How Litz Wire Maximizes Offline Multi-Output Flyback Transformer Efficiency for Battery Charger Applications

WHITE PAPER

INTRODUCTION

Flyback transformers are a robust, highly efficient and versatile option for AC-DC and DC-DC power supplies. Their wide input voltage range makes them an optimal choice for multiple designs while their use of minimal additional components makes them a cost-effective power conversion solution. Typically, flyback converter applications offer power levels up to 100 W allowing flyback transformers to be used for battery charger applications in EV (Electric Vehicle) and industrial ESS (Energy Storage System) solutions.

It is important that the size of the transformer be minimized in a power supply design as it is usually the biggest component on the PCB. However, minimizing the size of the transformer can lead to increased winding and core losses. A plus with flyback transformers is that they often offer multiple outputs, which can boost efficiency and provide more design flexibility. Conversely, this benefit can make it hard for the designer to minimize the size of the transformer while also balancing winding losses.

As the world moves to adopt greener energy sources, power supplies, in turn, need to become more and more efficient. This increased efficiency requirement frequently causes power conversion designs to be more complex and the best engineering techniques employed to optimize power loss.

Litz wire is becoming more and more popular for flyback transformers as it can reduce power loss and boost power efficiencies. Litz wire is constructed using multiple fine wires that are woven together to replicate a typical copper wire. The benefit of Litz wire is that by having multiple conductors bunched together, the skin effect is greatly reduced. Reducing the skin effect has been shown to reduce AC resistance and boost the efficiency of power conversion designs.

This paper investigates the temperature rise of a multi-output offline 60 W flyback transformer and it will illustrate what design steps can be made to reduce the temperature rise. Various flyback transformer designs are presented, and it evaluates each for winding, core and power loss, along with AC resistance.

FLYBACK TRANSFORMER OPERATION

A flyback is a unique type of transformer as it does not operate like a standard transformer. Essentially, it is a coupled inductor with a gapped core. The flyback converter circuit is shown in Figure 1 and the main voltage and current waveforms are displayed in Figure 2. When the primary switch is turned on, the current in the primary winding ramps up. The energy is stored in the gap during this cycle. The reverse-biased diode on the secondary side prevents the current flowing through the secondary winding. When the switch opens, the polarity on the primary winding changes, energy is transferred to the secondary side and current begins to flow in the secondary winding to the load.

