Structured Design of Switching Power Magnetics

Design of switching power magnetics can be accomplished in a relatively simple manner by limiting magnetic configurations to a few structures. These structures have been chosen not only for their versatility, but for their low cost. Coilcraft's "Power Magnetics" catalog and Document 128 contain dimensional information as well as design information in the form of design curves. By using these curves, the complete transformer can be designed.

STRUCTURE SIZE

The first step in the design consists of choosing a minimum structure size consistent with the output power required. The approximate power capabilities of each structure are given in the specifications. If five or six outputs are required, a larger structure may be required to allow the copper to fit in the available winding area.

TURN COUNT

For a given core size, the ability of an inductor to operate without saturating is directly proportional to its turn count N_P. The normal saturation specification is E-T or volt-time rating. The E-T rating is the maximum voltage, E, which can be applied over a time of T seconds. (The E-T rating is identical to the product of inductance L and peak current I.) Equation 1 defines a minimum value of N_P for a volt-time product of E-T:

$$N_P = \frac{E\text{–}T \times 10^8}{BA_E} \qquad (1)$$

Where:

- E–T is the minimum volt-time rating in volt-seconds.
- B is the maximum allowable flux density.
- A_E is the effective cross sectional core area (cm^2).

Equation 1 is plotted on page 9 of this catalog, assuming B = 3200 Gauss. To use Figure 1, locate the required E–T rating on the vertical axis. Move horizontally to the curve. From this point drop vertically to the horizontal axis and read N_P. This value for N_P should allow non-saturating operation to 100° C. For lower operating temperatures, a slightly smaller value for N_P can be used.

Secondary turn count is a function of duty cycle and primary turn count. For a flyback system:

$$N_S = N_P \frac{(V_s + V_D)}{V_L D} (1\text{–}D) \qquad (2)$$

For a forward converter:

$$N_S = N_P \frac{(V_s + V_D)}{V_L D} \qquad (3)$$

Where:

- N_S is the secondary turn count.
- V_S is the secondary output voltage.
- V_D is the voltage drop across the rectifier and choke in the secondary.
- D is the duty cycle.
- V_L is the voltage across the primary.

For the flyback system, D is seldom greater than .5. For the forward converter, D is the duty cycle of the rectified output, and can approach .9 for a wave rectified output. Known conditions should be used to calculate N_S. At minimum input voltage and maximum output power, the supply will operate at maximum duty cycle. This is therefore a good point to use to determine N_S.

WIRE SIZE

Once all the turn counts have been determined, wire size must be chosen for each winding. Power losses in the transformer windings cause

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a temperature rise ΔT in the transformer. The amount of loss will depend on how much current is being drawn from the winding, how many feet of wire and what wire size is used. The power loss is a function of the amount of resistance in the wire. This resistance is composed of a DC resistance, R_{DC} and an AC resistance, R_{AC}. At 20 kHz, wire smaller than about 20 AWG will have $R_{DC} \gg R_{AC}$, and R_{AC} can effectively be ignored. For larger wire sizes, it may be necessary to use stranded wire or foil. Let's assume R_{AC} is small and can be ignored. Then all of the copper losses will be due to R_{DC}. This power loss should be distributed among the primary and secondary windings to minimize hot spots in the transformer. The temperature rise in a given structure is a function of thermal resistance and surface area.

For flyback transformers:

$$R_{DC} = \frac{3P_L}{D_1 I^2} \tag{4}$$

For the forward converter:

$$R_{DC} = \frac{P_L}{I_{av}^2} \tag{5}$$

Where:

- P_L is the maximum allowable power loss in the winding.
- I is the peak current in the winding.
- D_1 is the duty cycle of the current ramp
- I_{av} is the average current in the winding.

Once R_{DC} for all the windings has been calculated, the wire size can be determined using the average length per turn listed for each coil form. Divide the R_{DC} by the product of the average length per turn times the turn count. This value of R_{DC} per foot can be found listed in any wire manufacturer's data sheet. From their data, choose a wire size that has the same or slightly less R_{DC} per foot.

WILL IT FIT?

After the wire sizes have been determined, it is necessary to check fit, to see if the available winding area will accommodate the copper calculated in the previous steps. The available winding area for the structure chosen is given on its data sheet. The area each winding occupies is determined. Then the areas occupied by each winding are added. To this total, an area allowing for interwinding insulation and shielding is added. The grand total is then compared to the available winding area. If the area of the windings is greater than the allowed structure area, either wire size must be reduced, or a larger structure must be chosen. Of course, a reduction in wire size will result in increased losses in the transformer.

To determine winding area, use Figure 2 from Coilcraft's data sheet "Switchmode Transformer Ferrite E Core Packages," Document 128. The first step is to determine the turns per layer, n_l. Using Figure 2, draw a horizontal line from the required wire size on the vertical axis. Where this line intersects the curve in part A, drop vertically to the horizontal axis and read n_l. Next find the number of layers, l, by dividing turns N by n_l.

$$l = \frac{N}{n_l} \tag{6}$$

If l contains a fractional part, round l up to the next integer value.

Next find the area per layer, a_l. Multiply the winding width as shown on the individual coilform drawing by the wire diameter. Multiply this value by the number of layers to find the area occupied by the winding.

$$a_m = l a_l \tag{7}$$

Repeat this procedure for each winding and add to find the total area occupied by the windings.

$$a_t = a_{m1} + a_{m2} + a_{m3} + ... \tag{8}$$

The total winding area, a_t, added to the area of insulation and shielding, a_i, must be less than the allowed structure area, a_w.

$$a_w \geq a_t + a_i \tag{9}$$

a_w is given in the structure data sheet.

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AIR GAP

Now that the structure size and winding turn counts have been found, the air gap must be determined. For most forward converters, inductance should be as large as possible and no air gap is required. However for flyback transformers and chokes, an air gap is necessary. For economic reasons, E cores are usually gapped in all three legs. The amount of gap per leg can be found from Figure 3 on the structure data sheet. To use Figure 3 it is necessary to convert inductance, L, to inductance factor, A_L.

$$A_L = \frac{L}{N^2} \tag{10}$$

Draw a horizontal line from the vertical axis at the A_L value obtained from equation 10. At the intersection of this line and the curve, drop vertically to the horizontal axis and read g, the required gap per leg.

SUMMARY

The transformer should now be ready to wind. Sufficient insulation must be used for the required voltage isolation. Windings must be uniform and carefully wound to minimize leakage inductance. Some small adjustments may be necessary to obtain the exact results desired, but this procedure will provide a good approximation.

GLOSSARY

A_E - Effective cross sectional core area
A_L - Inductance factor (nanoHenrys per turn squared)
a_i - Area of insulating system
a_l - Winding area of one layer
a_m - Winding area of m^{th} winding (m = 1,2,3 etc)
a_t - Total winding area
a_w - Available winding area
B - Maximum flux density (Gauss)
D - Duty cycle
D_1 - Duty cycle of current ramp
$E\text{-}T$ - Volt-time product (Volt-Seconds)
g - Air gap (per leg)
I - Peak current
I_{av} - Average current
L - Inductance
l - Layers
N - Turns
N_P - Primary turn count
N_S - Secondary turn count
n_l - Turns per layer
P_L - Power loss
R_{AC} - AC Resistance
R_{DC} - DC Resistance
ΔT - Temperature rise
V_D - Output rectifier and choke voltage drop
V_L - Input rectified line voltage
V_S - Output voltage

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