Chapter 13

Flyback Converter, Transformer Design

The author would like to thank **Dr. V. Vorperian**, Senior Engineer, Power and Sensor Electronics Group, Jet Propulsion Laboratory (JPL), **Richard Ozenbaugh** of Linear Magnetics and **Kit Sum**, Senior Consultant, for their help with the Flyback design equations.

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Introduction

The principle behind Flyback converters is based on the storage of energy in the inductor during the charging, or the "on period," t_{on}, and the discharge of the energy to the load during the "off period," t_{off}. There are four basic types that are the most common, energy storage, inductor type converter circuits.

1. Step down, or buck converter.
2. Step up, or boost converter.
3. Inverting, buck-boost converter.
4. Isolated, buck-boost converter.

Energy Transfer

Two distinct modes of operation are possible for the Flyback switching converters, shown in Figure 13-1:

Discontinuous Mode All energy stored in the inductor is transferred to an output capacitor and load circuit before another charging period occurs. This topology results in a smaller inductor size, but puts a larger stress on the capacitor and switching device.

Continuous Mode Energy stored in the inductor is not completely transferred to the output capacitor and load circuit before another charging period occurs.

The total period is:

$$T = \frac{1}{f} \quad [13\text{-}1]$$

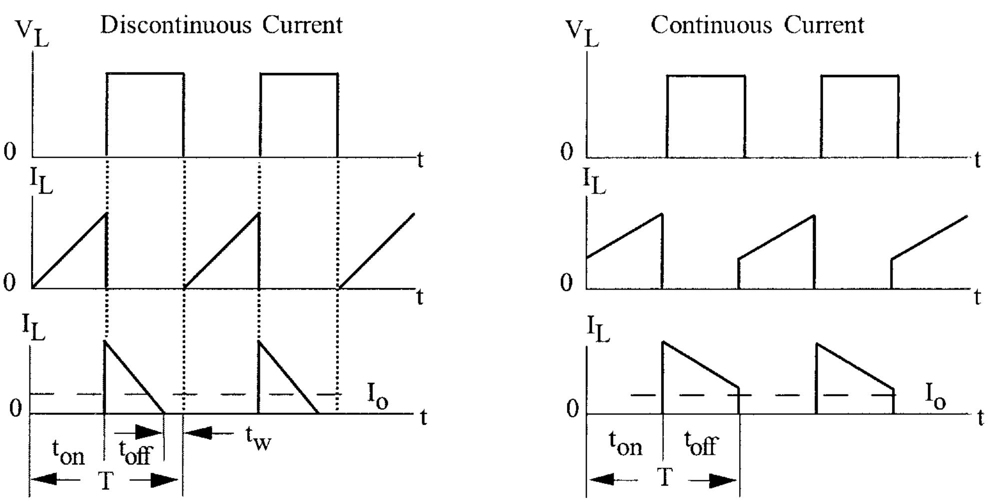

Figure 13-1. Comparing Discontinuous and Continuous Current Waveforms.

Discontinuous Current Mode

In the Discontinuous Mode, a smaller inductance is required, but the penalty results in higher peak currents in the switching transistor. As a consequence, the winding losses are increased because of the higher rms values, due to the higher peak currents. This also results, in a higher ripple current and ripple voltage in the input and output capacitor, and gives added stress to the switching transistor. The advantage of this circuit, other than having a smaller inductor, is that when the switching device is turned on, the initial current is zero. This means the output diode has completely recovered, and the switching device does not momentarily turn on into a short. This diode recovery reduces the EMI radiation. The discontinuous mode converter does not exhibit the right half plane zero. Without the right half plane zero, the loop is easy to stabilize.

Continuous Current Mode

In the Continuous Mode, a larger inductor is required; this results in a lower peak current at the end of the cycle than in a discontinuous system of equivalent output power. The Continuous Mode demands a high current flowing through the switch during turn-on, and can lead to high switch dissipation. The continuous mode converter does exhibit the right half-plane zero. With the right half-plane zero, the loop becomes very difficult to stabilize for a wide range of input voltage. The relationship between the B-H loops for continuous and discontinuous operation is shown in Figure 13-2.

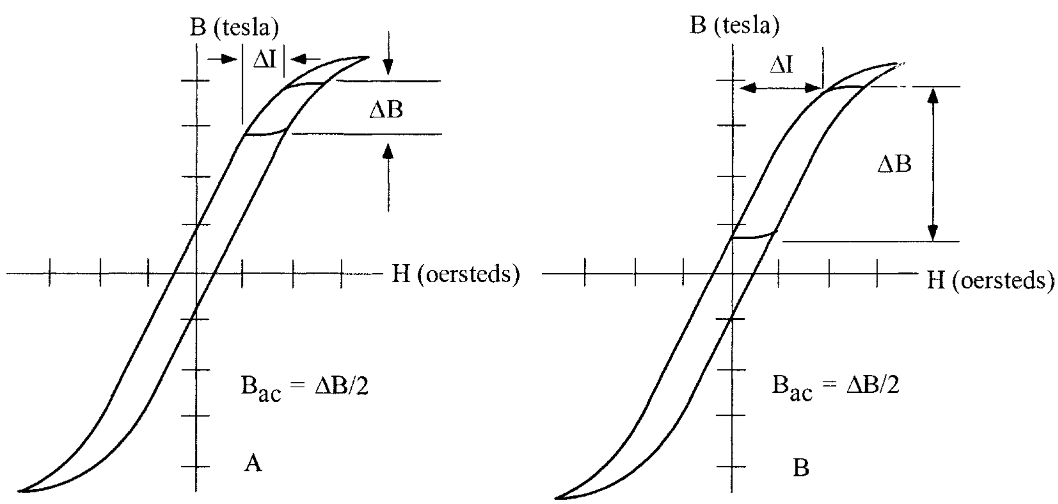

Figure 13-2. Continuous (A) and Discontinuous (B), B-H Loops, Showing ΔB and ΔI.

Continuous and Discontinuous Boundary

When the load current increases, the control circuit causes the transistor to increase the "on time," t_{on}. The peak current in the inductor will increase, resulting in a steady reduction in the dwell time, t_w. When the load current increases to a critical level, t_w becomes zero, and the discontinuous boundary is reached. If the load current is further increased, the inductor current will no longer discharge to zero on every cycle, and continuous current operation results.

The Buck Converter

The Buck Converter is shown in Figure 13-3. The output voltage of this converter is always less than the input voltage. In the buck circuit, the transistor switch, Q1, is placed in series with the dc input voltage. The transistor, Q1, interrupts the dc input voltage, providing a variable-width pulse, (duty ratio), to a simple averaging, LC, filter. When the transistor switch, Q1, is closed, the dc input voltage is applied across the output filter inductor, L1, and the current flows through the inductor to the load. When the switch is open, the energy, stored in the field of the inductor, L1, maintains the current through the load. The discontinuous voltage and current waveforms are shown in Figure 13-4, and the continuous waveforms in Figure 13-5.

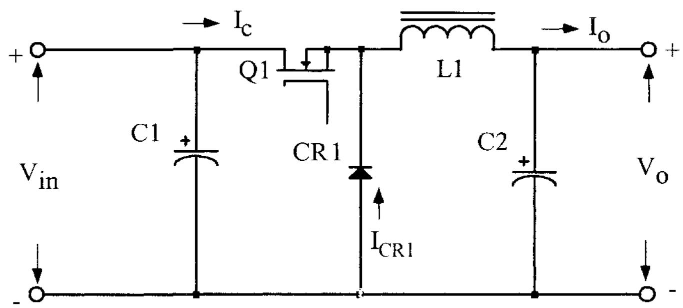

Figure 13-3. Schematic of a Buck Switching Converter.

Discontinuous Current Buck Converter Design Equations

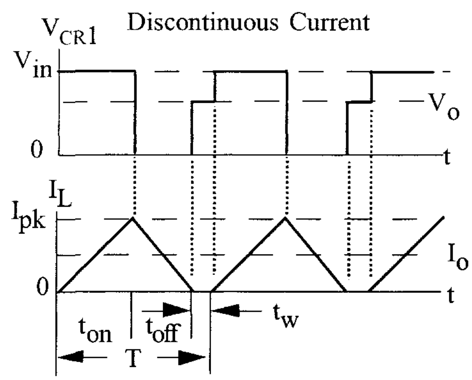

Figure 13-4. Discontinuous, Current Buck Converter Waveforms.

