Achieving Higher Efficiency Using Planar Flyback Transformers for High Voltage AC/DC Converters

WHITE PAPER

INTRODUCTION

The emphasis on improving industrial power supply efficiencies is both environmentally and economically motivated. Even incremental improvements in efficiency can result in electrical usage savings that contributes to cost reductions and the ability to minimize heat, and thus wasted energy in the application.

Adding to the challenge of making power supplies more efficient is the fact that today's designs are becoming more integrated, packing an increasing amount of functionality into smaller and smaller form factors. These complex, higher density applications create a much larger power envelope that is more difficult to manage effectively.

AC/DC power supplies of less than 100 W typically use flyback topologies to convert electrical power efficiently as they are the simplest and lowest cost of all isolated topologies. Planar magnetics are commonly the high-frequency application converter of choice for designs because they offer a low number of turns in helical windings and very low resistance. Using a planar transformer in a high voltage application provides several advantages including a reduced or lower mechanical profile. However, there are technical challenges to overcome with this approach that include considerations for high inductance values and the level of isolation needed for safety reasons.

This paper describes a planar flyback transformer designed by Bourns to meet the efficient conversion needed in high voltage applications. This customized planar transformer was tested on an AC/DC adaptor with an output of 5 V and delivered a peak efficiency of 91.05 % in this test.

PLANAR MAGNETICS ADVANTAGES

Planar transformers have some distinct advantages over wound transformers. The cores have wider surface areas than traditional E, EC or EP cores which allows for smaller numbers of turns in the windings. The wider core areas also enable lower DC resistance of the copper.

The rigid structure of the planar transformer's PCB (standard thickness 1.3 mm) eliminates the need for a plastic carrier or bobbin. Therefore, it can be made thinner and lower in profile than wound transformers. Another benefit is the repeatability allowed in PCB manufacturing that ensures higher tolerances in transformer specifications, such as inductance, resistance and turns ratios.

There are disadvantages to planar transformers, as well. Typical PCB substrates like FR4 are not considered as meeting safety requirements for insulation in high voltage applications. Differential surges can also jump across from vias to cores causing damage. Also, implementing multiple layers can be problematic in the design phase and expensive, especially if thick copper plating is required.

70TH ANNIVERSARY
BOURNS®
1947 ★ 2017

PLANAR TRANSFORMER DESIGN CONSIDERATIONS

Winding Structure

Bourns designed its custom planar flyback transformer for applications such as a USB power delivery system, which can deliver up to 100 W (20 V, 5 A) with the understanding that a continuous conduction mode is recommended for powers greater than 10 W. This is to avoid peak currents that can cause high switching losses and overheating of the core. Using the Bourns planar transformer solution, the main contributing factor to losses will be from the copper and not the core. An optimum primary inductance value of 530 μH was selected to keep peak currents to under 2.3 A, so as not to overstress the external 650 V MOSFET. The number of turns of 30, on the primary side, was calculated based on the saturation current, inductance value and area of the core (EC26).

The design uses 12-layer winding incorporating a primary and secondary winding produced using 2 oz. copper and FR4 material and two identical substrates (shown in Figure 1). The planar transformer PCBs form a split primary winding enclosing the secondary made from triple insulated wire.

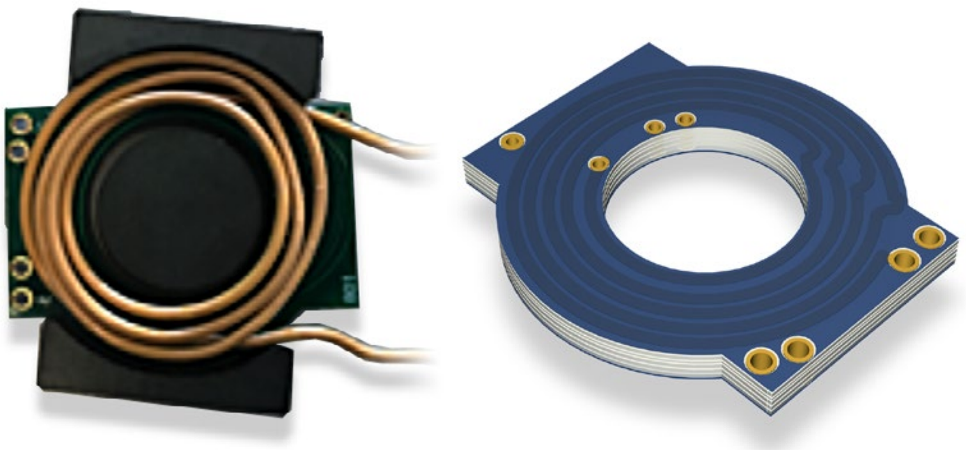

Figure 1. | *Photo of Secondary Winding and Isometric View of Planar Primary PCB*

The triple insulated wire on the secondary side provides the reinforced insulation between primary and secondary windings. As the design uses just four turns, it fits in a spiral shape around the core and between the two PCBs as shown in Figure 1.

