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Step-By-Step Process Of Designing Flyback-Converter Coupled Inductors (Part 2): A Practical Example

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In part 1[1] of this two-part article, I provided a review of magnetic theory and foundational design calculations for designing a coupled inductor magnetic for a flyback converter. In this second installment, I will show how to apply these calculations in an example design. Specifically I will calculate inductance, wire gauge and ac-dc losses, flux density, core and bobbin fill factor, and inductance rolloff; select a core material; and show how to achieve good coupling by properly layering the primary and secondary windings on a bobbin.

Design Flow Diagram

Fig. 1 shows the design flow diagram for a coupled inductor. Before starting the design, you must obtain a specification that includes the inductance, turns ratio, peak and RMS currents, output power, and frequency of the flyback converter being designed. You can select a core based on the output power, but there are a number of tradeoffs you'll need to make to determine which core to use for a given application. (For more information, see section 4 of reference 1.)

The bottom line is that there is no way to directly calculate the parameters for the optimum core for a given application; there are too many tradeoffs involved. The best you can hope for is to get close.

When it comes to core selection, there is no replacement for experience. The knowledge gained from iterating through a design many times and building and testing multiple designs to see which works best is invaluable. I have found by experience that economical flat design (EFD) cores allow easier interleaving of the secondary winding between the two halves of the primary because the winding window is wide—I'll address this topic more extensively later on.

The core and bobbin combinations that lend themselves to proper layering of the windings on the bobbin yield better coupling and lower leakage. These are two very important parameters when designing a flyback magnetic.

Once you have the core and inductance, you can calculate the wire losses and flux density. If the turns don't fit evenly on the bobbin, you may need to change the core gap, which in turn changes the inductance factor Al, to get the right number of turns on the bobbin to fit evenly. If the flux density is too high, you may need a *bigger core or a different core material*.

After determining the core and material, you can then calculate the bobbin factor. If the bobbin factor is too high or if the turns don't lie properly on the bobbin, you can change the gap of the core so that the bobbin will take more or fewer turns to achieve the same inductance.

You can also change the wire gauge to fit on the bobbin properly. That is why this is an iterative process; there are a number of ways to solve the same problem. Only you can determine which solution is best for a given application.

To summarize, here are the steps, called out in the design flow diagram (Fig. 1) for the coupled-inductor design example:

1. Complete inductor specification.
2. Pick a core (see section 4 of reference 2).
3. Calculate the inductance and turns based on inductance factor, Al.
4. Calculate the copper loss.
5. Calculate the flux density and core loss.
6. Calculate the bobbin fit factor.