Inductance, L:

$$L_{\max} = \frac{(V_o + V_d)T(1 - D_{\max} - D_w)}{2I_{o(\max)}}, \quad \text{[henrys]} \quad [13\text{-}2]$$

Maximum duty ratio:

$$D_{(\max)} = \frac{V_o(1 - D_w)}{(\eta V_{in(\min)})} \quad [13\text{-}3]$$

Maximum on time:

$$t_{on(\max)} = T D_{\max} \quad [13\text{-}4]$$

Maximum off time:

$$t_{off(\max)} = T(1 - D_{\min}) \quad [13\text{-}5]$$

The inductor peak current, $I_{(pk)}$:

$$I_{(pk)} = \frac{2 I_{o(\max)}}{(1 - D_w)} \quad [13\text{-}6]$$

Continuous Current Buck Converter Design Equations

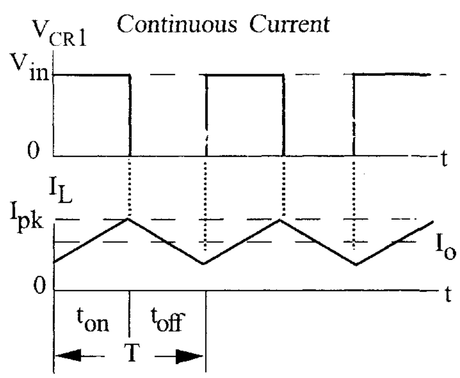

Figure 13-5. Continuous Current Buck Converter Waveforms.

Inductance, L:

$$L = \frac{V_o T(1 - D_{\min})}{2 I_{o(\min)}}, \quad [\text{henrys}] \quad [13\text{-}7]$$

Maximum duty ratio:

$$D_{(\max)} = \frac{V_o}{(\eta V_{in(\min)})} \quad [13\text{-}8]$$

Minimum duty ratio:

$$D_{(\min)} = \frac{V_o}{\left(\eta V_{in(\max)}\right)} \quad [13\text{-}9]$$

Maximum on time:

$$t_{on(\max)} = T D_{\max} \quad [13\text{-}10]$$

Maximum off time:

$$t_{off(\max)} = T\left(1 - D_{\max}\right) \quad [13\text{-}11]$$

The inductor delta current, ΔI:

$$\Delta I = \frac{\left(T V_{in(\max)} D_{(\min)}\right)\left(1 - D_{(\min)}\right)}{L} \quad [13\text{-}12]$$

The inductor peak current, $I_{(pk)}$:

$$I_{(pk)} = I_{o(\max)} + \frac{\Delta I}{2} \quad [13\text{-}13]$$

The Boost Converter

The Boost Converter is shown in Figure 13-6. The output voltage of this converter is always greater than the input voltage. The boost converter stores energy in the inductor, L1, and then, delivers the stored energy along with the energy from the dc source to the load. When the transistor switch, Q1, is closed, current flows through inductor, L1, and the transistor switch, Q1, charging inductor, L1, but does not deliver any current to the load. When the switch is open, the voltage across the load equals the dc input voltage plus the energy stored in inductor, L1. The energy is stored in, L1, then discharges, delivering current to the load. The discontinuous voltage and current waveforms are shown in Figure 13-7, and the continuous waveforms in Figure 13-8.

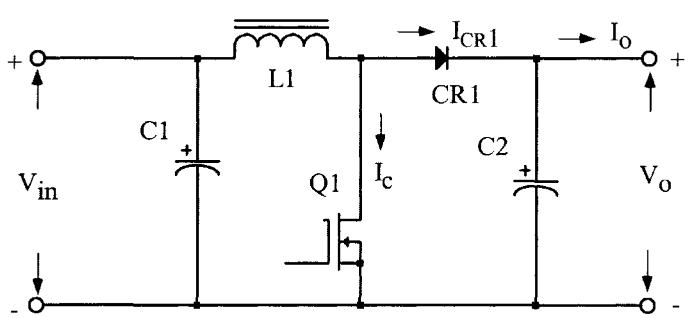

Figure 13-6. Schematic of a Boost Switching Converter.

Discontinuous Current Boost Converter Design Equations

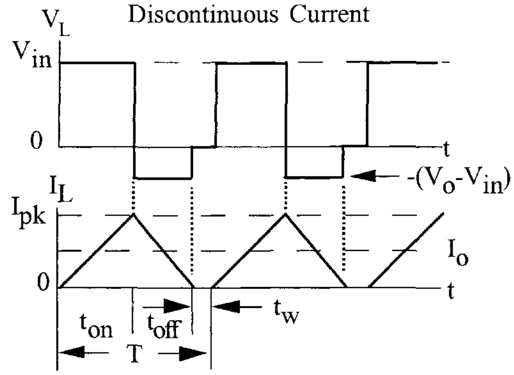

Figure 13-7. Discontinuous, Current Boost Converter Waveforms.

Inductance, L:

$$L_{max} = \frac{(V_o + V_d) T D_{(max)} (1 - D_{max} - D_w)^2}{2 I_{o(max)}}, \quad \text{[henrys]} \quad [13\text{-}14]$$

Maximum duty ratio:

$$D_{(max)} = (1 - D_w)\left(\frac{V_o - V_{in(min)} + V_d}{V_o}\right) \quad [13\text{-}15]$$

Minimum duty ratio:

$$D_{(min)} = (1 - D_w)\left(\frac{V_o - V_{in(max)} + V_d}{V_o}\right) \quad [13\text{-}16]$$

Maximum on time:

$$t_{on(max)} = T D_{max} \quad [13\text{-}17]$$

Maximum off time:

$$t_{off(max)} = T(1 - D_{min}) \quad [13\text{-}18]$$

The inductor peak current, $I_{(pk)}$:

$$I_{(pk)} = \frac{2 P_{o(max)}}{\eta (V_o D_{(min)})} \quad [13\text{-}19]$$

Continuous Current Boost Converter Design Equations

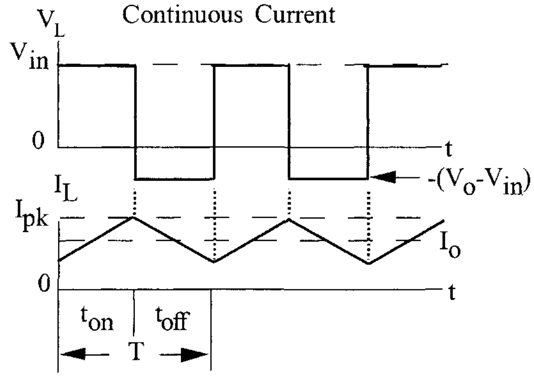

Figure 13-8. Continuous, Current Boost Converter Waveforms.

Inductance, L:

$$L = \frac{(V_o + V_d) T D_{(\min)} (1 - D_{\min})^2}{2 I_{o(\min)}}, \quad \text{[henrys]} \quad [13\text{-}20]$$

Maximum duty ratio:

$$D_{(\max)} = 1 - \left(\frac{V_{in(\min)} \eta}{V_o} \right) \quad [13\text{-}21]$$

Minimum duty ratio:

$$D_{(\min)} = 1 - \left(\frac{V_{in(\max)} \eta}{V_o} \right) \quad [13\text{-}22]$$

Maximum on time:

$$t_{on(\max)} = T D_{\max} \quad [13\text{-}23]$$

Maximum off time:

$$t_{off(\max)} = T (1 - D_{\min}) \quad [13\text{-}24]$$

The inductor delta current, ΔI:

$$\Delta I = \frac{\left(T V_{in(\max)} D_{(\min)} \right)}{L} \quad [13\text{-}25]$$

The inductor peak current, $I_{(pk)}$:

$$I_{(pk)} = \left(\frac{I_{o(\max)}}{1 - D_{(\max)}} \right) + \left(\frac{\Delta I}{2} \right) \quad [13\text{-}26]$$

The Inverting Buck-Boost Converter

The inverting buck-boost converter is shown in Figure 13-9. It is a variation of the boost circuit. The inverting converter delivers only the energy stored by the inductor, L1, to the load. The output voltage of the inverting converter can be greater, or less than, the input voltage. When the transistor switch, Q1, is closed, the inductor is storing energy, but no current is delivered to the load because diode, CR1, is back-biased. When the transistor switch, Q1, is open, the blocking diode is forward-biased and the energy stored in inductor, L1, is transferred to the load. The discontinuous voltage and current waveforms are shown in Figure 13-10 and the continuous waveforms in Figure 13-11.

