

Structured Design of Switching Power Transformers



Transformer Design Procedure

Design of switching power transformers can be accomplished in a relatively simple manner by limiting magnetic configurations to a few core and coilform structures. These structures have been chosen both for their versatility and their low cost. Dimensional information as well as design information in the form of design curves for the chosen structures may be found at the end of this document. By using these curves, the complete transformer can be designed.

Step 1. Structure size

The first step in the design is choosing a minimum structure size consistent with the output power required. The approximate power capabilities of each structure are provided in Table 1. If five or six outputs are required, a larger structure may be required to allow the copper along with insulation and winding crossovers to fit in the available winding area.

Step 2. Primary 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 $E-T$:

$$N_p = \frac{E-T \times 10^8}{BA_E} \quad (1)$$

Where:

- $E-T$ = the minimum volt-time rating in volt-seconds
- B = the maximum allowable flux density
- A_E = the effective cross sectional core

Equation 1 is plotted for the specific chosen core structures shown in Figure 1. *These plots are for $B = 3000$ Gauss, which will prevent the core from saturation and typically will provide low core loss suitable for operation in the range of 200 kHz to 400 kHz. For higher frequencies, a higher primary turn count should be used to ensure low core loss. To use this chart, 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 deter-*

mine N_p . This value for N_p should allow non-saturating operation to 100°C with reasonable core loss.

Step 3. Secondary turn count

Secondary turn count is a function of duty cycle and primary turn count.

For a flyback system:

$$N_s = N_p \frac{(V_s + V_D)}{V_p D} (1-D) \quad (2)$$

For a forward converter:

$$N_s = N_p \frac{(V_s + V_D)}{V_p D} \quad (3)$$

Where:

- N_p = the primary turn count.
- N_s = the secondary turn count.
- V_s = the secondary output voltage.
- V_D = the voltage drop across the rectifier and choke in the secondary.
- D = the duty cycle.
- V_p = the voltage across the primary.

For the flyback system, D is seldom greater than 0.5. For the forward converter, D is the duty cycle of the rectified output, and can approach 0.9 for a wave rectified output. Known conditions should be used to calculate N_s . For example, at minimum input voltage and maximum output power, the supply will operate at maximum duty cycle. This is a good point to use to determine N_s .

Step 4. 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 a temperature rise, ΔT , in the transformer. The amount of loss depends on how much current is being drawn from the winding, the length 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 low frequencies and small wire sizes, for example #30 AWG at 250 kHz, $R_{DC} \gg R_{AC}$, and R_{AC} can effectively be ignored. For larger wire sizes and high frequencies, >500 kHz, 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.

In order to calculate the wire size, it is necessary to assign an acceptable power loss P_L to each winding. The power loss is then used to calculate the required DCR.

For flyback transformers:

$$R_{DC} = \frac{3P_L}{D_1 I^2} \quad (4)$$

For the forward converter:

$$R_{DC} = \frac{P_L}{I_{AV}^2} \quad (5)$$

Where:

P_L = the maximum allowable power loss in the winding.

I = the peak current in the winding.

D_1 = the duty cycle of the current ramp

I_{AV} = 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 (Table 1) 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.

Step 5. 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 shown in Table 1. The area each winding occupies must be determined, then the areas occupied by each winding are added. To this total, an area allowing for interwinding insulation should be added. Assume about 10% of the available area for insulation. 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 results in increased losses in the transformer.

A fit of 100% of the available space should not be used. To accommodate winding crossovers, interwinding insulation and spaces between turns, it is recommended that a fit factor no greater than about 80% be used. For transformers with multiple outputs this factor may need to be reduced further.