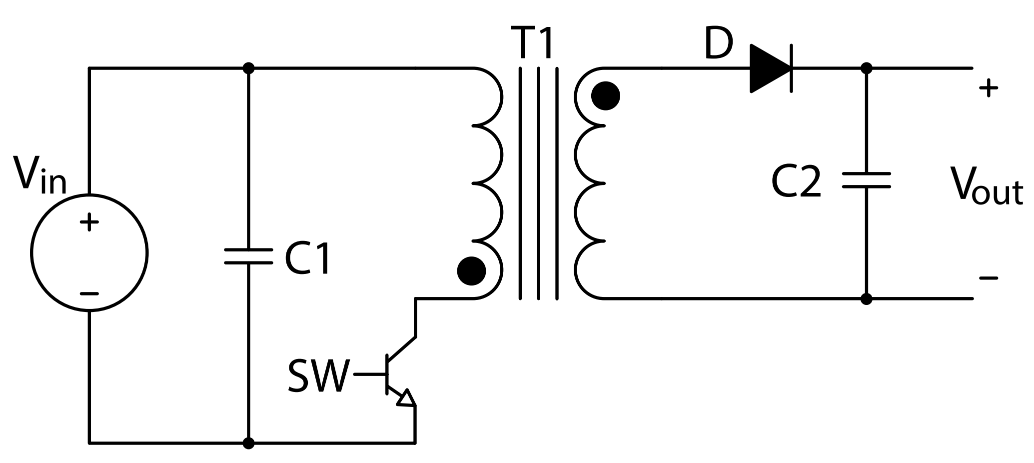

Figure 1 - Flyback converter schematic

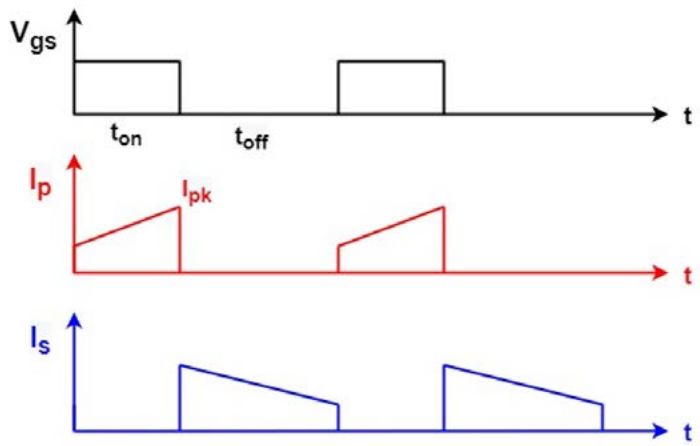

Figure 2 - Flyback main voltage and current waveforms

HOW FLYBACK TRANSFORMERS ARE DESIGNED

For a typical transformer design, the designer will use a blend of hand calculations, circuit simulators, analytical tools and FEA (Finite Element Analysis) software to arrive at the final solution. Often, the design may need to be optimized for size, winding losses and/or core losses and this is where simulation tools are useful. However, it is recommended to do hand calculations first so the designer can gauge how the design will operate. Hand calculations also help to verify the accuracy of the simulation tool used. For this paper, Ansys PEXPRT and Ansys PEMAG are both used to calculate the winding and core losses. These simulations provide a good representation of AC resistance as they account for the skin effect, fringing effect, and the proximity effect.

Different factors will influence AC resistance and it is helpful to know what can be done to reduce it. The initial design shown in this paper is of a multilayer flyback transformer where none of the high-frequency effects are taken into consideration. The design examples that follow deploy different techniques that can reduce AC resistance and help improve power loss.

DESIGN 1: 60 W FLYBACK TRANSFORMER

The design specifications for the 60 W flyback are listed in Table 1. There are five windings in total - a primary winding, three secondary windings and an auxiliary winding. For this design, the secondary windings will need reinforced insulation. This is common in power supply designs because safe isolation from hazardous voltages is required. Using insulated wires can increase the size of the wire by up to 20 to 30 percent. The core selected for this design is an EE30 3C94 Mn-Zn ferrite from Ferroxcube.

Table 1. Specifications

Input Voltage	250 V
Secondary Output Voltage 1	10 V
Secondary Output Voltage 2	5 V
Secondary Output Voltage 3	5 V
Auxiliary Output Voltage	5 V
Secondary Output Current 1	3.5 A
Secondary Output Current 2	2.5 A
Secondary Output Current 3	2.5 A
Auxiliary Output Current	100 mA
Frequency, f_{sw}	150 kHz
Primary Inductance	200 µH
Temperature Rise	40 °C
Ambient Temperature	25 °C

DESIGN 1: 60 W FLYBACK TRANSFORMER (Continued)

The winding construction is displayed in Figure 3 and described in Table 2.

Table 2. Winding construction for initial design

Winding	Color	Layer	Turns
Primary	Yellow	1,2	40
Auxiliary	Green	6	5
Secondary 1	Red	3	10
Secondary 2	Blue	4	5
Secondary 3	Purple	5	5