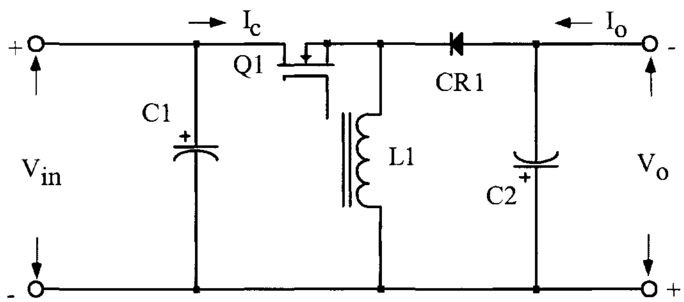

Figure 13-9. Schematic of an Inverting Buck-Boost Switching Converter.

Discontinuous Current Inverting, Buck-Boost Design Equations

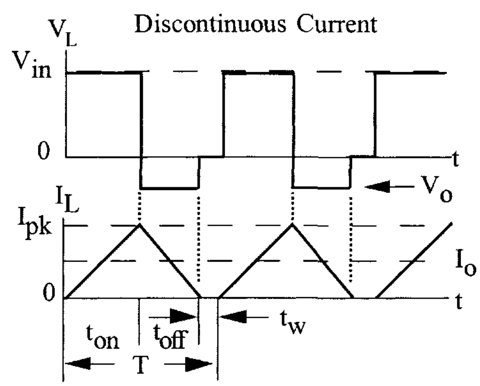

Figure 13-10. Discontinuous, Current Inverting, Buck-Boost Converter Waveforms.

Inductance, L:

$$L_{\max} = \frac{(V_o + V_d)T(1 - D_{\max} - D_w)^2}{2I_{o(\max)}}, \quad \text{[henrys]} \quad [13\text{-}27]$$

Maximum duty ratio:

$$D_{\max} = \frac{(V_o + V_d)(1 - D_w)}{\left(V_o + V_d + V_{in(\min)}\right)} \quad [13\text{-}28]$$

Minimum duty ratio:

$$D_{\min} = \frac{(V_o + V_d)(1 - D_w)}{V_o + V_d + V_{in(\max)}} \quad [13\text{-}29]$$

Maximum on time:

$$t_{on(\max)} = T D_{\max} \quad [13\text{-}30]$$

Maximum off time:

$$t_{off(\max)} = T(1 - D_{\min} - D_w) \quad [13\text{-}31]$$

The inductor peak current, $I_{(pk)}$:

$$I_{(pk)} = \frac{2P_{o(\max)}}{\left(D_{(\max)}V_{in(\min)}\eta\right)} \quad [13\text{-}32]$$

Continuous Current Inverting, Buck-Boost Design Equations

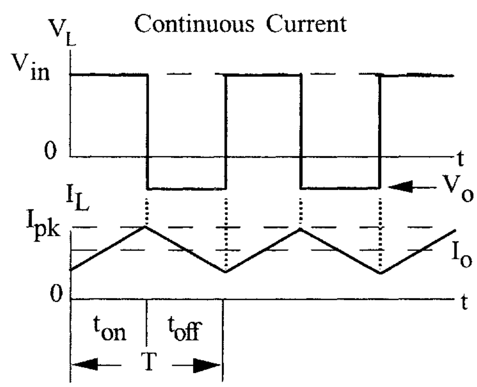

Figure 13-11. Continuous, Current Inverting, Buck-Boost Converter Waveforms.

Inductance, L:

$$L = \frac{(V_o + V_d)T(1 - D_{\min})^2}{2I_{o(\min)}}, \quad \text{[henrys]} \quad [13\text{-}33]$$

Maximum duty ratio:

$$D_{\max} = \frac{V_o}{V_o + \left(\eta V_{in(\min)}\right)} \quad [13\text{-}34]$$

Minimum duty ratio:

$$D_{\min} = \frac{V_o}{V_o + \left(\eta V_{in(\max)}\right)} \quad [13\text{-}35]$$

Maximum on time:

$$t_{on(\max)} = T D_{\max} \quad [13\text{-}36]$$

Maximum off time:

$$t_{off(\max)} = T(1 - D_{\min}) \quad [13\text{-}37]$$

The inductor delta current, ΔI:

$$\Delta I = \frac{\left(T V_{in(\max)} D_{(\min)}\right)}{L} \quad [13\text{-}38]$$

The inductor peak current, $I_{(pk)}$:

$$I_{(pk)} = \left(\frac{I_{o(\max)}}{1 - D_{\max}}\right) + \left(\frac{\Delta I}{2}\right) \quad [13\text{-}39]$$

The Isolated Buck-Boost Converter

The Isolated Buck-Boost Converter is shown in Figure 13-12. This converter can provide line isolation, and also has the capability of multiple outputs, which require only a diode and a capacitor; the filter inductor is built-in. The isolated buck-boost converter is quite popular in low power applications because of simplicity and low cost. This converter does not lend itself to the VDE specification because of the required voltage insulation between primary and secondary. Care must be taken because this leakage inductance could generate high voltage spikes on the primary. The discontinuous voltage and current waveforms are shown in Figure 13-13, and the continuous waveforms in Figure 13-14.

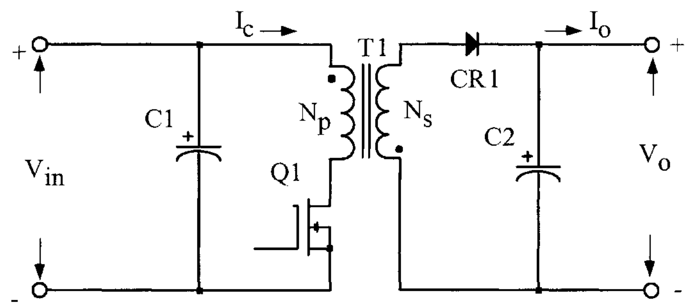

Figure 13-12. Schematic of an Isolated, Buck-Boost Switching Converter.

Discontinuous Current Isolated, Buck-Boost Design Equations

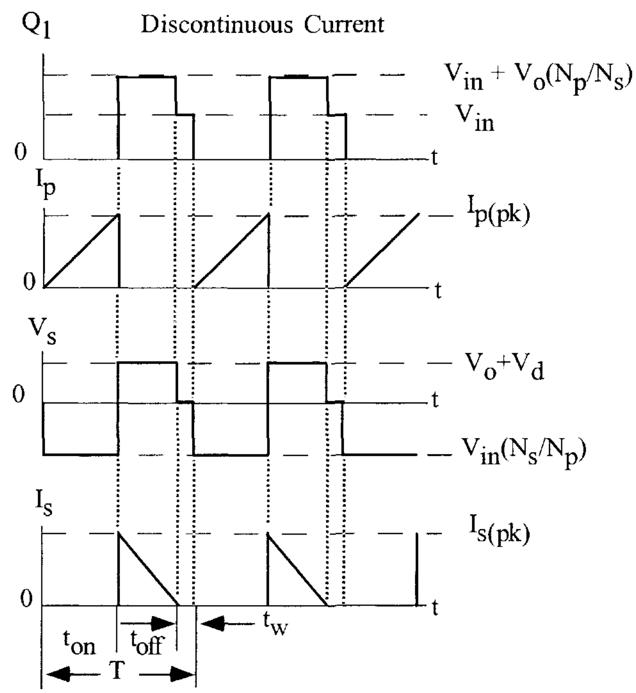

Figure 13-13. Discontinuous Current, Isolated, Buck-Boost Converter Waveforms.