PLANAR TRANSFORMER DESIGN CONSIDERATIONS *(Continued)*

Core Losses

The flux density is highest at the edge of the core as shown in Figure 2. The flux must travel through the side wall of the core to complete its path. Therefore, the flux density will increase at the side. However, the flux density in the center leg is well below saturation.

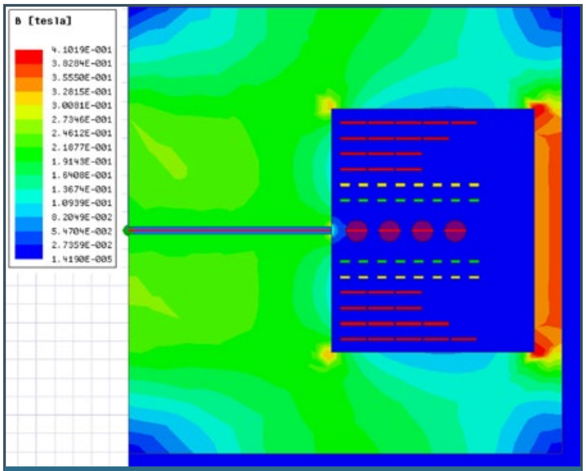

Figure 2. | *Flux Density in Transformer Using 2D FEA*

Leakage Inductance

The leakage inductance is a source of energy waste in a flyback converter and needs to be kept to a minimum to increase overall efficiency. The inductance value of this leakage depends on the magnetic field between the primary and secondary winding. According to Ampere's Law, the ampere turns across the interwinding region is the same as the ampere turns in either winding. In the Bourns® planar transformer, the winding width was kept at a maximum to reduce the field strength (H) in this region.

$$H = \frac{IN}{Wb}$$

The permeability of the interwinding region is that of air ($4\pi \cdot 10^{-7}$) and so the flux density in this region is as follows:

$$B = \mu H$$

The energy density in this interwinding region is, therefore:

$$\frac{Energy}{Volume} = \frac{BH}{2}$$

Energy is calculated at energy density multiplied by the interwinding volume, but it can also be shown as:

$$Energy = \frac{1}{2} LI^2$$

Therefore, the inductance value of this region is estimated by:

$$L = 2\frac{Energy}{I^2}$$

In the Bourns transformer design, the volume of the interwinding region was kept as small as possible to reduce leakage. Increasing the winding breadth (Wb) also reduces leakage inductance.

PLANAR TRANSFORMER DESIGN CONSIDERATIONS *(Continued)*

The effective winding breadth can be increased by interleaving the layers, if possible, which is what has been done in this transformer. For this particular design, there are four turns on the secondary and was implemented using insulated wire on a single layer. This eliminates the need for creepage and clearance distances between the primary and secondary windings. The secondary was interleaved with the primary, which effectively doubles the winding breadth of the primary and, therefore, cuts the leakage inductance value in half.

The interwinding volume could be better controlled if the secondary was also implemented in the PCB material. Though, using insulated wire on the secondary removes the need for creepage and clearance distances between the primary and secondary windings. This is particularly important in high voltage applications. Furthermore, interwinding capacitance is adversely affected as their distances decrease. This is a serious concern for high voltage applications as it worsens the coupling of AC power line noise through to the power supply output.

The leakage inductance on the Bourns® planar flyback transformer was recorded by shorting the secondary wire and measuring the primary inductance. The leakage was recorded as 14µH at 130kHz in this test.

AC Losses

In a flyback transformer, there is no benefit to the AC resistance in interleaving the primary and secondary windings as these windings are out of phase. If they were in phase, the magnetic field strength would dip to zero at every boundary, which would keep AC resistance low in an interleaved structure. The AC resistance on the primary side can be controlled by keeping the copper at less than the skin depth at the switching frequency. In this case, the skin depth is 0.2 mm while the thickness of copper is 0.07 mm.