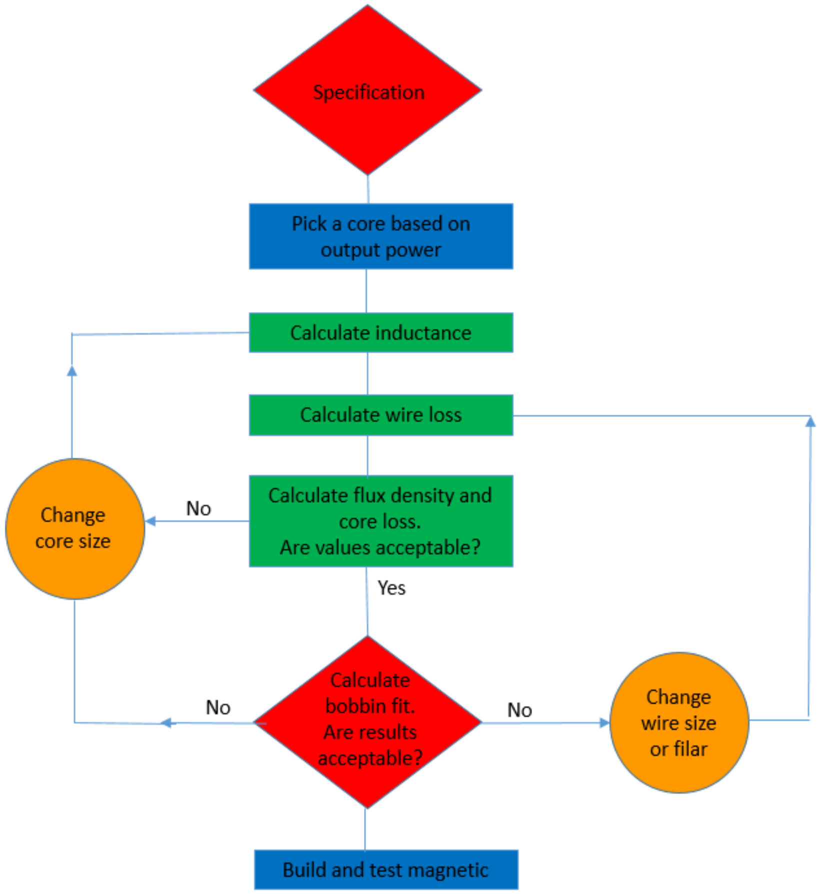


Fig. 1. Design flow for a coupled inductor.

Flyback Coupled-Inductor Example

Step 1: Complete Specification

Before designing a coupled inductor, you will need the information in Table 1. The values shown in the table are usually generated as part of the initial flyback converter specification.

Table 1. Magnetic specification with values for the design example.

General	
Topology	Quasi-resonant flyback
Main output power	10 W
Maximum switching frequency at full load	140 kHz
Input	
Minimum input voltage	85 Vac, 76 Vdc
Maximum input voltage	265 Vac, 375 Vdc
Primary peak current	1.155 A
Primary RMS current	0.425 A
Outputs	
Secondary output voltage	5 V
Secondary peak current	13.861 A
Secondary RMS current	5.382 A
Bias voltage	16 V
Bias current	50 mA

Inductance and turns ratio	
Primary inductance	190.918 µH
Leakage inductance	3.818 µH
Primary-to-secondary turns ratio	12

Step 2: Pick A Core

Core selection is based on size, material and gap. These factors work together to determine the flux density, core loss and inductance per turn of the core. Reference 2 has a lot of information about core selection, particularly section 4, "Power Transformer Design."

Unfortunately, as I said before, there is no replacement for experience when it comes to core selection. Magnetic design is a very iterative process; the more experience you have, the fewer iterations you will have to do. For this example, I selected a Ferroxcube EFD20 core using 3F3 material, setting the gap to obtain an Al = 82 x 10^{-9}.

As shown in the data from Ferroxcube in Table 2, the Al required is not standard; I had to custom-cut the core gap to obtain the necessary Al. The core gap was not determined initially, but only after iteration, by determining the number of turns that would fit in one layer on the bobbin.

Table 2. Manufacturer's core and material data (courtesy of Ferroxcube).

GRADE	A_L (nH)	μ_e	TOTAL AIR GAP (µm)	TYPE NUMBER
3C90	63 ±3%(1)	≈ 76	≈ 960	EFD20/10/7-3C90-E63
	100 ±3%	≈ 121	≈ 510	EFD20/10/7-3C90-A100
	160 ±5%	≈ 193	≈ 280	EFD20/10/7-3C90-A160
	250 ±8%	≈ 302	≈ 160	EFD20/10/7-3C90-A250
	315 ±10%	≈ 380	≈ 120	EFD20/10/7-3C90-A315
	1300 ±25%	≈ 1570	≈ 0	EFD20/10/7-3C90
3C94	63 ±3%(1)	≈ 76	≈ 960	EFD20/10/7-3C94-E63
	100 ±3%	≈ 121	≈ 510	EFD20/10/7-3C94-A100
	160 ±5%	≈ 193	≈ 280	EFD20/10/7-3C94-A160
	250 ±8%	≈ 302	≈ 160	EFD20/10/7-3C94-A250
	315 ±10%	≈ 380	≈ 120	EFD20/10/7-3C94-A315
	1300 ±25%	≈ 1570	≈ 0	EFD20/10/7-3C94
3C95 des	1540 ±25%	≈ 1865	≈ 0	EFD20/10/7-3C95
3C96 des	1200 ±25%	≈ 1450	≈ 0	EFD20/10/7-3C96
3F3	63 ±3%(1)	≈ 76	≈ 960	EFD20/10/7-3F3-E63
	100 ±3%	≈ 121	≈ 510	EFD20/10/7-3F3-A100
	160 ±5%	≈ 193	≈ 280	EFD20/10/7-3F3-A160
	250 ±8%	≈ 302	≈ 160	EFD20/10/7-3F3-A250
	315 ±10%	≈ 380	≈ 120	EFD20/10/7-3F3-A315
	1200 ±25%	≈ 1450	≈ 0	EFD20/10/7-3F3