Primary inductance, $L_{p(max)}$:

$$L_{p(\max)} = \frac{\left(R_{in(equiv.)}\right)T\left(D_{\max}\right)^2}{2}, \quad \text{[henrys]} \quad [13\text{-}40]$$

Maximum on time:

$$t_{on(\max)} = TD_{\max} \quad [13\text{-}41]$$

Maximum off time:

$$t_{off(\max)} = T\left(1 - D_{\min} - D_w\right) \quad [13\text{-}42]$$

Total output power:

$$P_{o(\max)} = I_{o1(\max)}\left(V_{o1} + V_d\right) + I_{o2(\max)}\left(V_{o2} + V_d\right) + ... \quad [13\text{-}43]$$

Maximum input power:

$$P_{in(\max)} = \frac{P_{o(\max)}}{\eta} \quad [13\text{-}44]$$

Equivalent input resistance:

$$R_{in(equv.)} = \frac{\left(V_{in(\min)}\right)^2}{P_{in(\max)}} \quad [13\text{-}45]$$

The primary peak current, $I_{p(pk)}$:

$$I_{p(pk)} = \frac{2P_{in(\max)}T}{T_{on(\max)}V_{in(\min)}} \quad [13\text{-}46]$$

Continuous Current Isolated, Buck-Boost Design Equations

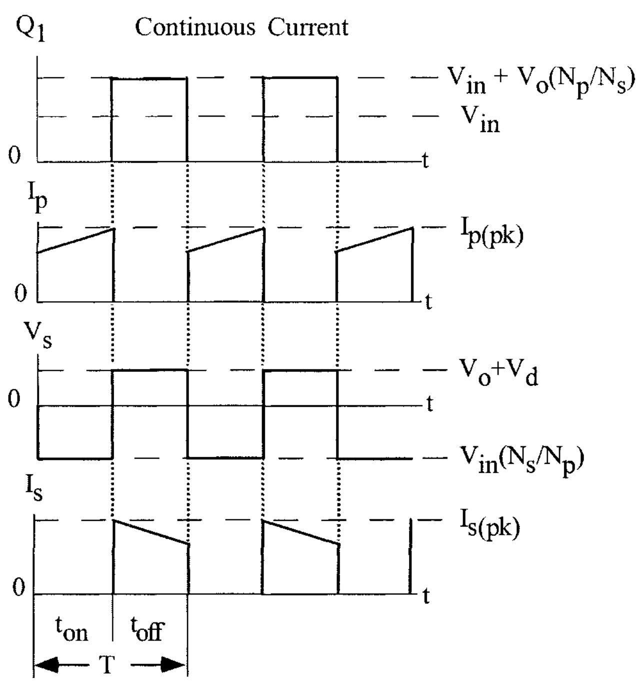

Figure 13-14. Continuous Current, Buck-Boost Converter Waveforms.

Inductance, L:

$$L = \frac{\left(V_{in(\max)} D_{(\min)}\right)^2 T}{2P_{in(\min)}}, \quad \text{[henrys]} \quad [13\text{-}47]$$

Minimum duty ratio:

$$D_{\min} = \left(\frac{V_{in(\min)}}{V_{in(\max)}}\right) D_{(\max)} \quad [13\text{-}48]$$

Maximum on time:

$$t_{on(\max)} = T D_{\max} \quad [13\text{-}49]$$

Maximum off time:

$$t_{off(\max)} = T\left(1 - D_{\min}\right) \quad [13\text{-}50]$$

Minimum output power:

$$P_{o(\min)} = I_{o1(\min)}\left(V_{o1} + V_d\right) + I_{o2(\min)}\left(V_{o2} + V_d\right) + \ldots\ldots\ldots\ldots \quad [13\text{-}51]$$

Minimum input power:

$$P_{in(\min)} = \frac{P_{o(\min)}}{\eta} \quad [13\text{-}52]$$

The inductor delta current, ΔI:

$$\Delta I = \frac{\left(T V_{in(\min)} D_{(\max)}\right)}{L} \quad [13\text{-}53]$$

The inductor peak current, $I_{(pk)}$:

$$I_{(pk)} = \left(\frac{I_{in(\max)}}{D_{\max}}\right) + \left(\frac{\Delta I}{2}\right) \quad [13\text{-}54]$$

Design Example, Buck-Boost Isolated Converter Discontinuous Current

1 Input voltage nominal, V_{in} ....= 28 volts

2. Input voltage minimum, $V_{in(min)}$ .... = 24 volts

3. Input voltage maximum, $V_{in(max)}$ .... = 32 volts

4. Output voltage, V_{o1} .... = 5 volts

5. Output current, I_{o1} .... = 2 amps

6. Output voltage, V_{o2} .... = 12 volts

7. Output current, I_{o2} .... = 0.5 amps

8. *Window utilization, K_u .... = 0.29

9. Frequency, f .... = 100 kHz

10. Converter efficiency, η .... = 90%

11. Maximum duty ratio, $D_{(max)}$ .... = 0.5

12. Dwell time duty ratio, $D_{(w)}$ .... = 0.1

13. Regulation, α .... = 1.0%

14. Operating flux density, B_m .... = 0.25 tesla

15. Diode voltage, V_d .... = 1.0 volt

*When operating at high frequencies, the engineer has to review the window utilization factor, K_u. When using a small bobbin ferrite, the ratio of the bobbin winding area to the core window area is only about 0.6. Operating at 100kHz and having to use a #26 wire, because of the skin effect, the ratio of the bare copper area is 0.78. Therefore, the overall window utilization, K_u, is reduced. The core geometries, K_g, in Chapter 3 have been calculated with a window utilization, K_u, of 0.4. To return the design back to the norm, the core geometry, K_g is to be multiplied by 1.35, and then, the current density, J, is calculated, using a window utilization factor of 0.29. See Chapter 4.

Skin Effect

The skin effect on an inductor is the same as a transformer. In the normal dc inductor, the ac current (ac flux), is much lower, and does not require the use of the same, maximum wire size. This is not the case in the discontinuous, current type, flyback converter, where all of the flux is ac and without dc. In the discontinuous, flyback design, the skin effect has to be treated just like a high frequency transformer.

There are times when the larger wire is just too difficult to wind. Large wire is not only hard to handle, but it does not give the proper lay. It is easier to wind with bi-filar or quad-filar wire, with the equivalent cross-section.

Select a wire so that the relationship between the ac resistance and the dc resistance is 1:

$$\frac{R_{ac}}{R_{dc}} = 1 \qquad [13\text{-}55]$$

The skin depth in centimeters is:

$$\varepsilon = \frac{6.62}{\sqrt{f}}, \quad [\text{cm}]$$

$$\varepsilon = \frac{6.62}{\sqrt{100,000}}, \quad [\text{cm}]$$

$$\varepsilon = 0.0209, \quad [\text{cm}]$$

Then, the wire diameter is:

$$\text{Wire Diameter} = 2(\varepsilon), \quad [\text{cm}]$$

$$\text{Wire Diameter} = 2(0.0209), \quad [\text{cm}]$$

$$\text{Wire Diameter} = 0.0418, \quad [\text{cm}]$$

Then, the bare wire area A_W is:

$$A_w = \frac{\pi D^2}{4}, \quad [\text{cm}^2]$$

$$A_w = \frac{(3.1416)(0.0418)^2}{4}, \quad [\text{cm}^2]$$

$$A_w = 0.00137, \quad [\text{cm}^2]$$

From the Wire Table in Chapter 4, Number 26 has a bare wire area of 0.00128 centimeters. This will be the minimum wire size used in this design. If the design requires more wire area to meet the specification, then, the design will use a multifilar of #26. Listed Below are #27 and #28, just in case #26 requires too much rounding off.

Wire AWG	Bare Area	Area Ins.	Bare/Ins.	μΩ/cm
#26	0.001280	0.001603	0.798	1345
#27	0.001021	0.001313	0.778	1687
#28	0.0008046	0.0010515	0.765	2142

Step No. 1 Calculate the total period, T.

$$T = \frac{1}{f} \quad [\text{seconds}]$$

$$T = \frac{1}{100000} \quad [\text{seconds}]$$

$$T = 10 \quad [\mu\text{sec}]$$

Step No. 2 Calculate the maximum transistor on time, t_{on}.

$$t_{on} = TD_{\max} \quad [\mu\text{sec}]$$

$$t_{on} = (10\text{x}10^{-6})(0.5) \quad [\mu\text{sec}]$$

$$t_{on} = 5.0 \quad [\mu\text{sec}]$$

Step No. 3 Calculate the secondary load power, P_{o1}.

$$P_{o1} = I_{o1}\left(V_{o1} + V_d\right) \quad \text{[watts]}$$
$$P_{o1} = (2)(5+1) \quad \text{[watts]}$$
$$P_{o1} = 12 \quad \text{[watts]}$$

Step No. 4 Calculate the secondary load power, P_{o2}.