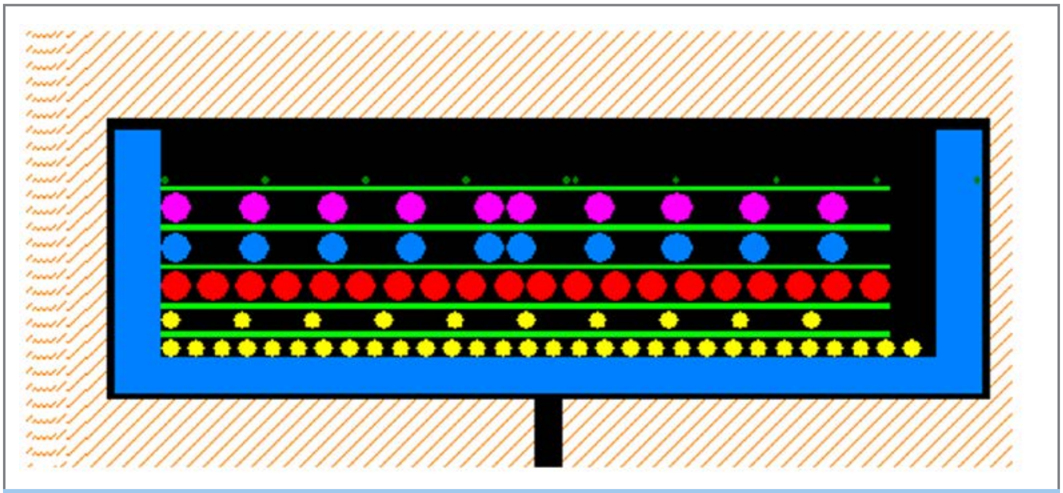

Figure 3 - Design 1 winding construction

DESIGN 1: 60 W FLYBACK TRANSFORMER (Continued)

Calculating Winding Loss

Table 3 displays the winding losses from design 1. The AC resistance is very large for all the windings and the power loss is expected to be high. To calculate the winding losses, the AC and DC resistance are obtained from the FEA simulation and multiplied by the RMS currents squared.

Table 3. | *Winding losses for design 1*

Winding	DCR (mΩ)	ACR @ 150 kHz (mΩ)	DC Copper Loss (W)	AC Copper Loss (W)
Primary	270	2600	0.12	1.16
Auxiliary	173	265	0.002	0.004
Secondary 1	16	200	0.22	2.95
Secondary 2	9	67	0.067	0.5
Secondary 3	10	89	0.075	0.67

The total copper loss is denoted P_{cu} where it is the DC and AC copper loss combined:

$$P_{(cu\ (total))} = 5.8\ \text{W}$$

Determining Core Loss

First, the flux density ripple ΔB is calculated from Faraday's law (Equation 1.1), where V_{in} is the input voltage, A_c is the core area, D is the duty cycle, T is the switching period and N_p is the number of primary turns:

$$V_L = -N\frac{d\varnothing}{dt} \qquad [1.1]$$

$$\Delta B = \frac{V_{in}DT}{N_pA_c} = \frac{50 \times 0.11}{150 \times 10^3 \times 40 \times 60 \times 10^{-6}} = 0.097\ \text{T}$$

Using the General Steinmetz Equation, the core loss P_{fe} is calculated where V_c is the core's volume, f is the switching frequency, B_{max} is the peak flux density and K_c, α and β are Steinmetz parameters which are derived from the core material:

$$P_{fe} = V_cK_cf^{\alpha}B^{\beta}_{max} \qquad [1.2]$$

$$P_{fe} = (4020 \times 10^{-9})(2.9)(150 \times 10^{3^{1.39}})\left(\frac{0.097^{2.59}}{2}\right) = 0.072\ \text{W}$$

Total Loss

The total loss P_{total} equals copper loss and core loss combined:

$$P_{total} = P_{cu} + P_{fe} = 5.8 + 0.072 = 5.872\ \text{W}$$

DESIGN 1: 60 W FLYBACK TRANSFORMER (Continued)

Thermal Analysis

The combined losses in the windings and core generate heat which must go somewhere. In general, the primary heat transfer will occur via conduction through the core and conduction through the terminals. In this design, there will be convection at the surface of the transformer. The transformer is a through-hole component, so, therefore, there will be no conduction between the core and PCB.

The target temperature rise is 40 °C. An ANSYS thermal was used to estimate the temperature rise. The core losses are applied to the core, the winding losses are applied to the winding and the temperature rise is simulated. The ambient temperature used is 22 °C. The temperature rise is displayed in Figure 4. Design 1 shows a temperature of 98 °C for the core and winding, which produces a temperature rise of 76 °C. This exceeds the target temperature rise. By analyzing the losses, it is shown that the AC resistance is contributing the most to the copper losses. The core losses are negligible compared to the winding losses.