Step 3: Calculate The Inductance And Turns Based On Al

Given that Lp = 190 µH, and from iteration, set Al = 82 x 10^{-9} and solve for Np:

$$\mathrm{Np} = \left(\frac{\mathrm{Lp}}{\mathrm{Al}}\right)^{1/2} = 48 \text{ primary turns}$$

Solve for secondary turns where the turns ratio = 12-to-1:

$$\mathrm{Ns} = \frac{\mathrm{Np}}{\text{Turns ratio}} = 4$$

Step 4: Calculate The Copper Loss

Determine the primary wire area, where J = 400 A/cm^2:

$$\text{Primary wire area} = \frac{\text{Iprimary\_rms}}{\text{J}} = 1.0625 \times 10^{-3}\ \text{cm}^2$$

Determine the skin depth, where f = 140 kHz:

$$\text{Skin depth at } 100°\text{C} = \frac{7.6}{\sqrt{\text{f}}} = 0.0203\ \text{cm}$$

You will need calculations for a wire gauge range from 26 AWG to 32 AWG because you have not yet determined the correct wire gauge. See Table 3.

Table 3. Copper wire data.[3]

AWG	Copper diameter in centimeters (cm)	Copper radius in centimeters (cm)	Copper area in centimeters squared (cm^2)	Ω/cm at 100°C
26	0.04	0.02	0.001287	0.001789
28	0.032	0.016	0.00081	0.002845
30	0.025	0.0125	0.000509	0.004523
32	0.02	0.01	0.00032	0.007192

Determine the annular inner ring diameter in centimeters squared (cm^2) at 100°C:

$$\text{Area ring 26 AWG } 100°\text{C} = \pi \times [\text{radius\_26 AWG}^2 - (\text{radius}_{26\text{AWG}} - \text{skin depth } 100°\text{C})^2]$$
$$= 1.256 \times 10^{-3}\ \text{cm}^2$$

Keep in mind that when the skin depth is greater than the radius of the wire, you must set the ring area equal to the area of the wire.

$$\text{Area ring 28 AWG } 100°\text{C} = \text{area 26 AWG cm}^2 = 8.1 \times 10^{-4}\ \text{cm}^2$$

$$\text{Area ring 30 AWG } 100°\text{C} = \text{area 30 AWG cm}^2 = 5.09 \times 10^{-4}\text{cm}^2$$

$$\text{Area ring 32 AWG } 100°\text{C} = \text{area 32 AWG cm}^2 = 3.2 \times 10^{-4}\text{cm}^2$$

Determine the ratio of Rdc to Rac for a range of wire gauges from 26 AWG to 32 AWG:

$$\text{Rskin 26 AWG } 100°\text{C} = \frac{\text{Area 26 AWG cm}^2}{\text{Area ring 26 AWG } 100°\text{C cm}^2} = 1.035$$

$$\text{Rskin 28 AWG } 100°\text{C} = \frac{\text{Area 28 AWG cm}^2}{\text{Area ring 28 AWG } 100°\text{C}} = 1$$

$$\text{Rskin 30 AWG } 100°\text{C} = \frac{\text{Area 30 AWG cm}^2}{\text{Area ring 30 AWG } 100°\text{C}} = 1$$

$$\text{Rskin 32 AWG } 100°\text{C} = \frac{\text{Area 32 AWG cm}^2}{\text{Area ring 32 AWG } 100°\text{C}} = 1$$

Determine the wire resistance in ohms per centimeter (Ω/cm) caused by skin effects:

$$\text{R copper 26 AWG } 100°\text{C} = \text{wire 26 AWG cm } 100°\text{C} \times \text{Rskin 26 AWG } 100°\text{C} = 1.833 \text{ x } 10^{-3}\ \Omega/\text{cm}$$

$$\text{R copper 28 AWG } 100°\text{C} = \text{wire 28 AWG cm } 100°\text{C} \times \text{Rskin 28 AWG } 100°\text{C} = 2.845 \text{ x } 10^{-3}\ \Omega/\text{cm}$$

$$\text{R copper 30 AWG 100°C} = \text{wire 30 AWG cm 100°C} \times \text{Rskin 30 AWG 100°C} = 4.523 \text{ x } 10^{-3}\ \Omega/\text{cm}$$