$$P_{o2} = I_{o2}\left(V_{o2} + V_d\right) \quad \text{[watts]}$$
$$P_{o2} = (0.5)(12+1) \quad \text{[watts]}$$
$$P_{o2} = 6.5 \quad \text{[watts]}$$

Step No. 5 Calculate the total secondary load power, $P_{o(max)}$.

$$P_{o(\max)} = P_{o1} + P_{o2} \quad \text{[watts]}$$
$$P_{o(\max)} = 12 + 6.5 \quad \text{[watts]}$$
$$P_{o(\max)} = 18.5 \quad \text{[watts]}$$

Step No. 6 Calculate the maximum input current, $I_{in(max)}$.

$$I_{in(\max)} = \frac{P_{o(\max)}}{V_{in(\min)}\eta} \quad \text{[amps]}$$
$$I_{in(\max)} = \frac{18.5}{(24)(0.9)} \quad \text{[amps]}$$
$$I_{in(\max)} = 0.856 \quad \text{[amps]}$$

Step No. 7 Calculate the primary peak current, $I_{p(pk)}$.

$$I_{p(pk)} = \frac{2P_{o(\max)}T}{\eta V_{in(\min)}t_{on(\max)}} \quad \text{[amps peak]}$$
$$I_{p(pk)} = \frac{2(18.5)\left(10\text{x}10^{-6}\right)}{(0.9)(24)\left(5\text{x}10^{-6}\right)} \quad \text{[amps peak]}$$
$$I_{p(pk)} = 3.43 \quad \text{[amps peak]}$$

Step No. 8 Calculate the primary rms current, $I_{p(pk)}$.

$$I_{p(rms)} = I_{p(pk)}\sqrt{\frac{t_{on}}{3T}} \quad \text{[amps]}$$
$$I_{p(rms)} = 3.43\sqrt{\frac{5}{3(10)}} \quad \text{[amps]}$$
$$I_{p(rms)} = 1.40 \quad \text{[amps]}$$

Step No. 9 Calculate the maximum input power, $P_{in(max)}$.

$$P_{in(\max)} = \frac{P_{o(\max)}}{\eta} \quad \text{[watts]}$$

$$P_{in(\max)} = \frac{18.5}{0.9} \quad \text{[watts]}$$

$$P_{in(\max)} = 20.6 \quad \text{[watts]}$$

Step No. 10 Calculate the equivalent input resistance, $R_{in(equiv)}$.

$$R_{in(equiv)} = \frac{\left(V_{in(\min)}\right)^2}{P_{in(\max)}}, \quad \text{[ohms]}$$

$$R_{in(equiv)} = \frac{(24)^2}{20.6}, \quad \text{[ohms]}$$

$$R_{in(equiv)} = 28, \quad \text{[ohms]}$$

Step No. 11 Calculate the required primary inductance, L.

$$L = \frac{\left(R_{in(equiv)}\right)T\left(D_{\max}\right)^2}{2} \quad \text{[henry]}$$

$$L = \frac{(28)\left(10\text{x}10^{-6}\right)(0.5)^2}{2} \quad \text{[henry]}$$

$$L = 35 \quad [\mu\text{h}]$$

Step No. 12 Calculate the energy-handling capability in watt-seconds, w-s.

$$\text{Energy} = \frac{LI_{p(pk)}^2}{2} \quad \text{[w-s]}$$

$$\text{Energy} = \frac{\left(35\text{x}10^{-6}\right)(3.43)^2}{2} \quad \text{[w-s]}$$

$$\text{Energy} = 0.000206 \quad \text{[w-s]}$$

Step No. 13 Calculate the electrical conditions, K_e.

$$K_e = 0.145 P_o B_m^2 \text{x}10^{-4}$$

$$K_e = (0.145)(18.5)(0.25)^2 \text{ x}10^{-4}$$

$$K_e = 0.0000168$$

Step No. 14 Calculate the core geometry, K_g. See the design specification, window utilization factor, K_u.

$$K_g = \frac{(\text{Energy})^2}{K_e \alpha} \quad [\text{cm}^5]$$

$$K_g = \frac{(0.000206)^2}{\left(16.8\left(10^{-6}\right)\right)(1.0)} \quad [\text{cm}^5]$$

$$K_g = 0.00253 \quad [\text{cm}^5]$$

$$K_g = 0.00253(1.35), \quad [\text{cm}^5]$$

$$K_g = 0.00342, \quad [\text{cm}^5]$$

Step No. 15 Select, from Chapter 3, an EFD core comparable in core geometry, K_g.

Core number	EFD-20
Manufacturer	Philips
Material	3C85
Magnetic path length, MPL	= 4.7 cm
Core weight, W_{tfe}	= 7.0 grams
Copper weight, W_{tcu}	= 6.8 grams
Mean length turn, MLT	= 3.80 cm
Iron area, A_c	= 0.31 cm^2
Window Area, W_a	= 0.501 cm^2
Area Product, A_p	= 0.155 cm^4
Core geometry, K_g	= 0.00506 cm^5
Surface area, A_t	= 13.3 cm^2
Core Permeability	= 2500
Winding Length, G	= 1.54 cm

Step No. 16 Calculate the current density, J, using a window utilization, $K_u = 0.29$.

$$J = \frac{2(\text{Energy})\left(10^4\right)}{B_m A_p K_u}, \quad [\text{amps/cm}^2]$$

$$J = \frac{2(0.000206)\left(10^4\right)}{(0.25)(0.155)(0.29)}, \quad [\text{amps/cm}^2]$$

$$J = 367, \quad [\text{amps/cm}^2]$$

Step No. 17 Calculate the primary wire area, $A_{pw(B)}$.

$$A_{pw(B)} = \frac{I_{prms}}{J} \quad [\text{cm}^2]$$
$$A_{pw(B)} = \frac{1.4}{367} \quad [\text{cm}^2]$$
$$A_{pw(B)} = 0.00381 \quad [\text{cm}^2]$$

Step No. 18 Calculate the required number of primary strands, S_{np}.

$$S_{np} = \frac{A_{wp(B)}}{\#26\left(\text{bare area}\right)}$$
$$S_{np} = \frac{(0.00381)}{(0.00128)}$$
$$S_{np} = 2.97 \quad \text{use } 3$$

Step No. 19 Calculate the number of primary turns, N_p. Half of the available window is primary, W_{ap} /2. Using the number of strands, S_{np}, and the area for #26.

$$W_{ap} = \frac{W_a}{2} = \frac{0.501}{2} = 0.250, \quad [\text{cm}^2]$$
$$N_p = \frac{K_u W_{ap}}{3\left(\#26\left(\text{Bare Area}\right)\right)}, \quad [\text{turns}]$$
$$N_p = \frac{(0.29)(0.25)}{3(0.00128)}, \quad [\text{turns}]$$
$$N_p = 18.9 \text{ use } 19, \quad [\text{turns}]$$

Step No. 20 Calculate the required gap, l_g.

$$l_g = \frac{0.4\pi N^2 A_c\left(10^{-8}\right)}{L} - \left(\frac{\text{MPL}}{\mu_m}\right), \quad [\text{cm}]$$
$$l_g = \frac{(1.26)(19)^2(0.31)\left(10^{-8}\right)}{(0.000035)} - \left(\frac{4.7}{2500}\right), \quad [\text{cm}]$$
$$l_g = 0.0384, \quad [\text{cm}]$$

Step No. 21 Calculate the equivalent gap in mils.

$$\text{mils} = \text{cm}(393.7)$$
$$\text{mils} = (0.0384)(393.7)$$
$$\text{mils} = 15$$

Step No. 22 Calculate the fringing flux factor, F.

$$F = 1 + \frac{l_g}{\sqrt{A_c}} \ln\left(\frac{2G}{l_g}\right)$$

$$F = 1 + \frac{(0.0384)}{\sqrt{0.31}} \ln\left(\frac{2(1.54)}{0.0384}\right)$$

$$F = 1.30$$

Step No. 23 Calculate the new number of turns, N_{np}, by inserting the fringing flux, F.

$$N_{np} = \sqrt{\frac{l_g L}{0.4\pi A_c F\left(10^{-8}\right)}}, \quad \text{[turns]}$$

$$N_{np} = \sqrt{\frac{(0.0384)(0.000035)}{(1.26)(0.31)(1.3)\left(10^{-8}\right)}}, \quad \text{[turns]}$$

$$N_{np} = 16, \quad \text{[turns]}$$

Step No. 24 Calculate the peak flux density, B_{pk}.

