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Design and Development of a Planar Flyback Transformer for Isolated Power Supply Applications

Abstract—The conventional wire wound magnetic components have exposed several limitations in terms of high power density, high operating frequency, and low profile in DC-DC power converters. The planar magnetic has eliminated the limitations of conventional transformers. Planar transformers are perfect for limited space applications since they are often smaller and flatter than wire-wound transformers where wire wound transformers are bulky. **In my summer internship I have simulated coupled of examples starting from simple coil , then two, four layer inductor ,two and four layer transformer , Em brake use in cars and planes doors . Here I am taking one project that I have followed from research papers.** This project involved a reduction in height of 50% from a conventional wire-wound transformer while achieving comparable electrical performance. In low-power DC- DC converter applications, flyback topology is often used as it is simple in structure and provides better isolation. In this project, a 2.5W flyback converter is designed with a planar transformer. The design of the planar transformer was accomplished by using Ansys PEmag. According to the PEmag simulation design, the PCB was designed in Kicad Designer. Then, it was exported to a finite element analysis-based software, Ansys Maxwell 3D, for further analysis including leakage inductance & coupling coefficient. A multi-physics circuit simulator, Ansys Simplorer, was also introduced in this project to observe the overall performance of the flyback converter with the designed planar transformer.

I. Key Design Parameters

A. Inductance

A planar flyback transformer was designed for this application as it provides galvanic isolation between the primary and secondary sides. The specifications of the flyback converter is given in Table 1

TABLE I: Design Specifications of The Flyback Converter

Parameters	Symbols	Values
Input Voltage	V_i	8 - 12 V
Output Voltage	V_o	24 V
Output Power	P_o	2 - 2.5 W
Switching Frequency	f_s	250 - 350 KHz

$$V_o = \frac{N_s}{N_p}\frac{D}{(1-D)}V_i \tag{1}$$

$$D = \frac{V_{or}}{V_i + V_{or}} \tag{2}$$

The flyback converter was designed by using Equations 1 & 2. The reflected voltage, V_{or} was adjusted to 8V so that the duty cycle, D is 0.5.
The primary to secondary turns ratio, $\frac{N_p}{N_s}$ is found to be 0.32 from Equation 3.

$$V_{or} = V_o\frac{N_p}{N_s} \tag{3}$$

The converter was designed to be operated in BCM (Border Conduction Mode) mode under specified input voltage and full load condition. The critical point has been calculated for this condition using Equation 5 [7].

$$K_{crit} = (1-D)^2 \tag{4}$$

$$\text{Where, } K_{crit} = \frac{2L_s}{RT_s} \tag{5}$$

The required secondary inductance, L_s was calculated by using Equation 6.

$$L_s = \frac{R_O K_{crit}}{2f_s} \tag{6}$$

$$= 74.40\mu H \tag{7}$$

and the primary inductace, $L_p = (\frac{N_p}{N_s})^2 L_s = 7.619\mu H$.

B. Selection of Core Geometry and Core Material

The design of the planar transformer starts with the selection of the core. The selection of a core is an iterative process with trade-offs between different core properties like core shape, size, and material. Selecting a core shape is vital as different core shapes have different window areas. For the flyback converter, selecting a core with more window area is suggested, which minimizes the leakage inductances and provides adequate winding isolation for maintaining the required creepage distance.

The $E14/3.5/5$ has been chosen it has has a window height of $2mm$ where the PCB will be around 1.6mm in thickness. A proper core material was selected for the planar core, which is appropriate for the desired switching frequency range. The desired switching frequency was around 0.2-0.35 MHz. So, 3F3 ferrite material was chosen as it operates in 0.2 - 0.5 MHz . In the datasheet of the selected core, it is mentioned that the maximum inductance factor for the ungapped core is $1300nH$ for 3F3 material.
For the design requirement, primary inductance was calculated $7.619\mu H$. Thus, the required turns for primary and secondary winding were calculated using Equation 8 and found to be 3 and 9, respectively.

$$\text{Inductance factor or AL value, } AL = \frac{L}{N^2} \tag{8}$$

While designing the planar transformer, the PCB traces have to be stacked in the available window area and layers. The maximum possible width of the PCB track and the number of turns per layer was calculated by using Equation 9 [11].