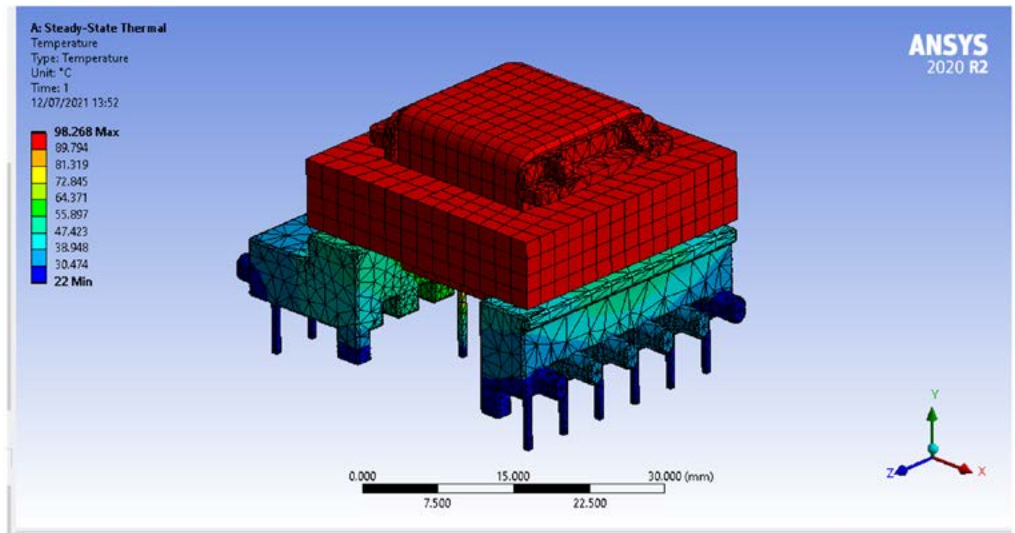

Figure 4 - Ansys thermal analysis for design 1

DESIGN 2: ACCOUNTING FOR FRINGING EFFECT

The second design accounts for the fringing effect by modifying the distance between the gap and the start of the first winding. When a transformer experiences a fringing effect, it causes an increase in AC resistance. This occurs because the flux lines bulge out around the gap, rather than travelling in straight lines. In design 2, the distance is modified by increasing the wall thickness on the bobbin. The winding construction is displayed and described in Figure 5 and Table 4.

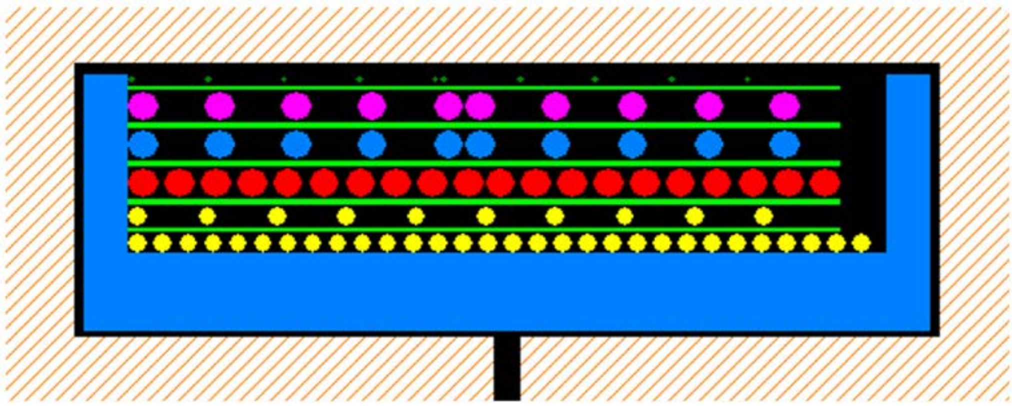

Figure 5 - Design 2 winding layout

Table 4. Winding construction for design 2

Winding	Color	Layer	Turns
Primary	Yellow	1,2	40
Auxiliary	Green	6	5
Secondary 1	Red	3	10
Secondary 2	Blue	4	5
Secondary 3	Purple	5	5

DESIGN 2: ACCOUNTING FOR FRINGING EFFECT (Continued)

Calculating Winding Loss

The winding loss for design 2 is shown in Table 5. The DC resistance slightly increases as the mean length turn (MLT) increases with the modified bobbin. However, there is a good reduction in AC resistance, which results in an overall power loss of 4.15 W. Design 2 gives a 30 percent reduction in copper loss.