Determine the number of primary wires in parallel required:

$$\text{Number of wires primary 26 AWG} = \frac{\text{Area required primary cm}^2}{\frac{\text{Area 26 AWG cm}}{\text{Rskin 26 AWG 100°C}}} = 0.906$$

$$\text{Number of wires primary 28 AWG} = \frac{\text{Area required primary cm}^2}{\frac{\text{Area 28 AWG cm}}{\text{Rskin 28 AWG 100°C}}} = 1.49$$

$$\text{Number of wires primary 30 AWG} = \frac{\text{Area required primary cm}^2}{\frac{\text{Area 30 AWG cm}}{\text{Rskin 30 AWG 100°C}}} = 2.371$$

Determine the primary copper loss, where the number of primary wires = 1 and the length per turn in millimeters from Fig. 2 is 34.1 mm:

$$\text{Length per turn cm} = \frac{34.1 \text{ mm}}{10} = 3.41 \text{ cm}$$

$$\text{Rcopper primary 26 AWG} = \text{R copper 26 AWG 100°C} \times \text{Np} \times \frac{\text{Length per turn cm}}{\text{Number of primary wires}} = 0.300\ \Omega$$

$$\text{Pcopper primary loss 26 AWG} = \text{Iprimary rms}^2 \times \text{Rcopper primary 26 AWG} = 0.0542 \text{ W}$$

Determine secondary wire AWG and losses, where Ns = 4 and J = 400 A/cm^2:

$$\text{Secondary wire area} = \frac{\text{Isecondary\_rms}}{\text{J}} = 14 \times 10^{-3} \text{ cm}^2$$

$$\text{Number of wires secondary 28 AWG} = \frac{\text{Secondary wire area cm}^2}{\frac{\text{Area 28 AWG cm}}{\text{Rskin 28 AWG 100°C}}} = 16.667$$

Only five wires of 28 AWG in parallel will fit on the chosen bobbin. Through iteration and winding factor calculations, I determined that the number of wires in the secondary = 5.

$$\text{Rcopper seconday 28 AWG} = \text{R copper 28 AWG 100°C} \times \text{Ns} \times \frac{\text{Length per turn cm}}{\text{Number of wires secondary}} = 7.761 \times 10^{-3}\ \Omega$$

$$\text{Pcopper secondary loss 28 AWG} = \text{Isecondary rms}^2 \times \text{Rcopper secondary 28 AWG} = 0.226 \text{ W}$$

Determine the bias wire AWG and losses. Only one wire of 32 AWG will fit on the chosen bobbin. Through iteration and winding factor calculations, I determined that the number of bias wires = 1.

$$\text{Number of turns bias winding (Nsb)} = \text{Ns} \times \frac{\text{Vbias}}{\text{Vout}} \approx 13$$

$$\text{Rcopper bias 32 AWG} = \text{R copper 32 AWG 100°C} \times \text{Nsb} \times \frac{\text{Length per turn cm}}{\text{Number of bias wires}} = 225 \times 10^{-3}\ \Omega$$

$$\text{Pcopper bias loss 32 AWG} = \text{Ibias rms}^2 \times \text{Rcopper bias 32 AWG} = 4.197 \times 10^{-4} \text{ W}$$

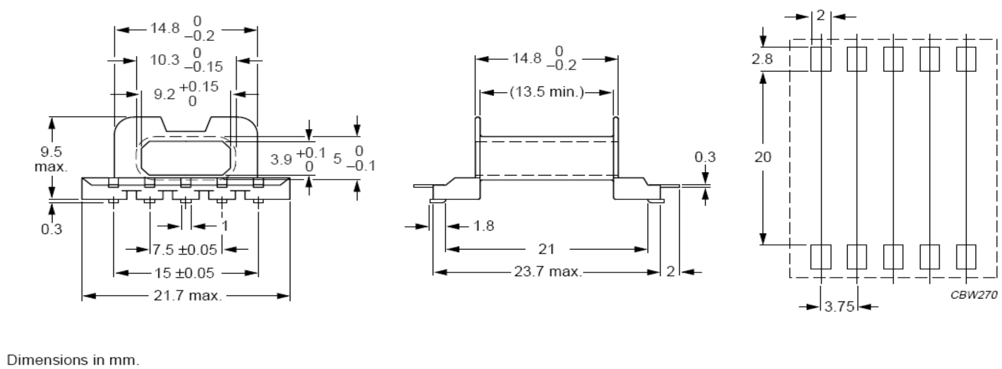


Fig.4 EFD20/10/7 coil former (SMD); 10-solder pads.

