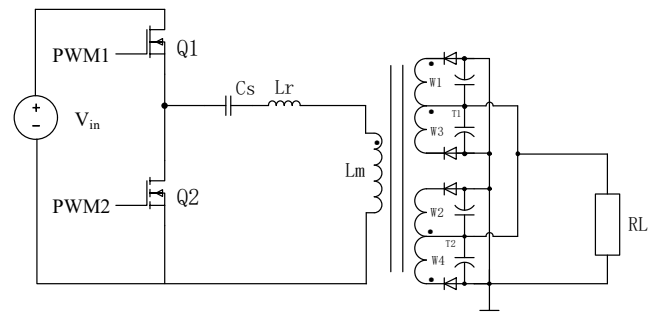


Fig. 1 A LLC converter with the proposed transformer

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The transformer proposed in this paper for the LLC converter has two features. The resonant inductor can be easily adjusted and this adjustment has a small impact on the main magnetizing inductance. The half turn transformer is designed with a standardized EI type ferrite core.

The integration of the resonant inductor with the transformer can improve the power density of the converter. However, the leakage inductance should be large enough in order to achieve the design requirement of the LLC converter. For the primary side winding, a flexible winding method which can adjust the leakage inductance of the transformer easily is preferred for the system debugging and improvement. Therefore, Litz wire is adopted to wind the coil. Meanwhile, wires are wound on all three legs of the EI core as shown in Fig. 2(a). This winding method is different from the traditional winding method which only winds wires on the center leg of core and shorten the length of center leg to adjust the leakage inductance.

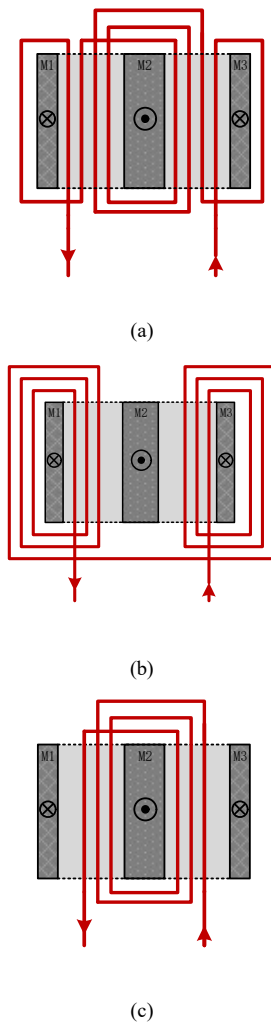


Fig. 2 Primary side winding method with different leakage inductance. (a) medium leakage inductance, (b) maximum leakage inductance and (c) minimum leakage inductance

In Fig. 2, M1~M3 are three legs of the magnetic core. It can be seen from the Fig. 2(a) that the wires wound on the outer

legs will generate more flux which flow through the outside air rather than the ferrite core. Therefore, this part of winding has a larger leakage inductance compared with the winding method whose wires are only wound on the center leg. This is because that the flux of the later winding method almost flows through the ferrite core completely. This means that the leakage inductance can be changed easily by changing the distribution of the windings on the center and side legs. When a bigger leakage inductance is needed, more wires will be wound on the outer leg. When a lower leakage inductance is needed, more wire will be wound on the center leg. Fig. 2(b) shows the primary coil winding method with the maximum leakage inductance. Fig. 2(c) shows the primary coil winding method with the minimum leakage inductance.

For the secondary coil, the copper foils are adopted instead of the copper wires because the copper foil has a larger surface area, which can provide a better heat dissipating capacity. Two U-shape secondary coils are employed in the transformer designed. These two U shaped coils are overlapped in reverse direction which form a half turn secondary winding together. The structure of secondary winding, rectifiers and filtering capacitor are shown in Fig. 3.

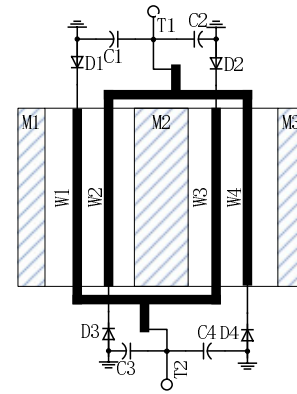


Fig. 3 Transformer structure of the secondary side

If the current flows through the primary side coil and generates magnetic flux, the alternative magnetic flux in the ferrite cores will be induced and alternative currents in the secondary coils will be generated. The operation principles of the proposed transformer are presented as following.