Table 5. Winding loss for design 2

Winding	DCR (mΩ)	ACR @ 150 kHz (mΩ)	DC Copper Loss (W)	AC Copper Loss (W)
Primary	317	1480	0.14	0.8
Auxiliary	192	270	0.002	0.004
Secondary 1	18	133	0.26	2.2
Secondary 2	10	53	0.07	0.47
Secondary 3	11	74	0.08	0.64

The total copper loss is denoted P_{cu} where it is the DC and AC copper loss combined:

$$P_{(cu\ (total))} = 4.15\ W$$

Determining Total Loss

The core loss remains the same for design 3. The total loss equals copper loss and core loss combined:

$$P_{total} = P_{cu} + P_{fe} = 4.15 + 0.072 = 4.22\ W$$

DESIGN 2: ACCOUNTING FOR FRINGING EFFECT (Continued)

Thermal Analysis

From the thermal simulation, the temperature of the core and winding was recorded as 78 °C. There was a reduction of 20 °C in the temperature. The losses in design 2 are still too high and are directly producing the large temperature rise displayed in Figure 6.

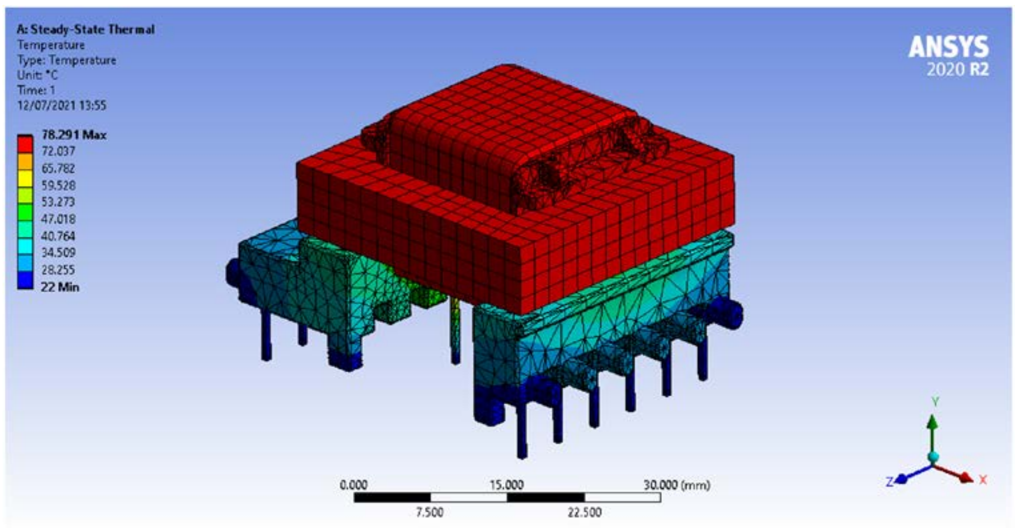

Figure 6 - ANSYS thermal analysis for design 2

DESIGN 3: ACCOUNTING FOR THE PROXIMITY EFFECT

Design 3 accounts for the proximity effect by reducing the number of layers in the winding construction. The proximity effect factor has a direct relation to AC resistance and occurs when the distribution of current in one layer of a winding influences the distribution in another layer. For instance, if a winding has current flowing in one direction, it would be labelled as positive and if the layer above it has current flowing in the opposite direction, it would be denoted as negative. Positive and negative charges attract, so the distribution of current will not travel uniformly through the conductor but bunch toward one side of it. The AC current travels in a smaller area which, therefore, increases the AC resistance. Reducing the number of layers in a transformer negates this effect as illustrated in Figure 7 where the number of layers is reduced. Table 7 describes the winding construction.