$$B_{pk} = \frac{0.4\pi N_{np} F\left(I_{p(pk)}\right)\left(10^{-4}\right)}{l_g + \left(\frac{\text{MPL}}{\mu_m}\right)}, \quad \text{[tesla]}$$

$$B_{pk} = \frac{(1.26)(16)(1.3)(3.43)\left(10^{-4}\right)}{(0.0384) + \left(\frac{4.7}{2500}\right)}, \quad \text{[tesla]}$$

$$B_{pk} = 0.223, \quad \text{[tesla]}$$

Step No. 25 Calculate the primary, the new $\mu\Omega$/cm.

$$(\text{new})\mu\Omega / cm = \frac{\mu\Omega / cm}{S_{np}}$$

$$(\text{new})\mu\Omega / cm = \frac{1345}{3}$$

$$(\text{new})\mu\Omega / cm = 448$$

Step No. 26 Calculate the primary winding resistance, R_p.

$$R_p = MLT\left(N_{np}\right)\left(\frac{\mu\Omega}{cm}\right)\text{x}10^{-6} \quad \text{[ohms]}$$

$$R_p = (3.8)(16)(448)\text{x}10^{-6} \quad \text{[ohms]}$$

$$R_p = 0.0272 \quad \text{[ohms]}$$

Step No. 27 Calculate the primary copper loss, P_p.

$$P_p = I_p^2 R_p \quad \text{[watts]}$$

$$P_p = (1.4)^2 (.0272) \quad \text{[watts]}$$

$$P_p = 0.0533 \text{ [watts]}$$

Step No. 28 Calculate the secondary turns, N_{s1}.

$$N_{s1} = \frac{N_{np}(V_{o1}+V_d)(1-D_{\max}-D_w)}{(V_p D_{\max})} \quad \text{[turns]}$$

$$N_{s1} = \frac{16(5+1)(1-0.5-0.1)}{(24)(0.5)} \quad \text{[turns]}$$

$$N_{s1} = 3.2 \text{ use } 3 \quad \text{[turns]}$$

Step No. 29 Calculate the secondary peak current, $I_{s1(pk)}$.

$$I_{s1(pk)} = \frac{2I_{o1}}{(1-D_{\max}-D_w)} \quad \text{[amps]}$$

$$I_{s1(pk)} = \frac{2(2.0)}{(1-0.5-0.1)} \quad \text{[amps]}$$

$$I_{s1(pk)} = 10 \quad \text{[amps]}$$

Step No. 30 Calculate the secondary rms current, $I_{s(rms)}$.

$$I_{s1(rms)} = I_{s1(pk)}\sqrt{\frac{(1-D_{\max}-D_w)}{3}} \quad \text{[amps]}$$

$$I_{s1(rms)} = (10)\sqrt{\frac{(1-0.5-0.1)}{3}} \quad \text{[amps]}$$

$$I_{s1(rms)} = 3.65 \quad \text{[amps]}$$

Step No. 31 Calculate the secondary wire area, $A_{sw1(B)}$.

$$A_{sw1(B)} = \frac{I_{s1(rms)}}{J} \quad \text{[cm}^2\text{]}$$

$$A_{sw1(B)} = \frac{3.65}{367} \quad \text{[cm}^2\text{]}$$

$$A_{sw1(B)} = 0.00995 \quad \text{[cm}^2\text{]}$$

Step No. 32 Calculate the required number of secondary strands, S_{ns1}.

$$S_{ns1} = \frac{A_{sw1(B)}}{\text{wire}_A}$$
$$S_{ns1} = \frac{(0.00995)}{(0.00128)}$$
$$S_{ns1} = 7.8 \text{ use } 8$$

Step No. 33 Calculate the, S_1 secondary, μΩ/cm.

$$(S_1)\mu\Omega / cm = \frac{\mu\Omega / cm}{S_{ns1}}$$
$$(S_1)\mu\Omega / cm = \frac{1345}{8}$$
$$(S_1)\mu\Omega / cm = 168$$

Step No. 34 Calculate the winding resistance, R_{s1}.

$$R_{s1} = MLT(N_{s1})\left(\frac{\mu\Omega}{cm}\right)\text{x}10^{-6} \quad \text{[ohms]}$$
$$R_{s1} = 3.8(3)(168)\text{x}10^{-6} \quad \text{[ohms]}$$
$$R_{s1} = 0.00192 \quad \text{[ohms]}$$

Step No. 35 Calculate the secondary copper loss, P_{s1}.

$$P_{s1} = I_{s1}^2 R_{s1} \quad \text{[watts]}$$
$$P_{s1} = (3.65)^2(.00192) \quad \text{[watts]}$$
$$P_{s1} = 0.0256 \text{ [watts]}$$

Step No. 36 Calculate the secondary turns, N_{s2}.

$$N_{s2} = \frac{N_{np}(V_{o2} + V_d)(1 - D_{\max} - D_w)}{(V_p D_{\max})} \quad \text{[turns]}$$
$$N_{s2} = \frac{16(12+1)(1-0.5-0.1)}{(24)(0.5)} \quad \text{[turns]}$$
$$N_{s2} = 6.9 \text{ use } 7 \text{ [turns]}$$

Step No. 37 Calculate the secondary peak current, $I_{s2(pk)}$.

$$I_{s2(pk)} = \frac{2I_{o2}}{(1 - D_{\max} - D_w)} \quad \text{[amps]}$$
$$I_{s2(pk)} = \frac{2(0.5)}{(1-0.5-0.1)} \quad \text{[amps]}$$
$$I_{s2(pk)} = 2.5 \quad \text{[amps]}$$

Step No. 38 Calculate the secondary rms current, $I_{s2(rms)}$.

$$I_{s2(rms)} = I_{s2(pk)}\sqrt{\frac{(1-D_{\max}-D_w)}{3}} \quad \text{[amps]}$$

$$I_{s2(rms)} = (2.5)\sqrt{\frac{(1-0.5-0.1)}{3}} \quad \text{[amps]}$$

$$I_{s2(rms)} = 0.913 \quad \text{[amps]}$$

Step No. 39 Calculate the secondary wire area, $A_{sw2(B)}$.

$$A_{sw2(B)} = \frac{I_{s2(rms)}}{J} \quad [\text{cm}^2]$$

$$A_{sw2(B)} = \frac{0.913}{367} \quad [\text{cm}^2]$$

$$A_{sw2(B)} = 0.00249 \quad [\text{cm}^2]$$

Step No. 40 Calculate the required number of secondary strands, S_{ns2}.

$$S_{ns2} = \frac{A_{sw2(B)}}{wire_A}$$

$$S_{ns2} = \frac{(0.00249)}{(0.00128)}$$

$$S_{ns2} = 1.95 \quad \text{use } 2$$

Step No. 41 Calculate the, S_2 secondary, μΩ/cm.

$$(S_2)\mu\Omega/cm = \frac{\mu\Omega/cm}{S_{ns2}}$$

$$(S_2)\mu\Omega/cm = \frac{1345}{2}$$

$$(S_2)\mu\Omega/cm = 672$$

Step No. 42 Calculate the winding resistance, R_{s2}.

$$R_{s2} = MLT(N_{s2})\left(\frac{\mu\Omega}{cm}\right)\text{x}10^{-6} \quad \text{[ohms]}$$

$$R_{s2} = 3.8(7)(672)\text{x}10^{-6} \quad \text{[ohms]}$$

$$R_{s2} = 0.0179 \quad \text{[ohms]}$$

Step No. 43 Calculate the secondary copper loss, P_{s2}.

$$P_{s2} = I_{s2}^2 R_{s2} \quad \text{[watts]}$$

$$P_{s2} = (0.913)^2(.0179) \quad \text{[watts]}$$

$$P_{s2} = 0.0149 \text{ [watts]}$$

Step No. 44 Calculate the window utilization, K_u.

$$[\text{turns}] = (N_p S_{np}) \quad [\text{primary}]$$
$$[\text{turns}] = (16)(3) = 48 \quad [\text{primary}]$$
$$[\text{turns}] = (N_{s1} S_{ns1}) \quad [\text{secondary}]$$
$$[\text{turns}] = (3)(8) = 24 \quad [\text{secondary}]$$
$$[\text{turns}] = (N_{s2} S_{ns2}) \quad [\text{secondary}]$$
$$[\text{turns}] = (7)(2) = 14 \quad [\text{secondary}]$$
$$N_t = 86 \text{ turns } \#26$$
$$K_u = \frac{N_t A_w}{W_a} = \frac{(86)(0.00128)}{(0.501)}$$
$$K_u = 0.220$$

