Designing a Low Power Flyback Power Supply

APPLICATION NOTE

INTRODUCTION

Bourns is a well-known supplier of standard off-the-shelf high power inductors for power supplies in consumer, medical and automotive applications. Bourns also has a strong reputation in resistive products for various functions. This application note explains the key steps in designing two of the most important components in a flyback converter - the transformer and the snubber resistor. Flyback converters are very popular topologies in a variety of segments, both in DC/DC and offline (50 Hz, 120 V or 230 V input) circuits. The chief reasons for their popularity are as follows:

- Isolation from high voltages
- Fewer components than other topologies
- Cost

However, this application note will demonstrate that flyback converters can generate losses, especially if the transformer is not designed properly. It is not common to see flybacks operating at higher than 100 W of power due to the losses in the transformer. Other topologies can achieve higher efficiencies. Power supplies of up to 100 W cover many consumer and automotive applications such as appliance control boards, LED drivers and many more.

Designing a Low Power Flyback Power Supply

OPERATION OF THE FLYBACK TOPOLOGY

The basic operation of the power stage of a flyback power supply is shown in figure 1. Turning on the switch causes the current in the primary winding and the switch to increase. A diode in the secondary side is used to prevent any current from flowing to the load during the time that the primary is conducting. The flyback transformer will have a gap in its core to store the energy from the primary side during the on time which is then discharged into the secondary side as soon as the primary switch is turned off and the diode becomes forward biased. As the switch turns off, the voltage across it "flies back" to a voltage that is fixed by an RCD snubber network.

In reality, the flyback transformer is an isolated inductor as it stores energy every cycle. A true transformer does not store any energy as it transfers energy immediately from a source to its load. The waveforms shown are taken from a flyback operating in "continuous mode", when the current in the inductor never reaches zero.

Figure 1. | *Waveforms and Basic Operation of a Flyback Converter*
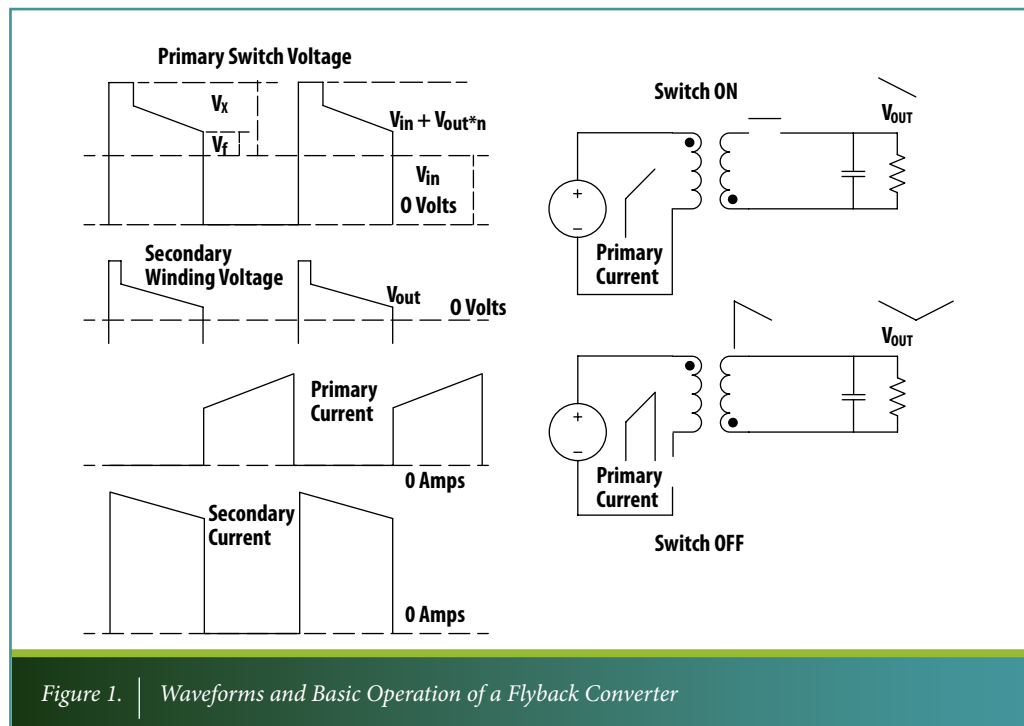
Designing a Low Power Flyback Power Supply