$$T_w = \frac{W - (N-1)S}{N} \tag{9}$$

Here, N is the number of turns per layer, W is the winding width, S is the spacing between traces.
Window utilization factor, k_w is the percentage of the core window area that is filled with copper tracks [12]. The window utilization for this planar transformer is illustrated in Figure 1. Using Equation 10, the k_w of this transformer was calculated and found to be around 0.032.

$$A_w.K_w = a_{cp}.N_p + a_{cs}.N_s \tag{10}$$

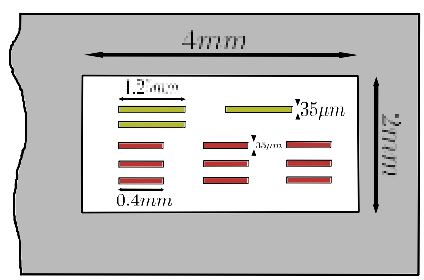


Fig. 1: Window Utilization of The Planar Transformer.

Here, A_w is the available core window area, k_w is the window utilization factor, a_{cp} & a_{cn} is the cross-sectional area of the primary and secondary traces and N_p & N_s is the primary and secondary number of turns.
$1oz$ copper was used in the PCB tracks of both primary and secondary. The current density, J of the tracks was calculated using Equation 11.

$$J = \frac{I_{P\,RMS}}{a_c} \tag{11}$$

Here, $I_{P\,RMS}$ is the primary RMS current.
For the chosen core, the specified maximum flux density, B_m

is around 0.4 T . It can be seen from the core's core loss vs flux density plot that core loss rises as operational flux density rises [10]. So, the maximum flux density was considered to be around 0.3 T for this operation.

The selection of core geometry was validated by calculating the relationship between area product ($A_c.A_w$) of the core and energy handling capacity of the inductor. [13].

$$A_c.A_w \geq \frac{L_p \times I_{P\,peak} \times I_{T\,RMS}}{B \times J \times K_w} \tag{12}$$

A_c is the effective area of the selected core. Area product is found to be 112 mm^4 and the selected core has area product of 113.6 mm^4.

$$l_g = \frac{N_P{}^2 \varepsilon_0 A_c}{2L_p} \tag{13}$$

The required air-gap was calculated using Equation 13 and air-gap is found around $10\mu m$ and air-gap per core leg comes out to be $3.34\mu m$. Air-gap was provided by placing insulating tap between the cores.

II. Planar Transformer Modelling

The required parameters to design planar transformer has been calculated using the design Equations discussed in section 2. The specifications for planar transformer modelling is given in Table 2.

TABLE II: Design Specifications Of The Flyback Converter.

Parameters	Values
Primary Winding	3 Turns
Secondary Winding	9 Turns
Primary Inductance	7.619 μH
Secondary Inductance	74.40 μH
Primary Current	1.5 A
Total RMS Current	1.225 A
Maximum Flux Density	0.3 T
Core Type	$E14/3.5/5$ & $PLT14/5/1.5$
Fill Factor	0.032
Core Material	$3F3$
Switching Frequency	350 kHz
Air-gap Per Leg	$3.34\mu m$

A. Planar Transformer Design in Ansys PEmag

The preliminary planar transformer design with the appropriate winding strategy given in Table 3 was simulated in Ansys PEmag to calculate the self-inductances of the primary and secondary windings. In PEmag, the winding type, required insulation and the operating frequency was defined accordingly. Ansys PEmag design of the planar transformer was illustrated in Figure 2.

B. PCB Design and 3D FEA Simulation

The proposed planar transformers PCB has been designed in Kicad PCB designer with the properties of Table 3. After completing the design in Kicad, the model was exported to ANSYS Maxwell 3D as a step file for further 3D

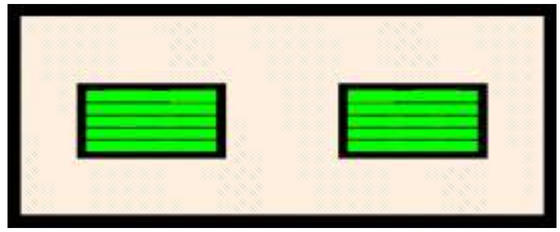


Fig. 2: Planar Transformer 2D Model - Ansys PEmag.