To determine winding area, use the curves in Figure 2. From this chart the number of turns per layer n_l can be read directly. Next find the number of layers, l , by dividing turns N by n_l .

$$l = \frac{N}{n_l} \quad (6)$$

Next, find the area per layer, a_l . Multiply the winding width as shown on the individual coilform drawing (Figures 4 and 5) by the wire diameter. Multiply this value by the number of layers to find the area occupied by the winding.

$$a_m = l a_l \quad (7)$$

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

$$a_t = a_{m1} + a_{m2} + a_{m3} + \dots \quad (8)$$

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

$$a_w \geq a_t + a_i \quad (9)$$

Step 6. Inductance

For a forward converter it is generally preferable to have as much inductance as possible. For a flyback, however it is necessary to calculate the desired primary inductance based on the amount of energy stored per cycle ($1/2 LI^2$) required to deliver an average output power P_o .

$$L = \frac{\eta(V \times t_{on})^2 f}{2P_o} \quad (10)$$

Where:

L = inductance

η = transformer efficiency (assume >0.9)

V = minimum DC input voltage applied to the primary

t_{on} = maximum on time for input voltage

f = switching frequency

P_o = output power

Step 7. 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 and for the best reduction of EMI, cores are usually gapped in the center leg. The amount of gap can be found in Figure 3. To use this chart it is necessary to convert inductance, L , to inductance factor, A_L .

$$A_L = \frac{L}{N^2} \quad (11)$$

Summary

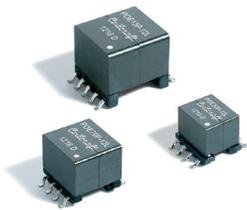
The transformer should now be ready to wind. Sufficient insulation must be used for the required voltage isolation. Windings must be uniform and carefully wound to minimize leakage inductance. Some small adjustments may be necessary to obtain the exact results desired, but this procedure will provide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

Appendix – Core data

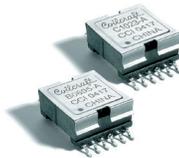
EP and EFD series cores have proven to be both versatile and cost effective for transformer design of about 50 Watts or less. EP cores are suitable for lower power and offer the smallest pcb area. EFD cores offer the lowest profile (height). The recommended core sizes are shown in Table 1.

Table 1. Core Data

	EP7	EP10	EP13	EFD15	EFD17	EFD20	EFD25
Power capacity @ 100 kHz	10 W	12 W	20 W	20 W	25 W	30 W	50 W
a_e (effective cross-sectional area) – cm ²	0.10	0.11	0.20	0.14	0.21	0.31	0.59
l_e (mean magnetic path length) – cm	1.57	1.92	2.47	3.29	3.88	4.61	5.65
a_w (bobbin winding area) – cm ²	0.045	0.122	0.141	0.173	0.198	0.286	0.4175
Required board space – mm	13.2 × 10.9	15.2 × 12.7	17.8 × 13.5	22.0 × 17.2	24.1 × 17.4	30.0 × 20.6	32.7 × 26.8
Maximum height – mm	9.0	11.0	12.3	8.5	10.0	11.4	14.0
Average length per turn – cm	1.79	2.15	2.38	2.60	3.15	3.90	4.64