When the current of primary coil is in the rising half period, the flux direction is positive and the strength of the flux is continuously increased. To diminish this increasing flux, a current will be induced in the secondary winding composed by W2 and W4 (two legs of the U-shape copper foil). Although the current induced in W2 and W4 is clockwise, the current can only flow through the W2 leg because the diode connected to the W4 is in block-state. The direction of this current is from D3 to T1, and T1 outputs a positive voltage. Meanwhile, a current will be induced in W1 and W3. The direction of this current is also clockwise. However, the current will only flow through the W3 because the diode D1 is in block-state. The direction of the current is from D2 to T2, and T2 outputs a positive voltage. T1 and T2 are connected together, so a node

which always has a positive voltage output during the rising half period is obtained.

During the decreasing period of the primary current, the flux in the center magnetic core leg M2 has a negative direction and the strength is also decreasing, to slow down this decreasing trend, a current will be induced in the secondary winding consisted of W2 and W4. The direction of this current is counter-clockwise. However, the current will only flow in W4 because the diode D2 is in block-state, and the direction of this current is from D4 to T1, and the T1 outputs a positive voltage. At the same time, a current will be induced in secondary winding composed of W1 and W3. This current will flow though in W1 solely because the diode connected to W3 is in block-state. The direction of this current is from D1 to T2, and T2 outputs a positive voltage. Therefore, a positive voltage output during the deceasing half period is obtained.

According to the above analysis, when T1 and T2 are connected together, a constant positive voltage output can be obtained during the whole period. At any time of the period, the output voltage between the nodes T1 and T2 is induced by half of the U-shape coil. In other word, the secondary coil can be considered as a half turn winding in the whole period. It should be noted that the four legs of the two U shaped coils are engaged alternatively, which eliminates the magnetic flux unbalance issue.

III. MAGNETIC SIMULATION AND OPTIMIZATION

Simulations are needed in order to optimize the parameters of the LLC converter. For the proposed magnetic integration half-turn planar transformer, simulations are performed to investigate the impact of the integrated leakage inductance for the transformer performance. ANSYS Maxwell and Simplorer are employed to perform the circuit-magnetic co-simulation in order to achieve an optimal design of the transformer. Two transformer structures with the leakage inductance integration are investigated and compared. The simulations, optimal analysis and manufacturing will be presented in the following paragraph.

A 3D model of the proposed transformer structure given in Fig. 2(a) is built in Maxwell as shown in Fig. 4. It can be seen from the Fig. 4 that the primary coils are wound on both the center leg and the outer legs, which can lead to an enough large leakage inductance to achieve the resonant inductor design requirements of the LLC converter.

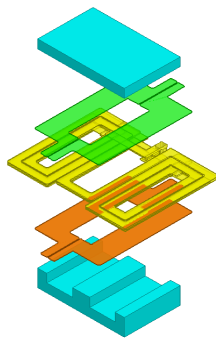


Fig.4 3D simulation model for Maxwell

Fig. 5 shows the relationship between the primary leakage/magnetizing inductance and the turns on the center leg. It can be seen from Fig. 5 that leakage inductance can be easily adjusted and this adjustment has a small impact on the main magnetizing inductance.

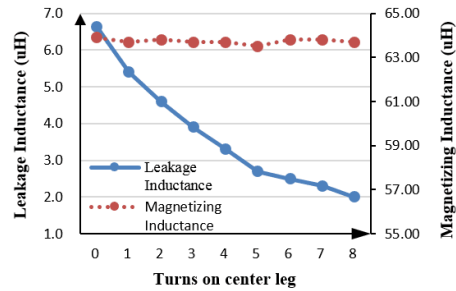


Fig. 5. Relationship between the primary leakage inductance and the turns on the center leg

Because multi-layer copper foils are adopted as the secondary side coils, the current balance is a crucial issue which should be taken into consideration. Unbalanced currents in the coils will induce the extra loss both in the copper foils and the magnetic cores. Consequently, this loss would induce the overheating issues. To verify the current balance performance of the proposed transformer, the magnetic field and the current field of the proposed transformer are plotted as shown in Fig. 6. The flux density of cores and the current density of coils are also given in Fig. 6.

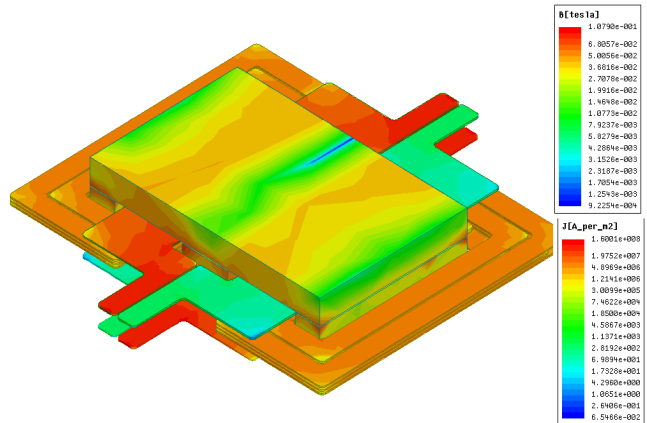


Fig.6 Flux and current density distribution of the proposed transformer

From the Fig. 6, it can be noticed that four half U-shape coils are engaged alternatively, the left upper side coil and the right bottom side coil output the currents simultaneously, or the right upper side coil and the left bottom side coil output the currents simultaneously. This work pattern is consistent with the operation principle of the proposed transformer. To observe the current waveforms in each coil, Simplorer is adopted to perform the magnetic-electric co-simulation as shown in Fig. 7. The current distributions in each secondary side coil is plotted as shown in Fig. 8.

