Planar Printed-Circuit-Board (PCB) Transformers with Active Clamp Flyback Converter for Low Power AC-DC Adapter Application

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***Abstract*—With ever-increasing demands of smaller size, lighter weight for all forms of AC-DC consumer electronics, and wire winding transformers have been most used in isolated adaptor for over a century. The most popular isolated AC-DC adaptor topology is the flyback, but the leakage inductance and switching losses of a traditional flyback limit the switching frequency and prevent the ability to achieve a small solution size. This paper demonstrates new ways to optimize flyback topology with planar PCB-embedded transformer to produce much higher efficiencies, even while switching at a higher frequency for adapter application.**

Keywords: Energy storage, Electric Vehicles, Redox flow battery, super-capacitor, fuel cell, active suspension, in-wheel motor, configurable EV, ABS.

I. Introduction

Power converter design is a major industry in the power conversion market [1-8]. In particular, the AC/DC power converter that is being used substantially for traveling and Power delivery (PD) is now a hot topic. It is expected that the market share is very large and is over $9 Billion in 2019. The users include smartphones, tablets, and a number of the mobile electronic appliance. The cost and size are the main driving force for the new generation of development. The operation frequency is usually limited to 100kHz because of the conservation design of switching loss at high frequency.

This paper targets 65W adaptor applications. With the resonant power technique and the switching loss can be reduced and the hence the soft switching version of flyback converter circuit should be chosen because of simple and low cost.The isolated version of the buck-boost converter that is commonly known as flyback converter is the proper topology for AC-DC conversion because of the simple topology and low component count. For the non-soft-switching version, a snubber or RCD clamp circuit is usually used to suppress the loss and spike voltage due to the leakage components and the design limits its switching frequency to 100kHz. The active clamp flyback (ACF) converter can clamp and recycle the voltage of transformer leakage energy [1, 2, 3]. Active clamp flyback with synchronous rectifier (SR) circuit is shown in Fig. 1. Its structure is simple: Certain clamping circuit can generate the zero-voltage switching (ZVS) and its leakage energy can be recycled to the source. In general, there are two operation modes which is so called the Discontinuous Conduction Condition (DCC) and the Continuous Conduction Condition (CCC). The DCC with SR method works current resonant switching but because of the current resonance, its current is therefore with high amplitude and the auspicated loss is larger. On the other hand, the CCC operation with less current stress, but its voltage stress is high in the secondary SR. The design is used pre-off topology of SR control to fast turn off and reduced SR's reverse-recovery loss in CCC condition.

Transformers are major components used for electrical isolation and energy transfer with power supplies application. The transformer consists of copper winding and also the magnetic core. No matter it is machine wounded or handmade, the tolerance of the turns per layer, packaging factor, separation between the winding layers are different and hence the tolerance of different transformers may vary a lot. Quality assurance is the major benefit of the planar PCB-embedded transformer, because of eliminates the manual winding process. Unfortunately, the leakage inductance and parasitic capacitance of a planar PCB-embedded transformer limit the switching frequency and prevent the ability to achieve a small solution size [6, 7]. Fortunately, there are new ways to optimize the flyback topology and transformer winding structure to produce much higher efficiencies, even while switching at a higher frequency with the AC adaptor application.

The working condition changes due to different input voltage in the universal application, challenging both exist switching devices tradeoff and transformer designs in AC-DC adaptor application. At low line input voltages, the on-stat loss of the primary switches components dominates due to the higher current. As the high line input voltage, the switching loss of the primary switches components due to higher dv/dt [5]. As a result, theDCC and CCC mode selection is more difficult in the design. The magnetic component design including the winding method, coupling, and winding ratio are key design information. The current-mode PWM controller, HY1801 from HYSEMI, is a high-performance Active-Clamp Flyback controller that uses proprietary ZVS tracking technology. The HY1801 uses different operating modes to optimize the conversion efficiency under the various lines, including Active-Clamp Mode, 140kHz Constant Frequency Mode. The switching frequency of the Active clamp Flyback converter using HY1801 is optimized to operate up to 250kHz.

