POWER TRANSFORMER DESIGN FOR SWITCHING POWER SUPPLIES

This design procedure applies to transformers used for coupling and isolation, in which energy storage is undesired. The 'transformers' used in Flyback circuits are actually coupled inductors used primarily to store energy and whose design procedure is covered in Section M6 of this manual.

Symbols, definitions, equations and various core and wire data used in this section are defined in Reference Sections M1, M2, and M3.

1. Determine the Flux Density Excursion

The first step in this design procedure is to define the flux density swing, ΔB, that will occur with normal steady-state operation. The transformer should be designed to operate with ΔB as large as possible, resulting in fewer turns in the winding, increased power rating and lower leakage inductance. In practice, ΔB is limited either by core saturation, B_{sat}, or core losses.

In most bridge, half-bridge and full-wave center-tap circuits, the transformer is symmetrically driven so that the flux swing is symmetrical around zero on the B-H characteristic. This allows a theoretical maximum ΔB of 2 times B_{sat}. In most single-ended circuits, such as the forward converter, the flux excursion is entirely within the first quadrant of the B-H characteristic, from zero toward B_{sat}. This limits the maximum ΔB to B_{sat} instead of 2 times B_{sat}, so that the transformer has only half the power handling capability in single-ended applications.

In voltage-fed circuits (which includes all of the commonly used buck regulator topologies), the volt-seconds applied to the primary establish ΔB in accordance with Faraday's Law. With normal steady state operation of the switching supply, the primary volt-seconds will be constant, equal to $V_{in(min)}t_{on(max)}$ or $V_{in(max)}t_{on(min)}$.

With the simple duty cycle control method used in most control ICs, it is possible to have nearly twice the normal primary volt-seconds, $V_{in(max)}t_{on(max)}$, during startup or after a large step increase in load current (assuming $V_{in(max)}$ is nearly double $V_{in(min)}$ in most off-line applications). This means that the normal steady-state maximum flux density, B_{max}, cannot be greater than one-half B_{sat} or the core will saturate under transient conditions. With volt-second control (voltage feed-forward) available in the UC1840 control IC, the maximum volt-seconds can be clamped to a level only slightly greater than normal, permitting larger B_{max} and ΔB values, improving transformer performance.

B_{sat} for most power ferrites such as 3C8 material is above 0.3 Tesla (3000 Gauss). In push-pull voltage-fed applications without volt-second clamping, B_{max} is limited to 0.15 T and ΔB to 0.3 T. Core losses at 50 KHz will then be comparable to copper losses. At higher frequencies, core losses increase necessitating further reduction of ΔB.

In single-ended circuits without volt-second clamping, B_{max} of 0.15 T results in a ΔB of 0.15 T. Core losses at 50 KHz will be almost

negligible with this small flux swing. With volt-second clamping, possible with the UC1840 control IC, a ΔB of nearly 0.3 T is acceptable, significantly reducing transformer size.

In current-fed circuits (all boost topologies and the Coupled Inductor, Current Driven Buck regulator), ΔB is governed by the volt-seconds on the secondary windings which are clamped to the output voltages. Since the volt-seconds are totally independent of input voltage variations, current-fed circuits can operate with B_{max} close to B_{sat} (except for core loss considerations) without the need for volt-second clamping.

2. Select the Core

The second step is to select a specific core that is able to support the required volt-seconds without saturating and with acceptable core losses and winding losses. This can be accomplished by an iterative process involving trial solutions. However, Equation 1 quickly points toward an approximate core size, by relating the area product, AP, of the core window and magnetic cross section to the requirements of the application. Equation 1 is from Equation A6 derived at the end of this section.

$$AP = A_w A_e = \left(\frac{P_{in}\,10^4}{K_t\,K_u\,K_p\,450\,\Delta B\,2\,f}\right)^{1.143} = \left(\frac{11.1\,P_{in}}{K\,\Delta B\,f}\right)^{1.143}\ \text{cm}^4 \qquad (1)$$

where $P_{in} = P_o/\eta$ = Power Output/Efficiency
$K_t = I_{in}/I_p$, Topology Factor
$K_u = A_w'/A_w$, Window Utilization Factor (0.40)
$K_p = A_p/A_w'$, Primary Area Factor
$K = K_t\,K_u\,K_c$
J = Current Density (450 A/cm²)
see Table I below and Section M2, page 2.

Equation 1 is based on the assumptions that the windings occupy 40% of the window area, the primary and secondary winding areas are proportioned for equal power density and the windings are operated at a current density appropriate for a 30°C temperature rise with natural convection cooling.

TABLE I — K Factors

		K	K_t	K_u	K_p
Forward Converter	SE/SE	0.141	0.71	0.40	0.50
Bridge/Half Bridge	SE/CT	0.165	1.0	0.40	0.41
Full Wave Center-Tap	CT/CT	0.141	1.41	0.40	0.25

3. Design the Windings

For voltage-fed circuits, Equation 2 calculates the minimum number of primary turns, N_p, required to support the normal volt-seconds. (For the half-bridge configuration, use $V_{in(min)}$ equal to 1/2 the total input voltage, throughout these calculations.)

$$t_{on(max)} = D_{max}/f = 0.5/f \quad \text{sec}$$

$$N_p > \frac{V_{in(min)}\,t_{on(max)}}{\Delta B\,A_e} \times 10^4 = \frac{5000\,V_{in(min)}}{\Delta B\,A_e\,f} \qquad (2)$$

The required primary to secondary turns ratio, n, is calculated at minimum V_{in} and maximum duty cycle. Vf is the rectifier forward drop. The factor 0.9 allows for inaccuracies and transistor storage times:

$$n = \frac{N_p}{N_s} = \frac{0.9\,[V_{in(min)} - V_{CE(sat)}]\,D}{V_o + V_F} \qquad (3)$$