Winding data and area product for EFD20/10/7 coil former (SMD) with 10-solder pads

NUMBER OF SECTIONS	WINDING AREA (mm^2)	MINIMUM WINDING WIDTH (mm)	AVERAGE LENGTH OF TURN (mm)	AREA PRODUCT Ae x Aw (mm^4)	TYPE NUMBER
1	27.7	13.5	34.1	859	CPHS-EFD20-1S-10P

Fig. 2. Winding data (courtesy of Ferroxcube).

Step 5: Calculate The Flux Density And Core Loss

Table. 4 is data from magnetic manufacturer Ferroxcube's data book.

Table. 4. Effective core parameters for an EFD20 style core (courtesy of Ferroxcube).

Symbol	Parameter	Value		Unit
Σ(l/A)	Core factor (C1)	1.52		mm^{-1}
V_e	Effective volume	1460		mm^3
l_e	Effective length	47.0		mm
A_e	Effective area	31.0		mm^2
A_{min}	Minimum area	29		mm^2
m	Mass of core half	≈3.5		g

Given Ae = 0.31 cm^2 from Table 4, Np = 48 from step 3, $Ipri_p$ = 1.155 A from Table 1 and Tonmax = 2.9 x 10^{-6} (which corresponds to Ton at the max duty cycle):

$$\mathrm{Bac} = \frac{\mathrm{Vinmin} \times \mathrm{Tonmax}}{\mathrm{Ae} \times \mathrm{Np}} \times 10^8 = 1.4817 \times 10^3\ \mathrm{Gauss} = 148.17\ \mathrm{mT}$$

$$\mathrm{Bmax} = \frac{\mathrm{Lp} \times \mathrm{Ipri\_p}}{\mathrm{Ae} \times \mathrm{Np}} \times 10^8 = 1.4817 \times 10^3\ \mathrm{Gauss} = 148.17\ \mathrm{mT}$$

For a flyback converter running in discontinuous current mode, the ac flux density, βac, is equal to the maximum flux density, βmax. Fig. 3 shows that the saturation point for the given core is about 250 mT. So this design is about 60% of maximum flux.

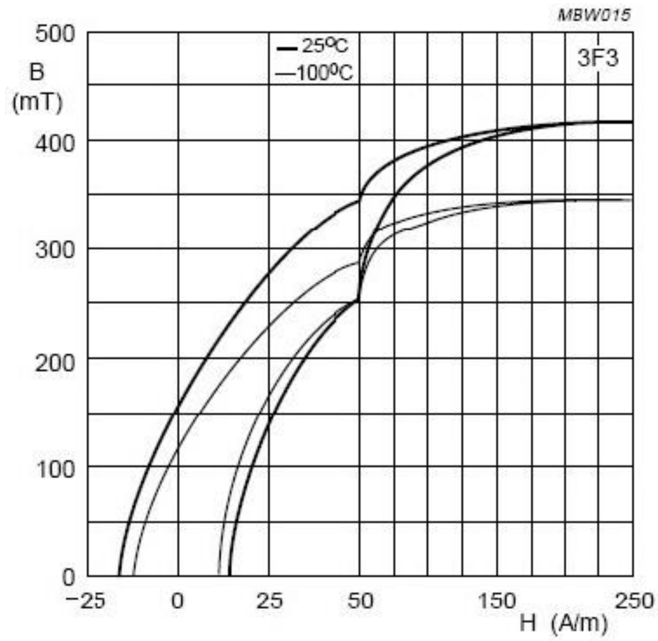


Fig. 3. BH curves (courtesy of Ferroxcube).

Determine the core loss:

$$\beta\text{unipolar} = \frac{\beta\text{ac}}{2} = 740.85\ \text{Gauss}$$

$$\beta\text{unipolar mT} = \frac{\beta\text{unipolar Gauss}}{10} = 74.085\ \text{mT}$$

From Fig. 4, obtain the core power dissipation in kilowatts per cubic meters (kW/m^3). In this case, with a peak flux density of ≈74 mT at a switching frequency of 140 kHz, Pcore ≈ 60 kW/m^3.