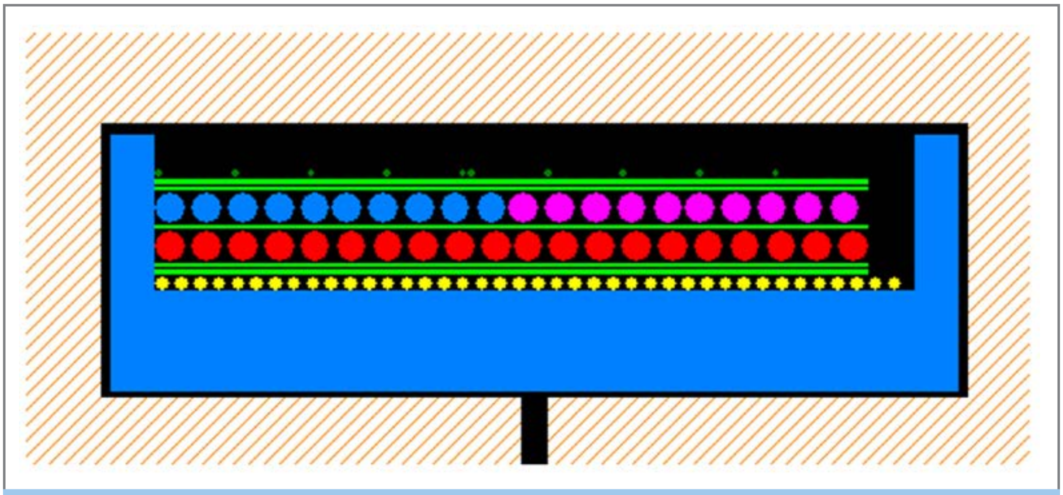

Figure 7 - Design 3 winding construction

Table 7. Design 3 winding construction

Winding	Color	Layer	Turns
Primary	Yellow	1	40
Auxiliary	Green	4	5
Secondary 1	Red	2	10
Secondary 2	Blue	3	5
Secondary 3	Purple	3	5

DESIGN 3: ACCOUNTING FOR THE PROXIMITY EFFECT (Continued)

Calculating Winding Losses

Reducing the number of layers results in a reduction in AC resistance of the primary winding and secondary winding 1. There is a worsening of AC resistance for secondary windings 2 and 3. This is because the wires are bunched together instead of evenly spaced across the breadth of the bobbin. This bunching increases the AC resistance.

Table 8. Winding losses for design 3

Winding	DCR (mΩ)	ACR @ 150 kHz (mΩ)	DC Copper Loss (W)	AC Copper Loss (W)
Primary	520	1200	0.23	0.8
Auxiliary	177	244	0.002	0.004
Secondary 1	18	90	0.26	1.59
Secondary 2	10	100	0.075	0.86
Secondary 3	10	87	0.075	0.73

The total copper loss is as follows:

$$P_{(cu\ (total)} = 4\ W$$

Determining Total Loss

The core loss remains the same for design 3. The total loss equals copper loss and core loss combined:

$$P_{total} = P_{cu} + P_{fe} = 4 + 0.072 = 4.072\ W$$

Thermal Analysis

The overall loss is marginally better, but the losses in design 3 are still too high. The ANSYS thermal simulation is not required here as the power losses have only marginally improved.

DESIGN 4: ACCOUNTING FOR SKIN EFFECT

Accounting for the proximity effect and the fringing effect has seen an improvement in power loss. However, it has not been sufficient. The AC resistance is still too large, and this is due to the skin effect. A wire carrying AC current will generate an AC magnetic field which produces eddy currents in the wire. These eddy currents give the effect of cancelling the current distribution in the middle of the conductor and pushing the distribution of current to the outside of the conductor. The thickness of this distribution on the outside of this conductor is known as the skin depth. As the frequency increases, the skin depth becomes lower. The AC resistance increases as the area where the current resides becomes smaller.

One way to combat this issue is by using Litz wire. Litz wire is a multi-stranded wire that is woven together so that it negates the skin depth effect. To further reduce the AC resistance, Litz wire is used on all the secondaries. Thicker wire was used on the windings to reduce the copper losses. Note that the design uses the standard bobbin as the fringing effect does not have a significant impact on the Litz wire. The winding construction is displayed in Figure 7 and is described in Table 8.