EP core styles



EFD core styles

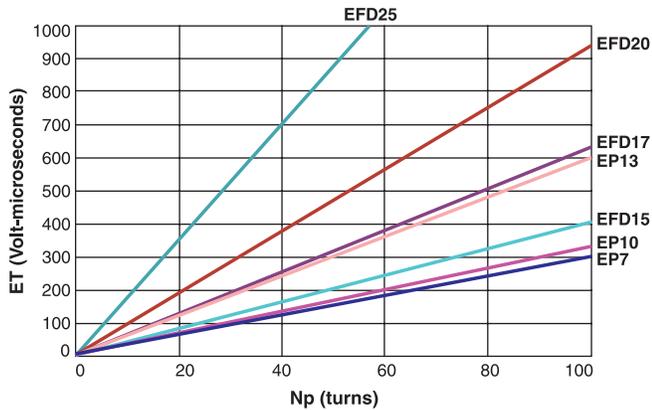


Figure 1. Volt time product vs primary turns

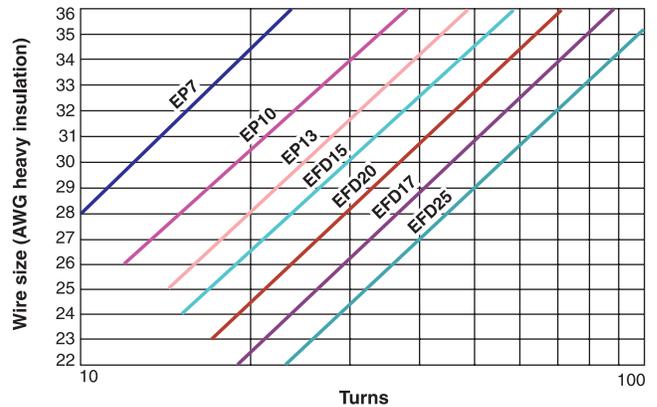


Figure 2. Turns per layer vs wire size