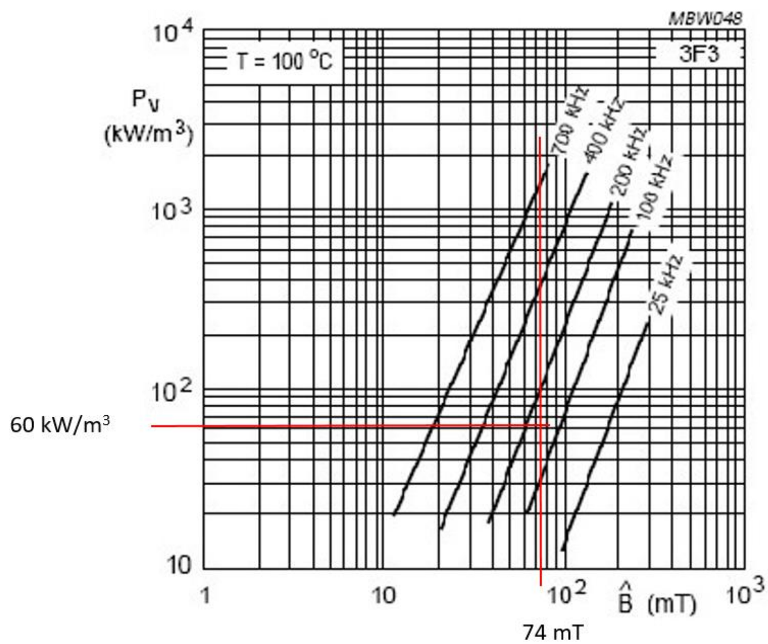


Fig. 4. Specific power loss as a function of peak flux density with frequency as a parameter (courtesy of Ferroxcube).

From the specific power loss we can calculate core loss for a core of a given volume. However, per Table 4, Ve is given in cubic millimeters (mm^3), so first you must convert Ve to cubic meters (m^3):

$$\text{Ve per m}^3 = \frac{\text{Ve}}{1{,}000^3} = 1.46 \times 10^{-6}\ \text{m}^3$$

Then core loss is simply

$$\text{Pcore loss} = \text{Pcore} \times \text{Ve per m}^3 = 88\ \text{mW}$$

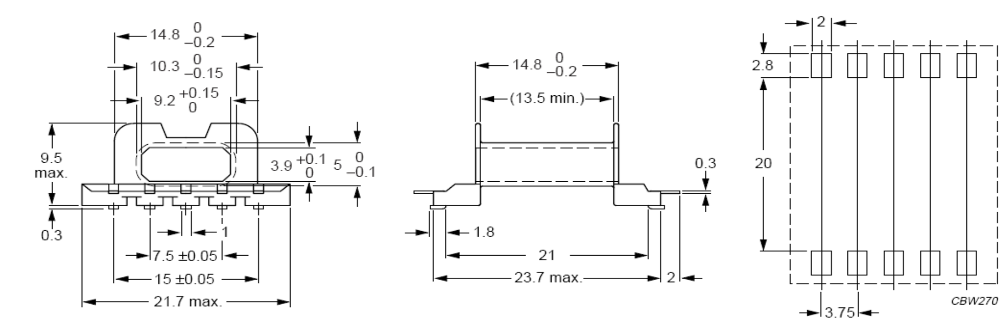
Adding the Pcore loss + the primary winding loss + the secondary winding loss + the bias winding loss = the total winding and power dissipation: 367 mW.

Step 6: Calculate The Bobbin-Fit Factor

Use Table 5 along with the manufacturer's data shown in Fig. 2 (repeated below as Fig. 5) to calculate the bobbin-fit factor.

Table 5. Copper wire dimensions.

AWG	**Copper diameter in centimeters (cm) with insulation**	**Copper area in square centimeters (cm^2) with insulation**
26	0.046	0.001671
28	0.037	0.001083
30	0.03	0.000704
32	0.024	0.000459



Dimensions in mm.

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Winding data and area product for EFD20/10/7 coil former (SMD) with 10-solder pads

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1	27.7	13.5	34.1	859	CPHS-EFD20-1S-10P

Fig. 5. Winding data (courtesy of Ferroxcube).