TABLE III: PCB Stacking of Primary & Secondary Windings.-

Primary winding	
Number of turns	3
Max turns per layer	2
Number of layers	2
Copper track thickness	35 μm
Copper track width	1.25 mm
Spacing between tracks	0.5 mm
Insulation between layers	60 μm
Insulation between primary & secondary	0.4 mm
Secondary winding	
Number of turns	9
Max turns per layer	3
Number of layers	3
Copper track thickness	35 μm
Copper track width	0.4 mm
Spacing between tracks	0.5 mm
Insulation between layers	60 μm

FEA analysis. Figure 3 & 4 shows the top view and the different layers of the designed planar transformer PCB.

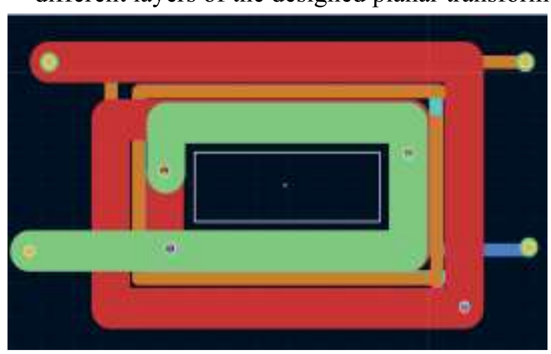
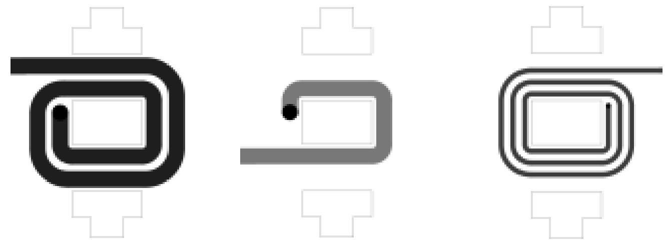


Fig. 3: Kicad design of planar transformer PCB.

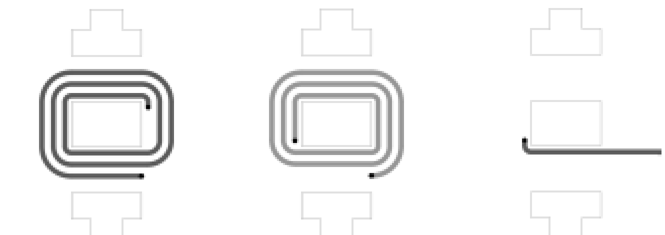
In ANSYS Maxwell 3D, the core was designed using the geometry in the datasheet, and 3F3 material properties were assigned to the core. The whole model was enclosed in a region of air which acts as a boundary.

Figure 5(a) shows the complete design of the planar transformer in Ansys Maxwell 3D. After assigning the excitations properly, the simulation was performed using eddy current solver. The primary and the secondary inductance from the simulation result were $6.5\mu H$ and $58.77\mu H$, respectively.

In figure 5(b), It was observed that the peak operating flux density

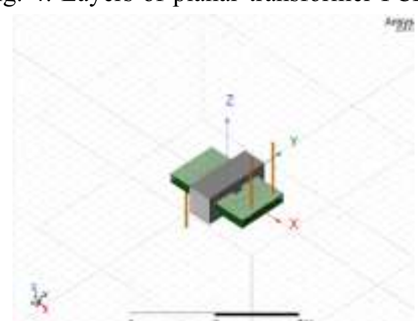


(a) Top Layer - Primary (b) Layer 2 - Primary (c) Layer 3 - Secondary



(d) Layer 4 - Secondary (e) Layer 5 - Secondary (f) Bottom Layer - Secondary

Fig. 4: Layers of planar transformer PCB.



(a) Planar Transformer 3D Model - Ansys Maxwell 3D.