Step No. 45 Calculate the total copper loss, P_{cu}.

$$P_{cu} = P_p + P_{s1} + P_{s2} \quad [\text{watts}]$$
$$P_{cu} = (0.0533) + (0.0256) + (0.0149) \quad [\text{watts}]$$
$$P_{cu} = 0.0938 \quad [\text{watts}]$$

Step No. 46 Calculate the regulation, α, for this design.

$$\alpha = \frac{P_{cu}}{P_o} \text{x} 100 \quad [\%]$$
$$\alpha = \frac{(0.0938)}{(18.5)} \text{x} 100 \quad [\%]$$
$$\alpha = 0.507 \quad [\%]$$

Step No. 47 Calculate the ac flux density, B_{ac}.

$$B_{ac} = \frac{0.4\pi N_{np} F \left(\frac{I_{p(pk)}}{2} \right) (10^{-4})}{l_g + \left(\frac{\text{MPL}}{\mu_m} \right)}, \quad [\text{tesla}]$$
$$B_{ac} = \frac{(1.26)(16)(1.3)(1.72)(10^{-4})}{(0.0384) + \left(\frac{4.7}{2500} \right)}, \quad [\text{tesla}]$$
$$B_{ac} = 0.111, \quad [\text{tesla}]$$

Step No. 48 Calculate the watts per kilogram, WK.

$$WK = 4.855(10^{-5})(f)^{(1.63)}(B_{ac})^{(2.62)} \quad [\text{watts/kilogram}]$$
$$WK = 4.855(10^{-5})(100000)^{(1.63)}(0.111)^{(2.62)} \quad [\text{watts/kilogram}]$$
$$WK = 21.6 \quad [\text{watts/kilogram}] \text{ or } [\text{milliwatts/gram}]$$

Step No. 49 Calculate the core loss, P_{fe}.

$$P_{fe} = \left(\frac{\text{milliwatts}}{\text{gram}}\right) W_{tfe} \text{x} 10^{-3} \quad \text{[watts]}$$

$$P_{fe} = (21.6)(7) \text{x} 10^{-3} \quad \text{[watts]}$$

$$P_{fe} = 0.151 \quad \text{[watts]}$$

Step No. 50 Calculate the total loss, core P_{fe} and copper P_{cu}, in watts, P_{Σ}.

$$P_{\Sigma} = P_{fe} + P_{cu} \quad \text{[watts]}$$

$$P_{\Sigma} = (0.151) + (0.0938) \quad \text{[watts]}$$

$$P_{\Sigma} = 0.245 \quad \text{[watts]}$$

Step No. 51 Calculate the watt density, ψ.

$$\psi = \frac{P_{\Sigma}}{A_t} \quad \text{[watts/cm}^2\text{]}$$

$$\psi = \frac{0.245}{13.3} \quad \text{[watts/cm}^2\text{]}$$

$$\psi = 0.0184 \quad \text{[watts/cm}^2\text{]}$$

Step No. 52 Calculate the temperature rise, T_r, in, °C.

$$T_r = 450(\psi)^{(0.826)} \quad [^{\circ}\text{C}]$$

$$T_r = 450(0.0184)^{(0.826)} \quad [^{\circ}\text{C}]$$

$$T_r = 16.6 \quad [^{\circ}\text{C}]$$

Design Example, Boost Converter, Discontinuous Current

1 Input voltage nominal, V_{in} ....= 28 volts
2. Input voltage minimum, $V_{in(min)}$ ....= 26 volts
3. Input voltage maximum, $V_{in(max)}$ ....= 32 volts
4. Output voltage, V_{o1} ....= 50 volts
5. Output current, I_{o1} ....= 1 amps
6. *Window utilization, K_u ....= 0.29
7. Frequency, f ....= 100 kHz
8. Converter efficiency, η ....= 92 %
9. Dwell time duty ratio, $D_{(w)}$ ....= 0.1
10. Regulation, α ....= 1.0%
11. Operating flux density, B_m ....= 0.25 tesla
12. Diode voltage, V_d ....= 1.0 volts

*When operating at high frequencies, the engineer has to review the window utilization factor, K_u. When using a small bobbin ferrite, the ratio of the bobbin winding area to the core window area is only about 0.6. Operating at 100kHz and having to use a #26 wire, because of the skin effect, the ratio of the bare copper area is 0.78. Therefore, the overall window utilization, K_u, is reduced. The core geometries, K_g, in Chapter 3 have been calculated with a window utilization, K_u, of 0.4. To return the design back to the norm, the core geometry, K_g is to be multiplied by 1.35, and then, the current density, J, is calculated, using a window utilization factor of 0.29. See Chapter 4.

Skin Effect

The skin effect on an inductor is the same as a transformer. In the normal dc inductor, the ac current, (ac flux), is much lower and does not require the use of the same maximum wire size. This is not the case in the discontinuous, current type, flyback converter, where all of the flux is ac and without dc. In the discontinuous, flyback design, the skin effect has to be treated just like a high frequency transformer.

There are times when the larger wire is just too difficult to wind. Large wire is not only hard to handle, but it does not give the proper lay. It is easier to wind with bi-filar or quad-filar, wire with the equivalent cross-section.

At this point, select a wire so that the relationship between the ac resistance and the dc resistance is 1:

$$\frac{R_{ac}}{R_{dc}} = 1$$

The skin depth in centimeters is:

$$\varepsilon = \frac{6.62}{\sqrt{f}}, \quad [\text{cm}]$$

$$\varepsilon = \frac{6.62}{\sqrt{100,000}}, \quad [\text{cm}]$$

$$\varepsilon = 0.0209, \quad [\text{cm}]$$

Then, the wire diameter is:

$$\text{Wire Diameter} = 2(\varepsilon), \quad [\text{cm}]$$

$$\text{Wire Diameter} = 2(0.0209), \quad [\text{cm}]$$

$$\text{Wire Diameter} = 0.0418, \quad [\text{cm}]$$

Then, the bare wire area A_w is:

$$A_w = \frac{\pi D^2}{4}, \quad [\text{cm}^2]$$

$$A_w = \frac{(3.1416)(0.0418)^2}{4}, \quad [\text{cm}^2]$$

$$A_w = 0.00137, \quad [\text{cm}^2]$$

From the Wire Table in Chapter 4, Number 26 has a bare wire area of 0.001028 centimeters. This will be the minimum wire size used in this design. If the design requires more wire area to meet the specification, then, the design will use a multifilar of #26. Listed Below are #27 and #28, just in case #26 requires too much rounding off.

Wire AWG	Bare Area	Area Ins.	Bare/Ins.	μΩ/cm
#26	0.001280	0.001603	0.798	1345
#27	0.001021	0.001313	0.778	1687
#28	0.0008046	0.0010515	0.765	2142

Step No. 1 Calculate the total period, T.

$$T = \frac{1}{f}, \quad [\text{seconds}]$$

$$T = \frac{1}{100,000}, \quad [\text{seconds}]$$

$$T = 10, \quad [\mu\text{sec}]$$

Step No. 2 Calculate the maximum output power, P_o.

$$P_o = (V_o + V_d)(I_o), \quad \text{[watts]}$$
$$P_o = (50 + 1.0)(1.0), \quad \text{[watts]}$$
$$P_o = 51, \quad \text{[watts]}$$

Step No. 3 Calculate the maximum input current, $I_{in(max)}$.

$$I_{in(\max)} = \frac{P_o}{V_{in(\min)}\eta}, \quad \text{[amps]}$$
$$I_{in(\max)} = \frac{(51)}{(26)(0.92)}, \quad \text{[amps]}$$
$$I_{in(\max)} = 2.13, \quad \text{[amps]}$$

Step No. 4 Calculate the maximum duty ratio, $D_{(max)}$.

$$D_{(\max)} = (1 - D_w)\left(\frac{V_o - V_{in(\min)} + V_d}{V_o}\right)$$
$$D_{(\max)} = (1 - 0.1)\left(\frac{(50) - (26) + (1.0)}{50}\right)$$
$$D_{(\max)} = 0.45$$

Step No. 5 Calculate the minimum duty ratio, $D_{(min)}$.