DESCRIPTION OF THE PROBLEM

The challenge is to design the power stage of a flyback converter for an appliance application with the following specifications:

Minimum Rectified Input Voltage	150 V_{RMS}
Output Voltage	12 VDC
Efficiency	70 %
Output Power	2.9 W
Switching Frequency	60 kHz
Maximum Duty Cycle	0.5
Safety Standard	IEC 61558-1, 61558-2
Pollution Degree	2

Table 1. | *Flyback Converter Appliance Application Specifications*

DESIGN PROCEDURE

The most important element in the power supply is the transformer. If this is designed incorrectly then the power supply may be inefficient and could cause increases to the EMI spectrum which may overheat, causing failures.

To design the transformer, we first have to calculate the turns ratio. This is done by looking at the circuit and calculating the secondary winding voltage. The output is 12 VDC but there are losses caused by the diode and the Printed Circuit Board (PCB) itself. The secondary winding voltage is, therefore: 12.5 V (12 V + 0.4 V (Diode) + 0.1 V (PCB conduction) = 12.5 V). We want to help ensure that the turns ratio will provide a minimum of 12.5 V which occurs at the lowest rectified voltage. If the rectified voltage is higher than 12.5 V, then the control loop can adjust the duty cycle accordingly. Therefore, we have an overall ratio of 12 (12 x 12.5 = 150 V). We could have any of the following turns as shown in the matrix below. However, the actual number of turns requires consideration and will be demonstrated later. Having an integer number of turns makes calculations and manufacturing easier.

The efficiency is set at 70 % making the input power 4.11 W. The average input current at 150 V is 0.0274 A. The input current will have a sawtooth shape where the peak-to-mean ratio is 4. Hence, the peak input current is 0.11 A.

Turns Scenario	Primary W1	Secondary W2
1	12	1
2	24	2
3	48	4
4	96	8
5	120	10
6	240	12

Table 2. | *Duty Cycle Turns Matrix*

The inductance, therefore, required in the primary side is 11.39 mH (taken from $e = L\frac{di}{dt}$). The gap required is $lg = \frac{N^2 \mu o A}{L}$. We need to select a suitable core before we can calculate the gap length. Again, for practical reasons we will round the inductance value up to 12 mH.

Designing a Low Power Flyback Power Supply

LAYOUT OF THE TRANSFORMER

The construction of the flyback transformer depends on the following components:

- Core shape and bobbin
- Core material

As the flyback transformer is really two coupled inductors, we have to be careful not to saturate the device. Therefore, the minimum number of turns in the primary is important.

The product of saturation flux density, turns and core area must be greater than the product of the primary inductance and the peak current to avoid saturation ($B_s.A.N > L_{pri}.I_{pk}$ (Equation 1)) .

If we select an EFD30 core with a 3F3 material, we can plug the following values into equation 1 giving us a minimum number of turns of 48.

| Description	Value	Variable
Area of Core mm^2	69	A
Saturation Flux Density of 3F3	0.4 T	B_s
Peak Current	0.11 A	I_{pk}
Primary Inductance	12 mH	L_{pri}
Minimum Number of Turns	48	N

Table 3. | *Equation 1 Matrix*

As this is the minimum number of turns, we can select any number above that. Our turns ratio is 12 so a multiple of 12 will provide us with an integer number of secondary turns. Let us try a primary of 60 turns.

The gap is, therefore: $\lg = \dfrac{N^2\mu A}{L} = \dfrac{(60)^2\mu A \cdot 4\pi.10^{-7}.69 10^{-6}}{12.10^{-3}} = 0.3$ mm

The wire thickness of the primary and secondary depends on the space available. According to EN 61558, the creepage and clearance for a flyback transformer in an AC mains application in a pollution degree 2 environment is 6 mm. This is the minimum distance allowed between the nearest live conductor, or in this case, the primary and secondary. To implement 6 mm creepage, blocking tape, otherwise known as margin tape, is stuck to the side of the bobbin. Putting 3 mm on each side will ensure a creepage and clearance of 6 mm between the two windings.