The active clamp resonance time can have a wide variation depending on the transformer leakage inductance, the clamping capacitor values, and other parasitic parameters. Although the HY1801 can track the ZVS automatically, it is still necessary for the application design to provide the resonance time information to allow the algorithm to operate more efficiently. To simplify the application, the operation schematics and resonance time thesis are used as shown in Fig. 2 & 3.

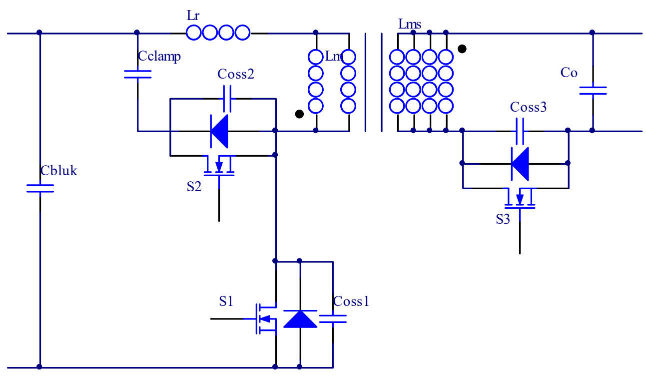
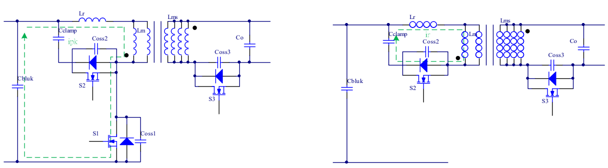
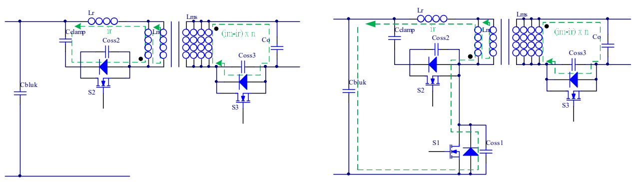


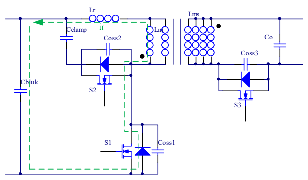
Fig.1 Active clamp flyback converter with syn. rectifier



i) Magnetizing region ii) Clamping region



iii) Discharging region iv) Output capacitor (C_{oss}) discharging region



V) Zero voltage region

Fig. 2 Active Clamp operation circuit diagram

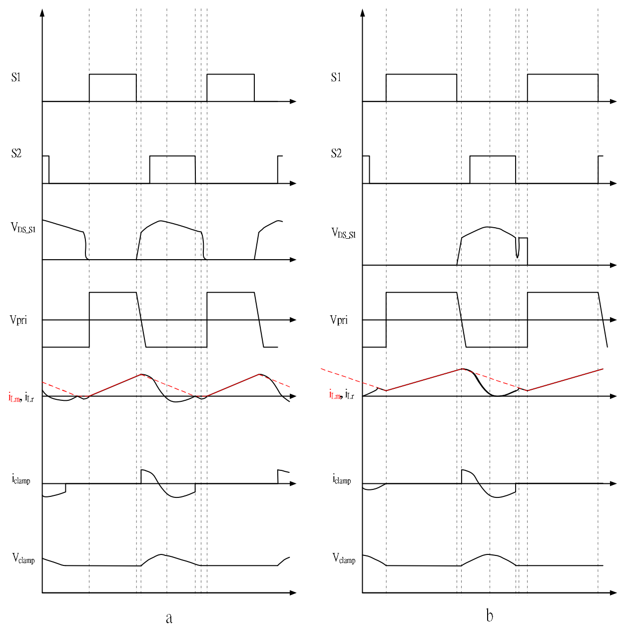


Fig. 3 Typical waveforms of ACF of (a) DCC, and (b) CCC

The characteristics between the DCC and CCC are different in terms of the control and ripple current. Researches may consider the DCC because of easy design and more linear control features, however, the ripple is large and therefore the filter capacitor may needs to increase.