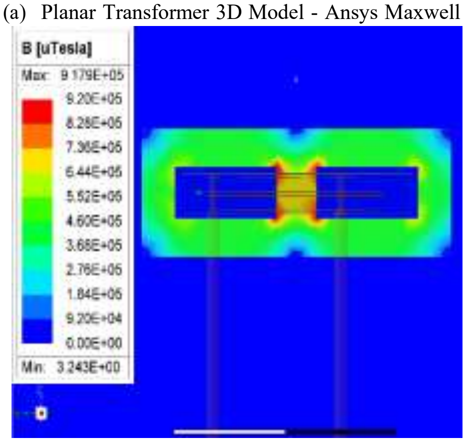


Fig. 5: 3D FEA Analysis of the planar transformer

of the core is 0.917T.

As Leakage inductance has some negative impact on the switching device. During ON time leakage inductance stores some energy that does not transfer to the secondary side. In OFF time this stored energy of the leakage inductance is dissipated either in the RCD clamping circuit or TVS(Transient Voltage Suppressor) diode to save the switching device from a voltage spike.

The primary (L_plk) and secondary (L_slk) leakage inductance of this planar transformer is calculated using Equation 14 & 15.

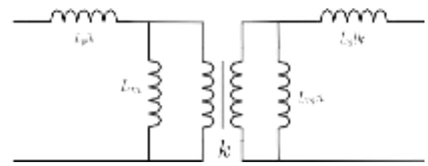


Fig. 6: Equivalent Model of a Transformer.

$$L_p = L_m + L_{plk} \tag{14}$$

$$L_m = L_p.k \tag{15}$$

From equation 14 & 15, primary leakage inductance is -

$$L_{plk} = L_p(1 - k) \tag{16}$$

Similarly, for secondary leakage inductance is -

$$L_{slk} = L_s(1 - k) \tag{17}$$

Here, L_p and L_s is the primary and secondary self inductance and K is the coupling coefficient. Coupling coefficient K, is be found by Equation 18.

$$k = \frac{M}{\sqrt{L_p L_s}} \tag{18}$$

here, M is the mutual inductance. The L_p, L_s and M can be determined by 3D FEA simulation in ANSYS Maxwell 3D.

TABLE IV: Simulated Parameters of the planar flyback transformer

L_{plk}	L_{slk}	M	K	L_p	L_s
35 nH	0.3 nH	19.44 μH	0.9946	6.5 μH	58.77 μH

A RCD Snubber circuit was designed for the flyback converter circuit. When the switch turns off, a high voltage spike appears on the switch due to the presence of the leakage inductance in the windings.

This high voltage spike may damage the MOSFET therefore a RCD snubber circuit is required to clamp the voltage.

The selected controller IC has an integrated MOSFET switch that has a maximum 65V drain to source voltage, V_{ds}. So, the maximum V_{ds} when the MOSFET is off should be less than 65V. For the designed flyback converter circuit, 20V is considered to be the maximum V_{ds}. So, $V_{sn} = V_{ds} - V_i$ = 12V.

Both R_{sn} & C_{sn} is determined by using Equation 19 & 20 -

$$R_{sn} = \frac{V_{sn}(V_{sn} - V_{or})}{\frac{1}{2} I_{p\,peak}^{2} L_{lk} f_s} \tag{19}$$

$$C_{sn} = \frac{V_{sn}}{\Delta V_{sn} R_{sn} f_s} \tag{20}$$

For this designed flyback planar transformer R_{sn} and C_{sn} is determined to be around $4k\Omega$ and $13nF$.

A diode that is fast and has sufficient reverse voltage breakdown has been chosen for this circuit. The main criterion for choosing the output diode is a reverse-voltage rating that the diode can withstand while operating. The rating of the diode has been selected by using below Equation 21.

$$V_D = V_{out} + \frac{V_{in}(max)}{N_{ps}} + (20\%\ safety\ factor) \qquad (21)$$

An ANSYS Simplorer simulation was performed where electromagnetic component and power electronic circuits were coupled together to determine the designed planar transformers performance. Figure 7 & 8 shows the simplorer simulation model and simulation results.