$$\text{Bobbin width cm} = 1.35\ \text{cm}$$

$$\text{Turns per layer 26 AWG} = \frac{\text{Bobbin width cm}}{\text{Diameter 26 AWG with isolation}} - 2 \approx 27$$

$$\text{Turns per layer 28 AWG} = 24 \qquad \text{Turns per layer 30 AWG} = 43$$

$$\text{Winding area in cm}^2 = 0.277\ \text{cm}^2$$

$$\text{Buildup in cm} = \frac{\text{Winding area cm}^2}{\text{Bobbin width cm}} = 0.205\ \text{cm}$$

$$\text{Layers} = \frac{\text{Buildup in cm}}{\text{Diameter 26 AWG with isolation}} \approx 4$$

$$\text{Total bobbin turns 26 AWG} = \text{turns per layer} \times \text{layers} = 108$$

$$\text{Total turns needed} = \text{Np} \times \text{number of primary wires} + \text{Ns} \times \text{number of secondary wires} + \text{Nsb} \times \text{number of bias wires} = 81$$

$$\text{Winding factor} = \frac{\text{Total turns needed}}{\text{Total bobbin turns 26AWG}} = 0.75$$

This is a worst-case winding factor, given the fact that the secondary windings are made up of 28 AWG and 32 AWG. On the secondary layer there are 20 turns of 28 AWG (which fills 59% of the layer) and 13 turns of 32 AWG (which fills 24% of the layer) for a total fill factor of 83%. This should leave enough room for tape.

Fig. 6 shows the layout for the coupled inductor. This is an interleaved winding in that the primary is split into two layers, with the secondary in the middle. This gives very good coupling and low leakage inductance. The secondary layer has both the secondary winding and the bias winding. The black lines show how the tape should run.

- First layer: 24 turns of 26 AWG single filar, half of primary.
- Second layer: Four turns of 28 AWG five filar secondary, plus 13 turns of 32 AWG bias winding.
- Third layer: 24 turns of 26 AWG single filar, half of primary.

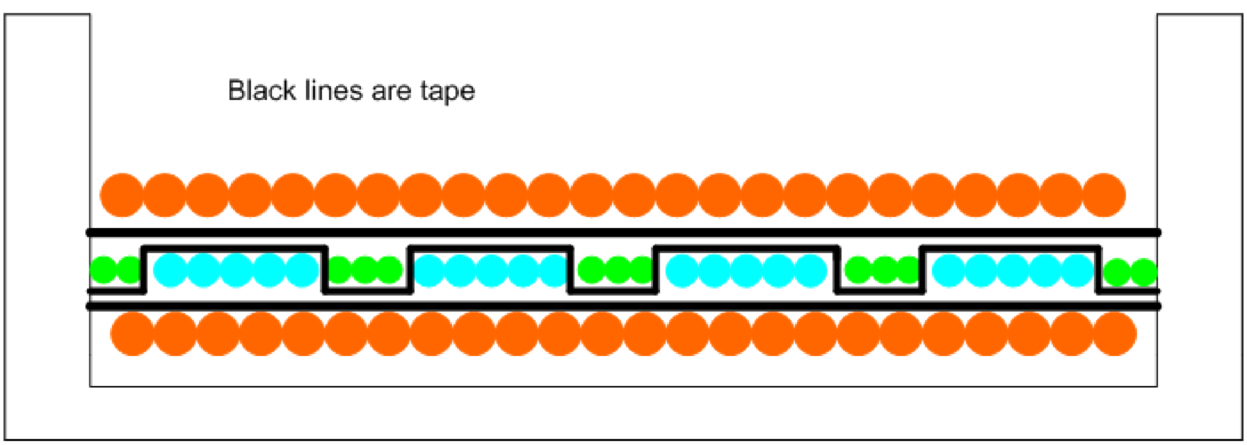

Fig. 6. Coupled inductor layout.

Conclusion

Designing magnetics can be complicated. As a young engineer, I was given the task of designing a flyback coupled inductor. I looked all over for information on how to do this, but was unsuccessful. I had to learn everything on my own, and it took a lot of discussions with experienced engineers to come up with an approach.

So I decided, why not make life a little easier for other engineers by writing this article? This article attempts to give a simple and straightforward approach to designing a coupled inductor. By following the steps I outlined, you should be able to move forward and design your own magnetic.

This article is an adaptation of the paper, "Practical Magnetic Design: Inductors and Coupled Inductors," created for the 2012 Texas Instruments Power Supply Design Seminar.[6]

References

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About The Author

Louis Diana is an analog field applications engineer and senior member technical staff at Texas Instruments. Louis joined TI in February of 2004 and holds more than 30 years of power design experience. Prior to his time at TI, he designed power systems for space satellites. Louis holds two U.S. patents along with a B.S. in electrical engineering from the New York Institute of Technology.

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