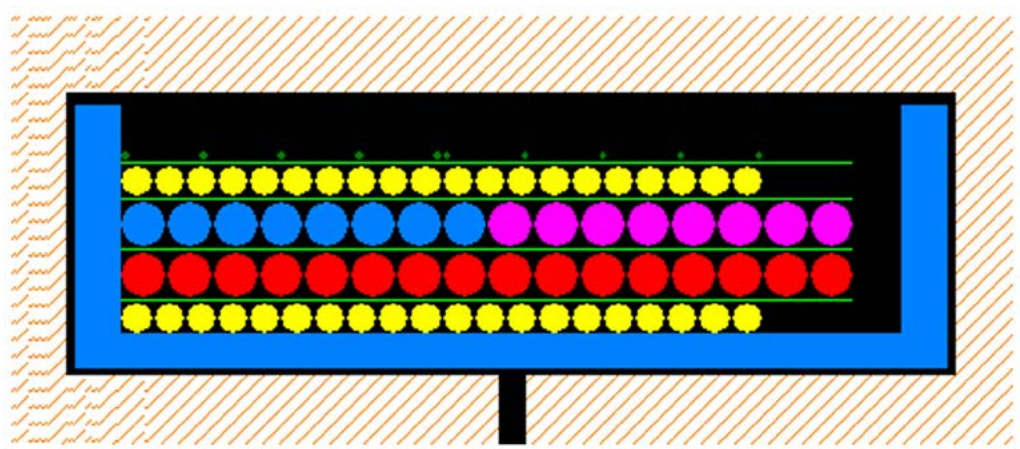

Figure 8 - Design 4 winding construction

Table 8. Design 4 winding construction

Winding	Color	Layer	Turns
Primary	Yellow	1 ,4	40
Auxiliary	Green	5	5
Secondary 1	Red	2	10
Secondary 2	Blue	3	5
Secondary 3	Purple	3	5

DESIGN 4: ACCOUNTING FOR SKIN EFFECT (Continued)

Winding Losses

The AC resistance decreases significantly on all secondaries as shown in Table 9.

Table 9. Winding losses for design 4

Winding	DCR (mΩ)	ACR @ 150 kHz (mΩ)	DC Copper Loss (W)	AC Copper Loss (W)
Primary	296	310	0.13	0.14
Auxiliary	177	244	0.002	0.004
Secondary 1	10	12	0.14	0.32
Secondary 2	6.5	6.7	0.049	0.1
Secondary 3	6.5	6.7	0.049	0.1

The total copper loss was obtained:

$$P_{(cu\ (total))} = 0.8\ \mathrm{W}$$

Determining Total Loss

The core loss remains the same for design 3. The total loss equals copper loss and core loss combined:

$$P_{total} = P_{cu} + P_{fe} = 0.8 + 0.072 = 0.872\mathrm{W}$$

DESIGN 4: ACCOUNTING FOR SKIN EFFECT (Continued)

Thermal Analysis

The total loss of 0.872 W is less than the maximum power dissipation of 1.33 W, so the temperature rise should be at an acceptable level. Figure 8 displays the ANSYS thermal analysis. The temperature of the windings is simulated as 42.9 °C and the temperature of the core is simulated as 48.9 °C. The temperature rise is simulated as 26.9 °C, producing a much-improved design.