II. METHODOLOGY

A. Circuit Operation and Turns Ratio study

Previous section has described the initial study of the ACF topology. It is simple and of high efficiency in high frequency operation to optimized size. Fig. 3 illustrates the key waveforms of DCC and CCC operation. In fact the magnetizing currentaffects and determines the operation in continuous and discontinuous mode. It is found that there is negative region of operation i_{Lm} in DCC whereas i_{Lm} is always positive when the operation is under CCC.The DCC condition is when the ΔI_{Lm} larger than 2 times of I'_{Lm}:

$$\Delta I_{Lm} \geq 2I'_{Lm} \quad (1)$$

$$I'_{Lm} = \frac{Io}{n} \times \frac{Vin + nVo}{Vin} \quad (2)$$

The design criterion is to focus on the reduction of the loss of the active components rather than the total loss reduction. Proper design of L_r and L_m to ensure which operation mode to work on and the associated turns ratio and frequency are determined. Because the maximum operating frequency of the ACF is up to 250kHz, it is more desired to DCC operation in the universal input voltage to safeguard operation. Thesimulation results are shown andthe typicalwaveform of the active clamp flyback circuit with different the input voltage V_{in} in optimized transformer parametersare illustrated in Fig. 6. It shows that the DCCis operated with ZVS until full loading condition in the universal input voltage.

B. Transformer Design and Optimization

Integration of the magnetic components to the PCB is proposed here. Hence the former for winding is eliminated. The magnetic components can be significantly reduced in size because the winding and the magnetic parts are highly integrated and the space between the original winding is eliminated. This is now called PCB-embedded transformer.

The core selection is referring to manufactory's core selection guide. The core suggested in table 1 is typical for universal input range, 67kHz switching frequency and single output application[9]. ATQ25 is selected for the 65W ACF universal adaptor application. Because of 65WACF adaptor is operation up to 250kHz, that is much higher than 67kHz, a small core can be selected.

Table 1 Core quick selection table

Output Power (W)	EI core	EE Core	ERR Core	EPC Core
0-10	EI12.5 EI16 EI19	EE8 EE10 EE13 EE16		EPC10 EPC13 EPC17
10-20	EI22	EE19		EPC19
20-30	EI125	EE22	EER25.5	EPC25
30-50	EI28 EI30	EE25	EER28	EPC30
50-70	EI35	EE30	EER28L	
70-100	EI40	EE35	EER35	
100-150	EI50	EE40	EER40 EER42	
150-200	EI60	EE50 EE60	EER49	

(For universal input voltage range, fs = 67kHz and single output)

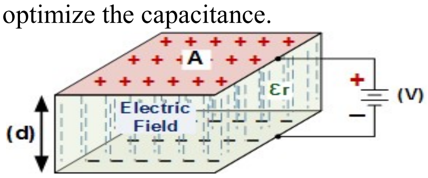
The transformer turn ratio (n) is depend on voltage of switching device and output voltage, the most comment used switching device of primary and secondary are 700V and 100V respectively.

$$V_{DS\_S1(max)} \times \text{Derating } \% \geq 1.1 \times \left[\sqrt{2}V_{in(max)} + n(V_o + V_{F)]}\right] \quad 4)$$

$$V_{DS\_S3(max)} \times \text{Derating } \% \geq 1.1 \times \left[\frac{1}{n}\sqrt{2}V_{in(max)} + (V_o + V_{F)]}\right] \quad (5)$$

The turns ratio of transformer is chosen 7 that between 6.25 and 7.5

Parasitic capacitance is major challenging of a planar PCB-embedded transformer limit the switching frequency. The 65W PCB-embedded transformer is used a different multilayer structure in the primary & secondary winding to optimize the capacitance.



$$C = \frac{\varepsilon \times A}{d} \quad (6)$$

Because of secondary side is small number of turn, the parallel structure in 4 layers PCB with via to ensure equal potential to each layer. In the primary side, the interleaving and sandwich structure in series of 2 pieces 2 layers PCB to reduce the dielectric area (A) and increase electric distance (d). The PCB-embedded transformer structure and model circuit are shown as Fig. 4 and Fig. 5.