The EFD30 bobbin has a window of 20.1 mm in total. If we take away our 6 mm of margin, this leaves us with a total window of 14.1 mm or 0.555 inches. This means we need a wire that can fit 60 turns in 0.555 inches or 108 turns per inch.
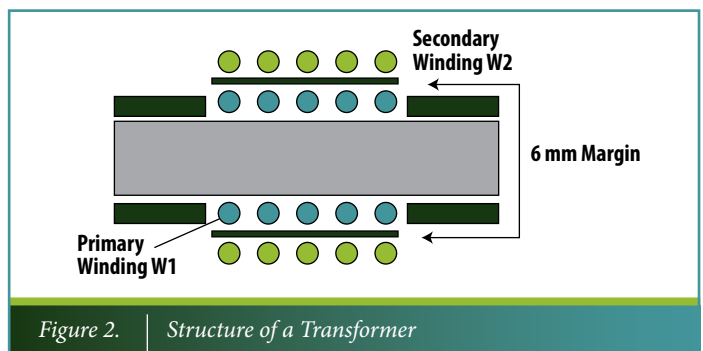
Figure 2. | *Structure of a Transformer*

LAYOUT OF THE TRANSFORMER *(Continued)*

Looking at winding tables, it is clear that 32 gauge enamel wire will fit 113 turns per inch. 32 gauge enamel wire has a resistivity of 0.0054 ohms per cm. The mean length per turn of an EFD30 bobbin is 56.7 mm, according to the manufacturer's data sheet. Therefore, the total DC resistance of the primary is 60 turns · 5.7 · 0.0054 ohms = 1.8 ohms

The rms current in the primary is given by the equation $l_{rms} = \frac{I_{peak}}{\sqrt{3}}$ = 0.064 A. The DC winding loss in the primary therefore is 13 mW, which is quite small.

The total flux generated by a flyback has two components called B_{dc} and B_{ac}. B_{dc} is generated by the Ampere Turns (Amperes Law) and is calculated as follows:

$$B_{dc} = \frac{\mu.Idc.N}{lg} = 4\pi.10^{-7}.0.0274. \frac{60}{0.3.10^{-3}} = 70 \text{ mT}$$

B_{ac} is generated by the voltage across the winding when the switch is on (Faraday's Law).

$$B_{ac} = \frac{E.t.N}{A} = 600 \text{ mT}$$

The peak flux density is 670 mT, which is above the saturation limit of 3F3 material. The curves for 3F3 material also show a core loss of 3000 kW/m³ or 18 W. The most obvious change to reduce the core loss is to increase the number of turns on the primary side to 144 and the secondary turns to 12. This will give a flux density of 250 mT with a density of 120 kW/m^3 or a core loss of 0.55 W.

We therefore need to reduce the size of the wire we are using. We now require 259 turns per inch. 40 gauge wire will suit this application giving a resistance of 30 ohms. Despite the high resistance of the primary, the rms current is low enough to make the winding losses insignificant.

A key factor in the flyback transformer is leakage inductance. An ideal transformer has perfect coupling between the primary and secondary windings with no losses. However, in reality, the coupling is less than 100 percent, leaving what is in effect an inductance in series with the primary coil. This is known as leakage inductance which is minimized by adhering to the following methods:

- Fill each layer with a winding. In our design, the wire width is optimized to fill the layer. If there were empty spaces, the winding could be made spiral to take up more space.
- Interleaved windings - this can be done by splitting the primary into two layers and fitting the secondary in the center. However, this increases the proximity effect.

These measures reduce the leakage inductance but will not eliminate it. Therefore, at switch turn off there will be a high voltage generated across the leakage inductance in accordance with Lenz's law. The combination of the leakage inductance and any parasitic capacitance will cause a ringing waveform to appear across the drain of the switch and this can be destructive if not dampened. The ringing frequency created can also affect the EMI spectrum. This is where the snubber network can be used to attenuate the energy generated by this L, C combination.