Calculate the number of turns required for the lowest voltage secondary, and round up to the next larger integral number of turns:

$$N_s = \mathrm{Integer}(N_p/n) \qquad (4)$$

Recalculate the primary turns:

$$N_p = n\,N_s \qquad (5)$$

The RMS current in the primary winding, Ip, is:

$$I_{p(max)} = I_{in(max)}/K_t = \frac{P_{in(max)}}{V_{in(min)}\,K_t} \quad \mathrm{A} \qquad (6)$$

Find the maximum current density for 30°C rise with natural convection cooling for the core AP found in Equation 1:

$$J_{max} = 450\,AP^{-.125} \quad \Omega/cm^2 \qquad (7)$$

The minimum primary wire area, A_{xp}, is:

$$A_{xp} = I_{p(max)}/J_{max} \quad cm^2 \qquad (8)$$

Look up the primary AWG wire size in the Wire Table in Section M2 under AREA, Copper.

The maximum RMS secondary current, I_s, occurs at 50% duty cycle:

$$I_{s(max)} = I_{o(max)}/1.414 \quad \mathrm{A} \qquad (9)$$

Minimum secondary wire area, A_{xs}, is:

$$A_{xs} = I_{s(max)}/J_{max} \quad cm^2 \qquad (10)$$

Look up the secondary AWG wire size in the Wire Table. Avoid using wire larger than AWG 18 to avoid severe eddy current losses and to make winding easier. When a larger wire is called for, use multiple paralleled turns of finer wire with equivalent total cross-section area. For high current secondaries, thin copper strip is often used.

Double-check the wire fit in the window. The total copper are of all windings should be less than 40% of the total window area of the core. Don't forget to double the number of turns of all Center-Tap windings.

$$A_w' > N_p A_{xp} + N_s A_{xs} \quad cm^2 \qquad (11)$$

Calculate Losses and Temperature Rise

The total losses in the windings can be approximated by doubling the primary losses. Use the mean length per turn, l_t, and Ω/cm at 100°C from the Wire Table in Section M2:

$$P_w = 2\,I_p^2\,N_p\,l_t\,(\Omega/cm) \quad \text{watts} \qquad (12)$$

The total core losses for 3C8 ferrite are obtained from from Figure 1 in Section M3. The flux density axis of this graph assumes the transformer is operating with a symmetrical flux swing about the origin, so enter the graph with ΔB/2. With the forward converter, this assumes that the losses swinginging symmetrically about the origin are approximately the same as the same swing offset into the first quadrant. Multiply the core loss per unit volume from the graph by the core volume to obtain the core loss, P_c.

Total transformer losses are:

$$P_t = P_w + P_c \quad \text{watts} \qquad (13)$$

The temperature rise of the core for natural convection cooling is calulated as follows, where A_s is the surface area of the transformer.

$$\Delta\theta = \frac{850\,P_t}{A_s} \quad {}^{o}C \qquad (14)$$

TRANSFORMER CORE AREA PRODUCT DERIVATION

The DC (average) component of the switching regulator input current, I_{in}:

$$I_{in} = P_{in}/V_{in}\,, \qquad P_{in} = P_o/\eta$$

Maximum RMS primary current, $I_{p(max)}$, occurs with minimum V_{in}. Topology Factor K_t relates the RMS primary winding current to the DC input current:

$$I_{p(max)} = I_{in(max)}/K_t = \frac{P_{in(max)}}{V_{in(min)}\,K_t} \qquad \text{(A1)}$$

The number of turns that will fill the available primary window area when operated at current density J depends upon the Window Utilization Factor, K_u, and the Primary Area Factor, K_p:

$$N_p I_p = A_p J = K_u K_p A_w J, \qquad N_p = K_u K_p A_w J/I_p$$

Substituting for I_p from Equation (1):

$$N_p = V_{in(min)}\,K_t\,K_u\,K_p\,A_w\,J/P_{in(max)}, \qquad A_w = \frac{N_p\,P_{in(max)}}{V_{in(min)}\,K_t\,K_u\,K_p\,J} \qquad \text{(A2)}$$

From Faraday's Law:

$$E\,dt = N\,d\Phi$$

$$V_{in}\,t_{on} = N_p\,\Delta B\,A_e, \qquad A_e = \frac{V_{in(min)}\,t_{on(max)}}{N_p\,\Delta B}$$

Forward Converter: $t_{on(max)} = D_{max}/f = 0.5/f = 1/2f$
Bridge, Half Bridge, C.T.: $t_{on(max)} = D_{max}/2f = 1/2f$
ΔB is the total flux density swing during normal operation.

$$A_e = \frac{V_{in(min)}}{N_p\,\Delta B\,2\,f} \qquad \text{(A3)}$$

Combining (2) and (3):

$$AP = A_w A_e = \frac{P_{in(max)}}{K_t\,K_u\,K_p\,J_{max}\,\Delta B\,2\,f} \quad m^4 \qquad \text{(A4)}$$

To obtain Area Product in cm^4, use J in A/cm^2 and multiply result by 10^4.

Maximum current density, J_{max}, for 30°C rise with natural convection cooling for a core with Area Product of 1 cm^4 is 450 A/cm^2 (2900 A/in^2). Maximum current density decreases as core size increases because the heat dissipating surface area increases less than the heat producing volume:

$$J_{max} = 450\,AP^{-.125} \quad A/cm^2 \qquad \text{(A5)}$$

Substituting (5) into (4):

$$AP = A_w A_e = \left[\frac{P_{in}\,10^4}{K_t\,K_u\,K_p\,450\,\Delta B\,2\,f}\right]^{1.143} cm^4 \qquad \text{(A6)}$$