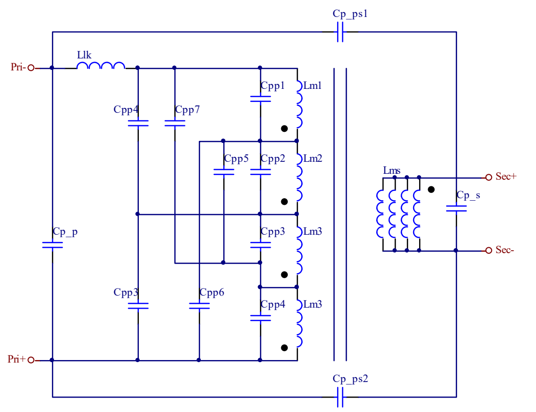
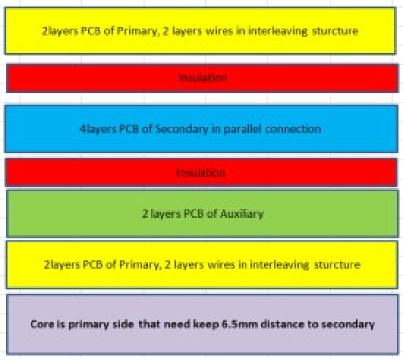
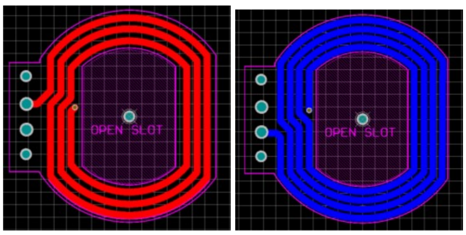


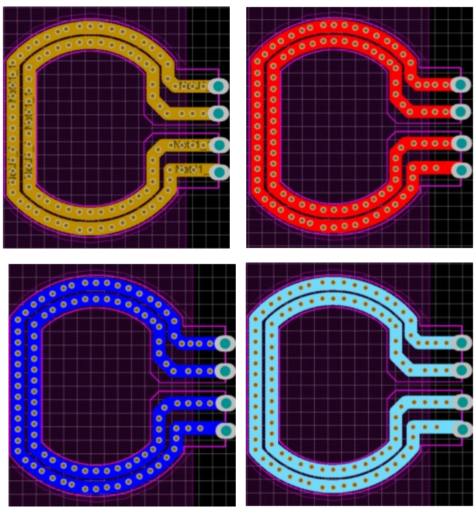
Fig. 4 Model circuit of high frequency PCB-embedded Transformer



a) Transformer winding cross section



b) Primary winding PCB layout

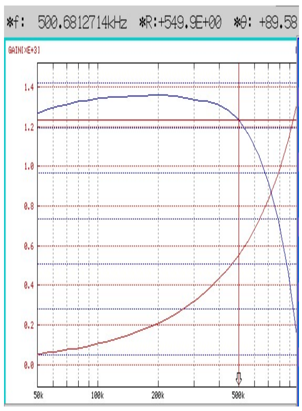


c) Secondary winding PCB layout

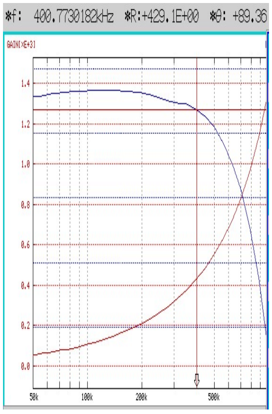
Fig. 5 Flyback transformer winding structure & PCB layout