LAYOUT OF THE TRANSFORMER *(Continued)*

The interwinding capacitance is also responsible for the destructive ringing which can exceed the rated drain to source voltage (V_{ds}) of the switch and the output diode reverse breakdown voltage. The capacitance is given by the equation $C = \frac{\varepsilon o.\varepsilon A}{d}$ where εo and ε are the absolute and relative electrical permittivity constants. A is the area of the exposed winding and d is the distance between windings. Increasing the distance between the windings using insulation tape is one way to reduce capacitance. However, the increased distance reduces the coupling factor which in turn increases the leakage inductance. The largest reduction in capacitance is done by putting a Faraday shield between the windings. This is normally a single conductive foil with one connection to ground. This adds to the cost of the transformer.

The primary snubber network is connected between the drain and the source of the switch. To calculate the size of the snubber resistor there are a few steps, as follows:

- Measure the leakage inductance. This is done using a precision LCR meter.
- Check the maximum voltage that the switch can withstand and decide on a clamp voltage.
- Calculate the power that the leakage inductance will absorb at the peak current.
    - $P \text{ leakage} = \frac{I_{pk}^2 \, L.fs}{2}$
- Calculate the power from the equation $P = P \text{ leakage}. \left(1 + \frac{V_f}{V_x}\right)$
- The clamp voltage V_x should be selected so that you do not exceed the stated V_{ds} on the manufacturer's data sheet. For offline power supplies, the power switch can have a maximum voltage of as much as 700 V.
- The value of the resistor is calculated from the equation $V_x. \left(\frac{V_f + V_x}{P_{leakage}}\right)$
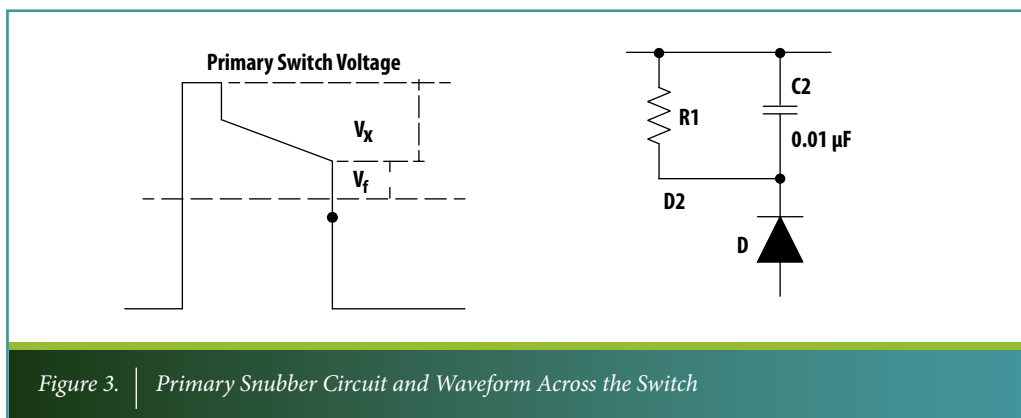- Where V_f is the flyback voltage and V_x is the clamped voltage.

Figure 3. | *Primary Snubber Circuit and Waveform Across the Switch*

The flyback voltage is generated by the secondary winding coupling its voltage to the primary winding during the off time of the switch. Due to the turns ratio this voltage can be quite high. The sum of the clamped voltage and the flyback voltage must be kept below the maximum rated V_{ds} of the switch.