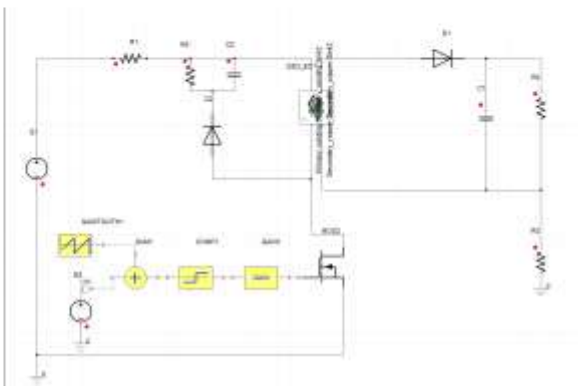
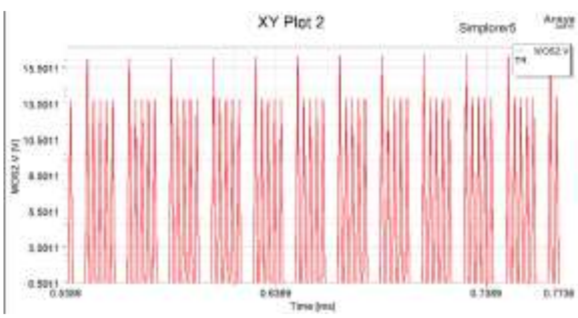
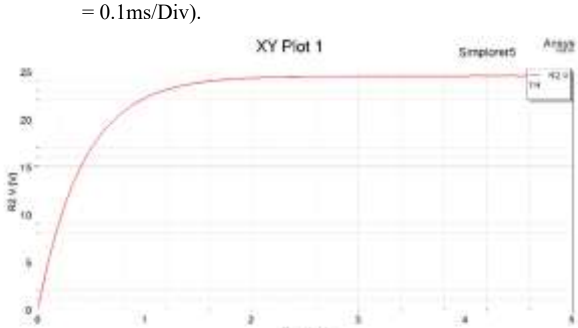


Fig. 7: Ansys Simplorer Simulation Model.



(a) Drain to Source voltage, Vds of the MOSFET (V= 2.5/Div; Time = 0.1ms/Div).



(b) Output voltage accross the load resistor (V =5V/Div; Time = 1mS/Div).

(a) Drain to Source voltage, Vds of the MOSFET (V= 2.5/Div; Time = 0.1ms/Div).

Fig. 8: ANSYS Simplorer Simulation

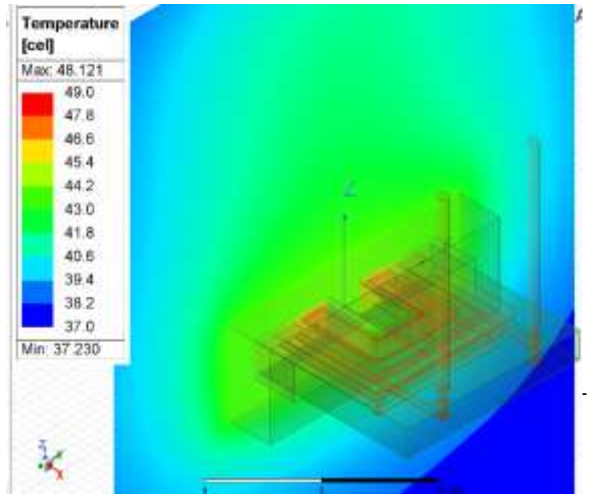


Fig. 12: Thermal Distribution of the Designed Planar Transformer (3D FEM Simulation).

A two-way coupled simulation was performed using ANSYS Maxwell and ANSYS Icepak to evaluate the thermal performance of the planar transformer .The result are shown in fig 12.

V. Conlcusion

This paper has presented a comprehensive design study and development of a 350kHz PCB integrated flyback planar transformer. Through this project, various aspects of planar transformers have been explored, including their design principles, winding patterns and manufacturing techniques. The research findings suggest that planar transformers offer a compelling solution for compact power electronics applications, including renewable energy systems, electric vehicles, and aerospace. However, further research is necessary to optimize planar transformer design and manufacturing processes to enhance their performance and reduce their production cost. One of the disadvantages of the planar transformer is inter- winding capacitances. These inter-winding capacitances must be integrated into the converter design or minimized through improved winding layout design. Potential future research scope involves exploring an analytical approach to precisely simulate the planar inductor, considering skin, proximity, and parasitic effects. Overall, this paper highlights the potential of planar transformers in the power electronics industry and sustainable energy system

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