In Fig.8, second.11 and second.42 represent the currents of the upper secondary coils on the same outer leg; second.41 and second.12 represent the currents of bottom secondary coils on

the same outer leg. It can be seen from the Fig. 8 that the currents of the left leg and the right leg have a certain degree of difference. The reason for this issue is the relative positions of the coils to the air gap. Although all the secondary side coils are set as the same size in the simulation, the top layer coil is closer to the air gap, which results the difference in the parameters. To compensate this difference and achieve a balanced current distribution, an improved secondary side coil structure is proposed as shown in Fig. 9.

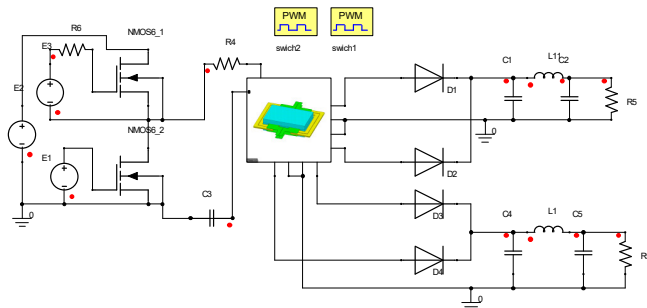


Fig.7 Magnetic-electric co-simulation model in Simplorer

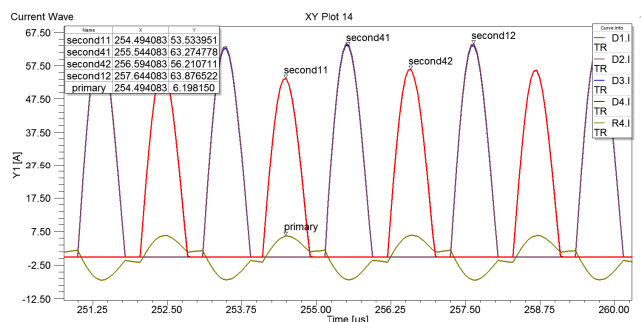


Fig.8 Current distributions in each secondary side coil

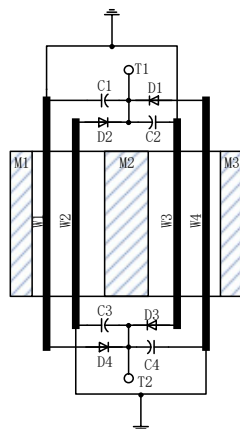


Fig. 9 Improved secondary side coil structure

It can be seen from the Fig. 9 that the four legs of secondary side coils are separated, which make it is possible to arrange the legs more fixable and place the output terminals at the same layer. A co-simulation is also performed in order to evaluate the performance of the improved transformer structure. The simulation results of the improved transformer structure are shown in Fig. 10 and Fig. 11.

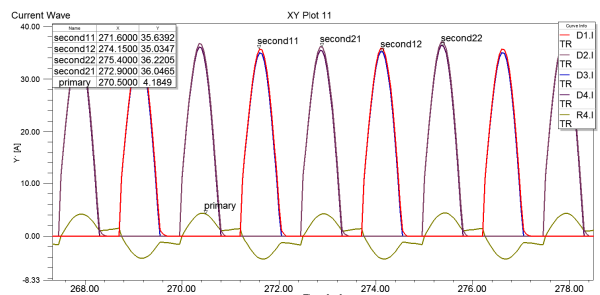


Fig. 10 Current distributions of the improved secondary side coil structure

It can be seen from the Fig. 10 that the current unbalance issue has been solved. Based on the simulation results, a transformer is fabricated with a Computer Numerical Control (CNC) machine. Fig. 11 shows the picture of the transformer prototype.

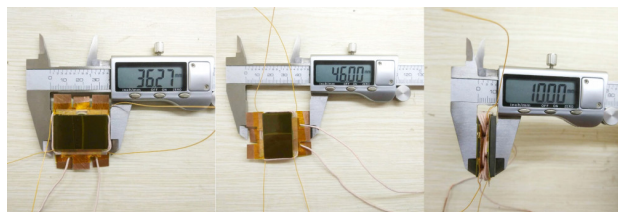


Fig.11 Picture of the transformer

IV. EXPERIMENTAL RESULTS

In order to test the LLC converter with the proposed magnetic integration transformer, an integrated controller NCP1398 from Onsemi is selected for the converter control and protection. The operation frequency of the NCP1398 is from 50kHz to 750kHz, thus a reasonable nominal frequency is about 500kHz. SiC MOSFET C3M0120090J is chosen as the primary side switches. The parameters of the LLC converter is listed in Table I.