BOURNS®

LAYOUT OF THE TRANSFORMER *(Continued)*

In our example, we calculate a value of 2 megohms for the snubber resistor with an average power of 0.129 Watts. It is possible to select lower resistors, and the net effect of this is to quicken the discharge of the capacitor and reduce the voltage across the drain of the switch. On the other hand, this will also increase the dissipation in the resistor. As an example, at 2 megohms the voltage across the switch is 670 volts. However, 670 volts is a high voltage and will exceed the dielectric voltage withstanding specification of many chip resistors. If we want to lower this voltage for safety reasons we could use a 100K ohm resistor which lowers the voltage to 537 volts peak, but increases the loss in the snubber resistor from 0.129 watts to 1.4 watts.
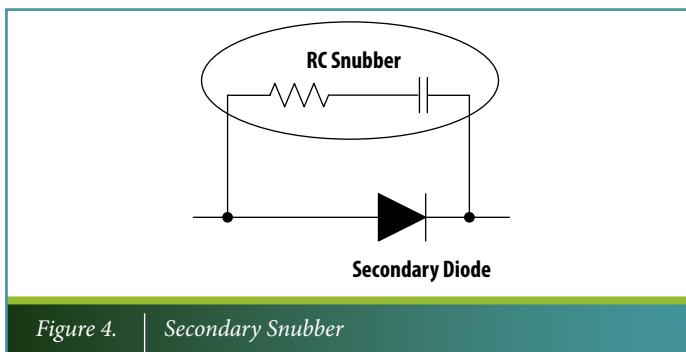
Snubber Resistor	Primary Switch (Vx+Vin +Vout x n)	Average Power in Resistor (W)
2 megohms	670 V	0.129 W
100K ohms	537 V	1.4 W

Table 4.	Snubber Matrix

The secondary voltage winding will also have a leakage inductance which is generally the primary leakage inductance divided by the turns ratio squared. Even though the diode selected is small, the diode must have a reverse breakdown voltage high enough to resist the ringing which occurs when the switch is turning off. Often, Schottky rectifiers are quite sensitive to this. The solution is to add an RC combination across the diode to dampen the ringing produced.

The procedure for selecting the snubber resistor in an RC configuration is as follows:

- Calculate the secondary leakage inductance.
- Measure the ringing frequency using an oscilloscope.
- Calculate the impedance Z of the leakage inductance at the ringing frequency and select a resistor value equal to $Z = 2\pi f_r L$.
- To select the capacitor value, make the impedance of the capacitor equal to the resistor $\frac{1}{2\pi fR}$.
- Correctly size the resistor by calculating the power rating $CV^2.fs$ where fs is the switching frequency.

RC Snubber

Secondary Diode

Figure 4.	Secondary Snubber

BOURNS®

SUMMARY OF RESULTS

By putting together a matrix of losses we can calculate the efficiency of our design.

Maximum Losses at 70 % Input Power	1.24 W
Winding Losses (0.025 A² 30 Ohms)	0.02 W
Core Loss	0.55 W
Primary Snubber (2 Megohms)	0.129 W
Subtotal	0.699 W
Margin for Other Losses (Maximum – Subtotal)	0.541 W

Table 5. | *Result Summary Matrix*

Semiconductor losses will include the forward diode as well as the switch. Schottky diodes have a low forward voltage and lower losses. The reverse recovery time should be at a minimum to avoid ringing back and forth with the secondary leakage inductance. We can reduce the stress on the switch by reducing the snubber resistor as discussed previously, although this increases the losses in the resistor. Advances in soft-switching have led to the development of resonant converters, which also reduces switching losses and improves efficiencies. Significant losses remain the core loss of the flyback transformer. The small dimensions of the transformer means there are limits on the actual number of turns available and an increased flux density. The high input voltage also increases the flux.

Designing a Low Power Flyback Power Supply

SUMMARY

Bourns has been a leading manufacturer of resistive and inductive products for many decades. Its resistor products include surface mount thick film resistors which can be used in flyback converters up to 50-60 W and higher, power converters and inverters in RCD and RC snubber configurations.

Bourns has a wide range of high power ferrite and iron powder off-the-shelf inductors for power converters in consumer, medical and automotive electronics. Bourns also has the capability for custom transformer designs including requirements such as low leakage inductance and interwinding capacitance with the experience to meet international safety standards.

ADDITIONAL RESOURCES

For more information on Bourns' resistive and inductive components, visit Bourns online at:

www.bourns.com