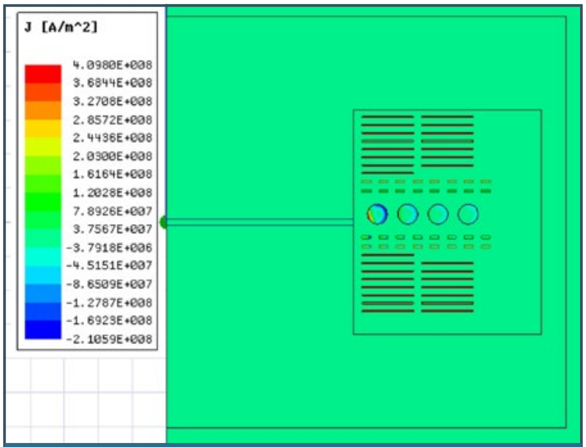

Figure 3. | Current Density in Transformer Using FEA

At maximum load, the secondary AC current is 7.3 A due to the pulsating nature of current on the secondary side. This would lead to copper losses of 1.5 W on the secondary side due to the thickness of the wire (0.8 mm diameter).

Finite Element Analysis (FEA) shows the conductor closest to the gap experienced a hot spot due to the high circulating AC currents and eddy currents induced by fringing effects as shown in Figure 3.

Bourns found that to reduce the copper losses at high frequencies, the insulated secondary wire would have to be replaced with a helical winding. As FR4 is not considered safe in this application, a barrier such as mylar or polyimide tape must be bonded to the PCB substrate.

SATISFYING INTERNATIONAL SAFETY STANDARDS

Bourns followed the IEC 61558 international safety standard for its design. IEC 61558 specifies the creepage and clearance between primary and secondary windings according to:

A. Working Voltage
B. Level of Insulation (Functional, Basic, Reinforced)
C. Degree of Pollution
D. Material Group

The design complies with IEC 61558 through the following features:

A. The secondary winding is made of UL listed triple insulated wire. According to the standard, there is no requirement for extra clearance or creepage between the primary, secondary and auxiliary.
B. The secondary winding is a flying lead. The required creepage and clearance between the conductive pin of the secondary and the conductive core with a working voltage of 300 V is 5.5 mm. The insulated secondary wire is kept at least 5.5 mm from the core.

IEC 61558 also specifies the Dielectric Isolation (also known as Hi POT) between the primary and secondary windings, which was also followed.

AC/DC ADAPTOR APPLICATION EXAMPLE

The Bourns® planar flyback transformer was tested on an AC/DC adaptor shown in Figure 4. The design is based on a Discontinuous Conduction Mode (DCM) Flyback Converter topology with valley switching and synchronous rectification. Both the valley switching and synchronous rectification reduce power losses in the external MOSFET and rectifier, respectively. Operating in DCM mode meant that there would be zero ampere turns in the transformer for a period every switching cycle.

The operating mode of the transformer is shown by the voltage across the drain of the MOSFET. Figure 6 shows the drain voltage and secondary Pulse Width Modulation (PWM) waveform of the Bourns® AC/DC adaptor. The voltage across the drain consists of the bulk voltage across the primary plus the reflected output voltage from the secondary. However, once the secondary current reaches zero, there are no more ampere turns in the windings meaning that the mutual inductance collapses. This leads to a period of oscillation around the bulk input voltage. The controller IC senses this from the auxiliary voltage and switches off the synchronous rectifier (blue line in Figure 6) to save energy. If the load is increased, this period of resonance is reduced until it disappears and the converter passes into continuous conduction mode.

Figure 4. | *View of an AC/DC Adaptor with a Planar Transformer and other Bourns® Components*