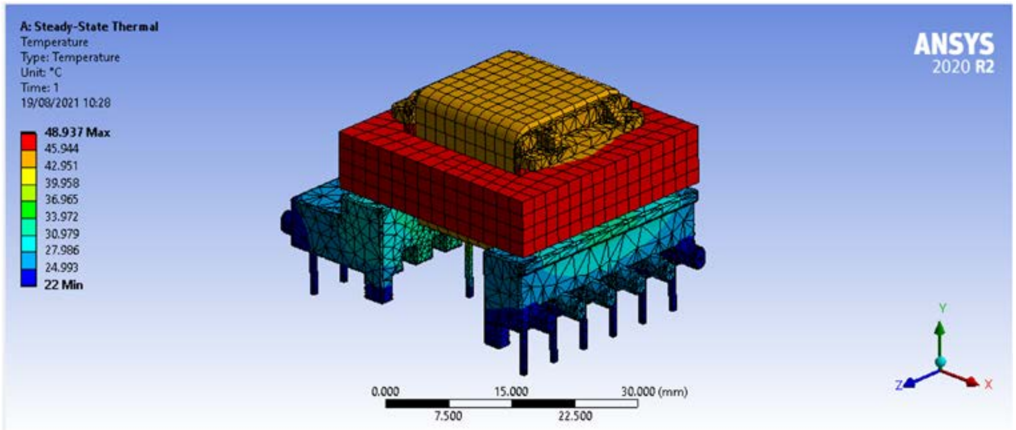

Figure 9 - ANSYS thermal analysis for design 4

Real Thermal Results

The above design was tested in an actual development board for a battery charger in an energy storage application and the results are recorded in Table 10 below.

Table 10. Temperature results for design 4

Design	Max. Temperature, T_{max}, °C	Ambient Temperature, T_A, °C	Temperature Rise, Δ, °C	Temperature Rise Simulated, T_{sim}, °C
Design 1	91	26.7	64.3	76°C
Design 2	75.3	28.2	47.1	56.3
Design 3	NA	NA	NA	NA
Design 4	64.5	30.8	33.7	26.9

DESIGN REVIEW

This paper has presented different design techniques to reduce the copper loss for a multi-output flyback converter. The results conveyed that the skin effect contributed to the largest copper loss. This was confirmed when Litz wire was introduced into the design causing the AC resistance to drop dramatically. The overall power loss was reduced from 5.7 W (initial) to 0.8 W. The temperature in the core and windings was reduced from 98 °C to 45 °C under the same operating conditions. There was a 12 °C difference between the real and simulated temperature results. The simulated result only considers the conduction of heat through the pins to the PCB. It does not consider convection via air at the surface of the core which may produce a few degrees of cooling.

Introducing Litz wire into the design offered the best solution. In a different design, Litz wire may need to be used only in one winding to reduce the power loss to an acceptable level. Moreover, if there is cooling in a system, higher power losses can be allowed. But no power losses were assumed in this paper, and that is why using Litz wire was crucial.

When the fringing effect was considered, there was a power loss reduction from 5.7 W to 4.22 W. However, this reduction was not sufficient to reduce the temperature rise. A 2D FEA analysis was used to measure the AC resistance. For more accurate results, a 3D simulation should be performed as this will provide a better approximation for the fringing effect. The simulated temperature rise was recorded as 56.3 °C, which is directly proportional to the power loss. The temperature rise in the actual application was recorded as 47.1 °C. There is a 9.2 °C difference between real and simulated values and it is believed that this is due to convection that is typically not considered.

In design 3, the layers were reduced to negate the proximity effect. The AC resistance was reduced on the primary and secondary 1 winding. But the AC resistance increased in the secondary 3 and 4 windings. There was only a marginal improvement of 0.22 W in overall loss between design 3 and design 2. Secondary 1 caused the AC resistance to rise in secondaries 2 and 3.

The AC resistance was simulated using Ansys 2D FEA. The ACR simulation can only approximate real-life results, and power loss calculations can never truly be accepted until the transformer is tested in a real-life working application. Additionally, convection was not considered in the Ansys thermal simulation and this is probably why there is a small variation between the real and simulated results.

CONCLUSION

Incorporating Litz wire into a flyback transformer demonstrated the greatest reduction in copper loss as it reduces the temperature to an appropriate level. Using Litz wire was superior to any other method applied in the Bourns tests at reducing the AC resistance. It was demonstrated that the use of Litz wire produces a much lower AC resistance than conventional wire. Litz wire offers a practical solution that comes in a wide variety of sizes and can meet many flyback designs. Also, Litz wire is widely available as there are several Litz manufacturers in the market. In recent years, power supply designs have become more complex as the need for maximum efficiencies has become more prevalent. The Bourns tests have demonstrated that Litz wire is a superior solution for maximum efficiencies in flyback converter solutions. The engineers at Bourns believe it will be used more commonly as the drive towards energy-efficient technologies continue.

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