The picture of the LLC converter with the proposed magnetic integration half-turn planar transformer is shown in Fig. 12. The test setup of the LLC converter is shown in Fig. 13. Fig. 14 shows the measured voltage and current waveforms. The measured efficiency of the converter is shown in Fig. 15, in which a peak efficiency of 97% is achieved at half load condition. The power dissipation of the auxillary power supplies has been taken into consideration in the efficiency measurement. A power density of 375W/in³ is achieved.

TABLE I
Parameters of LLC converter with the proposed transformer

Parameters	Values
Frequency f_r	500kHz
Dead Time	200 ns
Ferrite Core	TDK N49, EILP32
Primary Winding	Litz wire 0.04*400
Secondary Winding	0.2mm*8mm copper
Turns ratio	8:0.5:0.5:0.5:0.5
Magnetizing Inductance	64μH
Leakage Inductance	5.4μH
Resonant Capacitance	19nF
Primary Devices	C3M0120090J*2
Secondary Devices	BSC011N03LSI*8

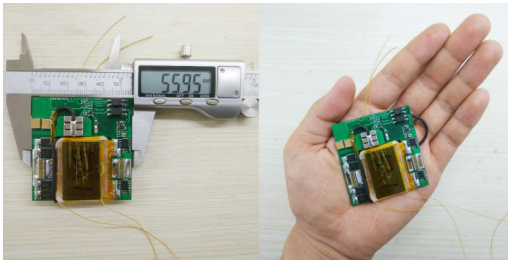


Fig. 12 Picture of the LLC converter with the proposed transformer

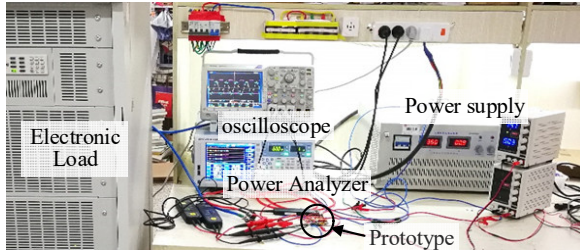


Fig. 13 Test setup of the LLC converter

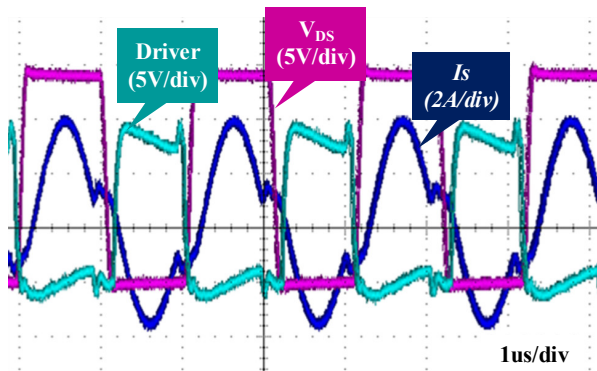


Fig. 14 Measured voltage and current waveforms

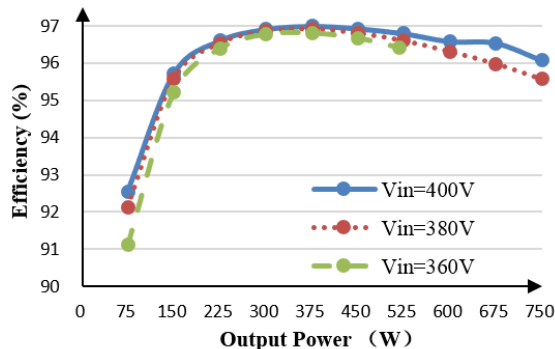


Fig. 15 Measured efficiency of the converter

V. CONCLUSION

A new half-turn planar transformer with integrated leakage inductance for LLC resonant DC-DC converters is proposed in this paper. In the proposed transformer, A EILP32 ferrite core

is employed and the primary side windings are placed at both the center and outer legs of the magnetic core. Meanwhile, the leakage inductance of the transformer can be changed by adjusting the distribution of the windings on the center and side legs. In addition, the number of turns on the secondary side of the transformer is 0.5, which can balance the core loss and the ferrite loss. Two configurations of secondary winding and circuit structure are presented and compared. The performance of the proposed transformer is evaluated by both the simulations and the experimental tests based on a 380/12V, 750W, LLC converter which achieves a peak efficiency of 97% at half load condition and a power density of 375W/in³.

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