AC/DC ADAPTOR APPLICATION EXAMPLE *(Continued)*

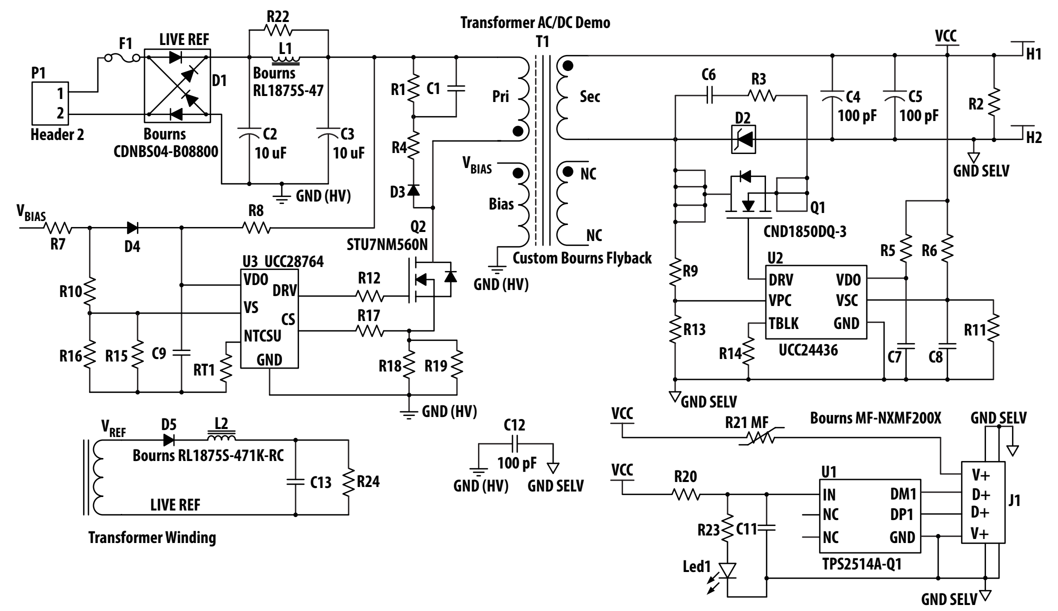

Figure 5. | *Schematic Diagram of an AC/DC Adaptor*

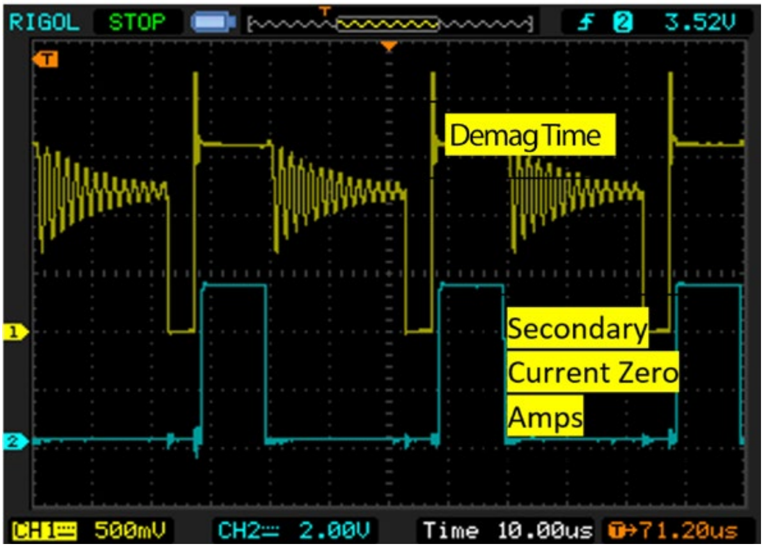

Figure 6. | *Drain Voltage and Secondary Rectifier Activation Waveforms*

AC/DC ADAPTOR APPLICATION EXAMPLE *(Continued)*

Increasing Power Supply Efficiency

In this example, the power supply operated at 115 V AC input with a 5 V output. Bourns measured the efficiency at different output powers as shown in Figure 7.

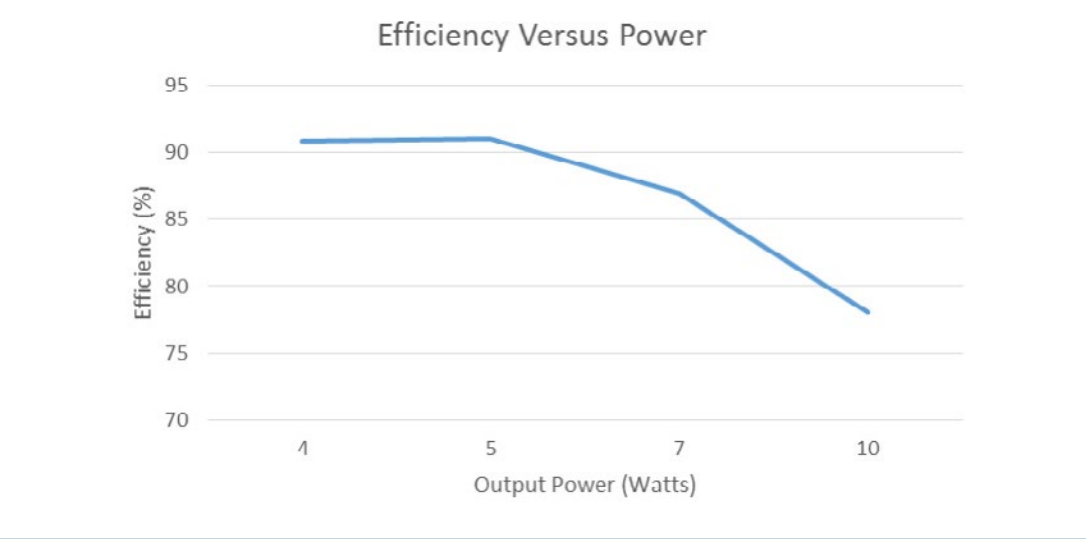

Figure 7. | *Efficiency versus Power Curve of an AC/DC Adaptor*

The thermal image shown in Figure 8 captures where the inefficiencies lie at 10 W where the external MOSFET, inductor and the secondary winding of the transformer are at their warmest state.