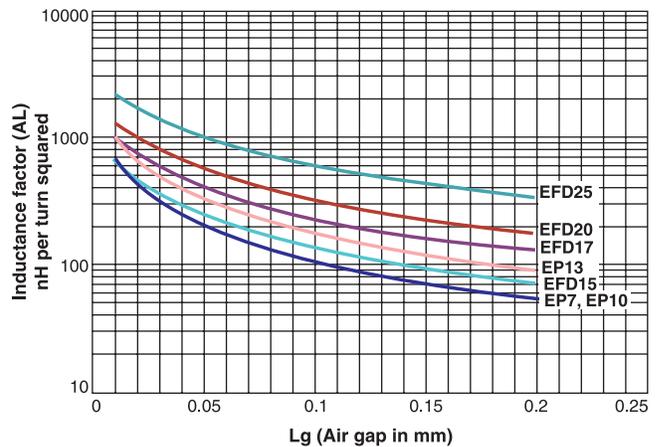


Figure 3. Inductance factor vs air gap

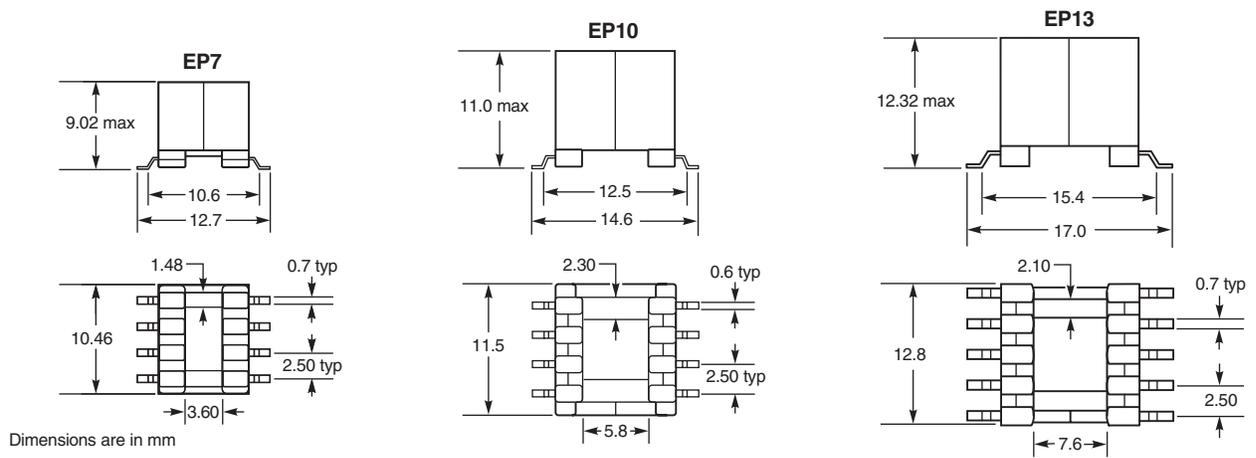


Figure 4. EP core dimensions

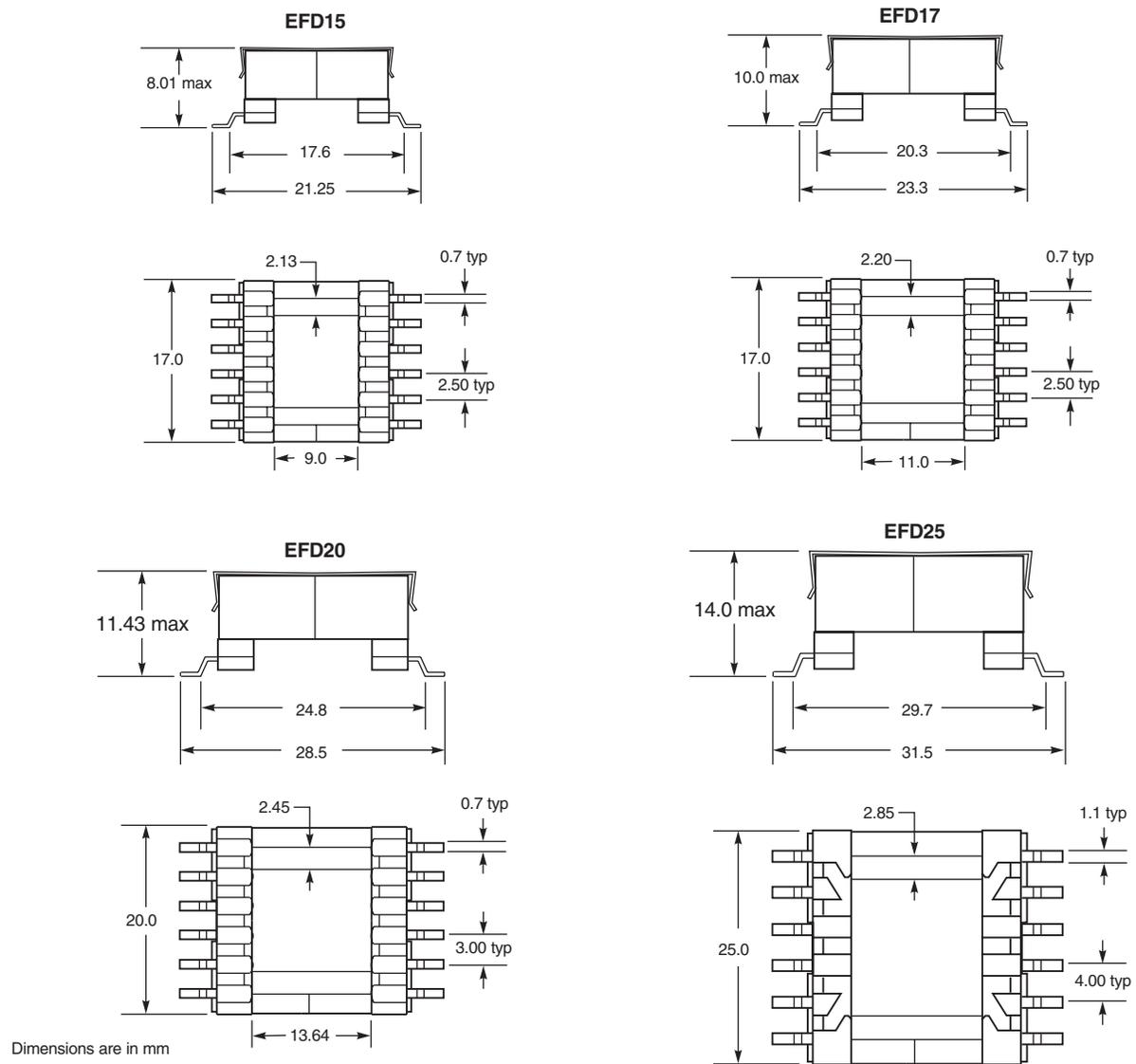


Figure 5. EFD core dimensions