III. Simulation and Result

The Multi layer PCB-embedded transformer optimization is to maximize power density and operation frequency. There are four optimization factors: the primary track width, secondary track width, coupling area, coupling distanceand the power transfer turn number*n*. In the ATQ25 transformer core, the frequency response of PCB-embedded transformer is Fig. 6. It shows a typical characteristic. According the result, the 0.7mm track with interleaving can be used in HY1801 ACF application. The optimized parameters of PCB-embedded transformer are shown Table 2:



a) 0.6mm track interleaving



b) 0.7mm track interleaving

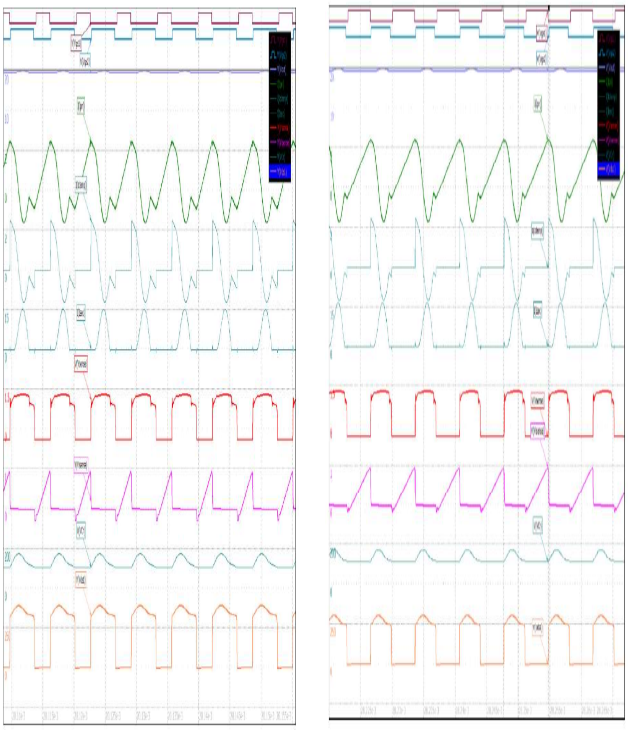
Fig. 6 Impedance Response of Transformer with difference interleaving levels

Table 2 Optimized parameters of PCB-embedded transformer

L_m	162 µH
L_{lk}	4.9 µH
Rs	0.55Ω
L_{ms}	4.07 µH
R_{ss}	0.105Ω

The selected parameters are reasonable for power conversion design parameter. They are all within the design range.

In order to study the performance further a simulation using PSpice based simulator has been conducted. The study is to examine the operation under different load conditions and its effect to its operation against the design criteria.



a) 110Vac 20V 3.25A loading b) 230Vac 20V 3.25A loading

Fig. 7 Simulation waveforms of universal input voltage ACF

Fig. 7 shows the simulation results in full load condition at universal input voltage. The output voltage, SR current, clamping current, clamping voltage, transformer current, drain-source voltage of the S1, gate signals of S_1 and S_2 are nomenclated as V_o, I_{sec}, I_{clamp}, V_{cr}, I_{pri}, V_{ds1}, V_{gs1}, and V_{gs2}, respectively.ZVS operation of switching devices are successes because the Mosfet's body diode conduct before devices turn on under universal input voltage.

VI. SUMMARY AND CONCLUSION

Leakage inductances and self-parasiticcapacitance of PCB-embedded planer magnetic device with various geometric factors have been examined. Based on an analytical method, the self-parasitic capacitance of PCB-embedded planer transformers can be controlled. The frequency response results have been confirmed with the impedance analysis measurements. The frequency response of PCB-embedded planer transformers depends on the interleaving area and conduct track width. Variations of interleaving area and conduct track width affect all of the capacitance parameters. The self-parasitic capacitance of planer PCB-embeddedtransformers is a proportion to track width and interleaving area. The frequency response of PCB-embedded planer transformer is affected by self-capacitance. The frequency characteristics of PCB-embedded planer transformer is measuredthe testing frequency ranges between 50 kHz to 500 kHz. It shows that the magnetize impedanceof the transformeragainst frequency do not changed significantly.

This paper examines the 65W ACF converter with a PCB-embedded planar transformer for the use in low power adaptors. The ACF topology is proposed because of its advantage in the tradeoff against simplicity, high power density and efficiency. SR topology is also selected for increasedefficiency to aid small size. The PCB-embedded technique improve significantly the power density. A simulation is conducted and it achieves a ZVS in a universal input range of 110 V to 230 V. Furthermore, the ACF adaptor prototype is under building.

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