The biggest loss came from the snubber diode. The image in Figure 9 shows it is the hottest component reaching 51.3 °C. Optimization of the snubber resistor value and reduction of the leakage inductance in the transformer will help to improve power loss in this area.

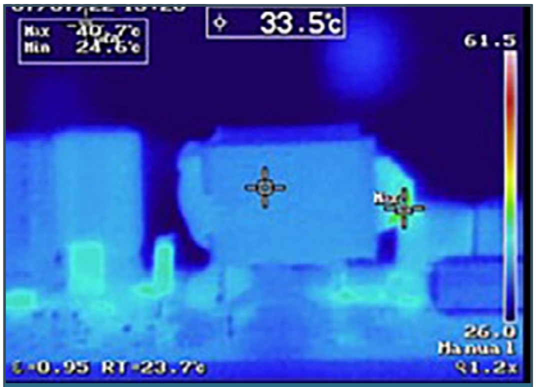

Figure 8. | *Thermal Image of an AC/DC Adaptor during Testing*

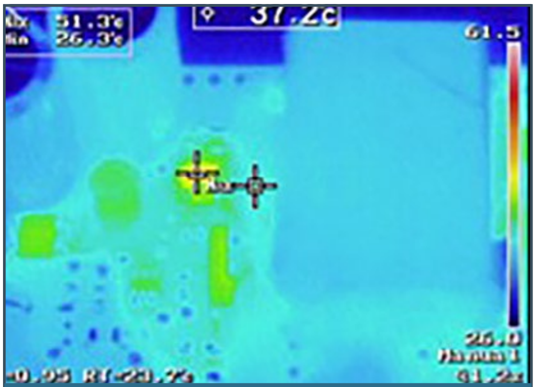

Figure 9. | *Thermal Image Highlighting the Heat from the Snubber Diode*

AC/DC ADAPTOR APPLICATION EXAMPLE *(Continued)*

Increasing Power Supply Efficiency *(Continued)*

Figure 10. Test Bench Showing Input and Output Power (91.05 % Efficiency)

CONCLUSION

Using the Bourns® planar flyback transformer design in this paper has illustrated that planar magnetics can be optimal conversion solutions for high frequency, high current applications including high voltage applications such as AC/DC adaptors. The planar transformer example provided the advantages of a compact, low profile design combined with PCB construction for high quality manufacturing.

Bourns developed this planar transformer with reinforced insulation, which was created by splitting the primary into two PCBs and sandwiching a four-turn secondary using triple insulated wire providing a necessary barrier between primary and secondary. Since the leakage inductance of a transformer is a source of wasted energy in a power supply, Bourns split the primary resulting in a leakage reduction of 50 %. Using this structure and testing it on an AC/DC flyback in DCM mode with 5 V output provided a peak efficiency of 91.05 % in the test conducted by Bourns.

The AC currents circulating in the secondary coil generate losses that could be mitigated if planar coils embedded in PCBs were used. By controlling the distances between the primary and secondary PCB, reductions in leakage inductance can also be achieved. Further transformer design improvements can be realized by focusing on reducing leakage inductance.

Bourns has extensive experience in supporting customers with custom transformer design for any topology in switch mode power supplies. The company's extensive use of 2D Finite Element Analysis allows them to achieve optimal magnetic and thermal performance in the design phase. Bourns' state-of-the-art laboratory enables its team to quickly assemble prototypes and test (Hi POT, Climatic, EMI, Impedance) according to customer specifications. Layout and test application board capabilities are also available to support customers, and Bourns' manufacturing facilities are TS16949 certified.

ADDITIONAL RESOURCES

Please contact your local Bourns Application Engineer or Bourns Sales Representative for additional information. Visit Bourns online at:

www.bourns.com

70TH ANNIVERSARY BOURNS® 1947 ★ 2017

Americas: *Tel* +1-951 781-5500
Email americus@bourns.com

EMEA: *Tel* +36 88 520 390
Email eurocus@bourns.com

Asia-Pacific: *Tel* +886-2 256 241 17
Email asiacus@bourns.com