$$D_{(\min)} = (1 - D_w)\left(\frac{V_o - V_{in(\max)} + V_d}{V_o}\right)$$
$$D_{(\min)} = (1 - 0.1)\left(\frac{(50) - (32) + (1.0)}{50}\right)$$
$$D_{(\min)} = 0.342$$

Step No. 6 Calculate the required inductance, L.

$$L_{\max} = \frac{(V_o + V_d)T D_{(\max)}(1 - D_{\max} - D_w)^2}{2I_{o(\max)}}, \quad \text{[henrys]}$$
$$L_{\max} = \frac{(50 + 1.0)(10(10^{-6}))(0.45)(1 - 0.45 - 0.1)^2}{2(1.0)}, \quad \text{[henrys]}$$
$$L = 23.2 \text{ use } 23, \quad [\mu\text{h}]$$

Step No. 7 Calculate the peak current, I_{pk}. In a discontinuous current boost the peak current is, $I_{(pk)} = \Delta I$.

$$I_{(pk)} = \frac{2P_{o(\max)}}{\eta\left(V_o D_{(\min)}\right)}, \quad \text{[amps]}$$

$$I_{(pk)} = \frac{2(51)}{(0.92)((50)(0.342))}, \quad \text{[amps]}$$

$$I_{(pk)} = 6.48, \quad \text{[amps]}$$

Step No. 8 Calculate the rms current, $I_{(rms)}$.

$$I_{(rms)} = I_{pk}\sqrt{\frac{TD_{(\max)}}{3T}}, \quad \text{[amps]}$$

$$I_{(rms)} = (6.48)\sqrt{\frac{\left(10x10^{-6}\right)(0.45)}{3\left(10x10^{-6}\right)}}, \quad \text{[amps]}$$

$$I_{(rms)} = 2.51, \quad \text{[amps]}$$

Step No. 9 Calculate the total energy-handling capability in watt-seconds, w-s.

$$\text{Energy} = \frac{LI_{pk}^2}{2}, \quad \text{[w-s]}$$

$$\text{Energy} = \frac{\left(23x10^{-6}\right)(6.48)^2}{2}, \quad \text{[w-s]}$$

$$\text{Energy} = 0.000483, \quad \text{[w-s]}$$

Step No. 10 Calculate the electrical conditions, K_e.

$$K_e = 0.145P_o B_m^2\left(10^{-4}\right)$$

$$K_e = 0.145(51)(0.25)^2\left(10^{-4}\right)$$

$$K_e = 0.0000462$$

Step No. 11 Calculate the core geometry, K_g.

$$K_g = \frac{(\text{Energy})^2}{K_e\alpha}, \quad [\text{cm}^5]$$

$$K_g = \frac{(0.000483)^2}{(0.0000462)(1.0)}, \quad [\text{cm}^5]$$

$$K_g = 0.00505, \quad [\text{cm}^5]$$

$$K_g = 0.00505(1.35), \quad [\text{cm}^5]$$

$$K_g = 0.00682, \quad [\text{cm}^5]$$

Step No. 12 From Chapter 3, select a core that is comparable in core geometry, K_g.

Core number RM-6
Manufacturer .... TDK
Magnetic path length, MPL .... = 2.86 cm
Core weight, W_{tfe} .... = 5.5 grams
Copper weight, W_{tcu} .... = 2.9 grams
Mean length turn, MLT .... = 3.1 cm
Iron area, A_c .... = 0.366 cm^2
Window Area, W_a .... = 0.260 cm^2
Area Product, A_p .... = 0.0953 cm^4
Core geometry, K_g .... = 0.0044 cm^5
Surface area, A_t .... = 11.3 cm^2
Permeability, μ_m .... = 2500
Winding Length, G .... = 0.82

Step No. 13 Calculate the current density, J, using a window utilization, K_u = 0.29.

$$J = \frac{2(Energy)(10^4)}{B_m A_p K_u}, \quad [\text{amps/cm}^2]$$

$$J = \frac{2(0.000483)(10^4)}{(0.25)(0.0953)(0.29)}, \quad [\text{amps/cm}^2]$$

$$J = 1398, \quad [\text{amps/cm}^2]$$

Step No. 14 Calculate the wire area, $A_{w(B)}$.

$$A_{w(B)} = \frac{I_{rms}}{J} \quad [\text{cm}^2]$$

$$A_{w(B)} = \frac{2.51}{1398} \quad [\text{cm}^2]$$

$$A_{w(B)} = 0.00179 \quad [\text{cm}^2]$$

Step No. 15 Calculate the required number of strands, S_n.

$$S_n = \frac{A_{w(B)}}{\#26 \text{ (bare area)}}$$

$$S_n = \frac{(0.00180)}{(0.00128)}$$

$$S_n = 1.41 \text{ use } 2$$

Step No. 16 Calculate the number of turns, N, using the number of strands, S_n, and the area for #26.

$$N = \frac{K_u W_a}{S_n \#26}, \quad \text{[turns]}$$
$$N = \frac{(0.29)(0.26)}{2(0.00128)}, \quad \text{[turns]}$$
$$N = 29.5 \text{ use } 30, \quad \text{[turns]}$$

Step No. 17 Calculate the required gap, l_g.

$$l_g = \frac{0.4\pi N^2 A_c (10^{-8})}{L} - \left(\frac{\text{MPL}}{\mu_m}\right), \quad \text{[cm]}$$
$$l_g = \frac{(1.26)(30)^2 (0.366)(10^{-8})}{(0.000023)} - \left(\frac{2.86}{2500}\right), \quad \text{[cm]}$$
$$l_g = 0.179, \quad \text{[cm]}$$

Step No. 19 Calculate the equivalent gap in mils.

$$\text{mils} = \text{cm}(393.7)$$
$$\text{mils} = (0.179)(393.7)$$
$$\text{mils} = 70$$

Step No. 20 Calculate the fringing flux factor, F.

$$F = 1 + \frac{l_g}{\sqrt{A_c}} \ln\left(\frac{2G}{l_g}\right)$$
$$F = 1 + \frac{(0.179)}{\sqrt{0.366}} \ln\left(\frac{2(0.82)}{0.179}\right)$$
$$F = 1.66$$

Step No. 21 Calculate the new number of turns, N_n, by inserting the fringing flux, F.

$$N_{np} = \sqrt{\frac{l_g L}{0.4\pi A_c F (10^{-8})}}, \quad \text{[turns]}$$
$$N_{np} = \sqrt{\frac{(0.179)(0.000023)}{(1.26)(0.366)(1.66)(10^{-8})}}, \quad \text{[turns]}$$
$$N_{np} = 23, \quad \text{[turns]}$$

Step No. 22 Calculate the peak flux density, B_{pk}.

$$B_{pk} = \frac{0.4\pi N_n F\left(I_{(pk)}\right)\left(10^{-4}\right)}{l_g + \left(\dfrac{\text{MPL}}{\mu_m}\right)}, \quad \text{[tesla]}$$

$$B_{pk} = \frac{(1.26)(23)(1.66)(6.48)\left(10^{-4}\right)}{(0.179) + \left(\dfrac{2.86}{2500}\right)}, \quad \text{[tesla]}$$

$$B_{pk} = 0.177, \quad \text{[tesla]}$$

Step No. 23 Calculate the new, μΩ/cm.

$$(\text{new})\mu\Omega/\text{cm} = \frac{\mu\Omega/\text{cm}}{S_n}$$

$$(\text{new})\mu\Omega/\text{cm} = \frac{1345}{2}$$

$$(\text{new})\mu\Omega/\text{cm} = 673$$

Step No. 24 Calculate the primary winding resistance, R.

$$R = MLT\left(N_n\right)\left(\frac{\mu\Omega}{cm}\right)\text{x}10^{-6} \quad \text{[ohms]}$$

$$R = (3.1)(23)(673)\text{x}10^{-6} \quad \text{[ohms]}$$

$$R = 0.0480 \quad \text{[ohms]}$$

Step No. 25 Calculate the copper loss, P_{cu}.

$$P_{cu} = I_{rms}^2 R \quad \text{[watts]}$$

$$P_{cu} = (2.51)^2(.0480) \quad \text{[watts]}$$

$$P_{cu} = 0.302 \text{ [watts]}$$

Step No. 26 Calculate the regulation, α, for this design.

$$\alpha = \frac{P_{cu}}{P_o}\text{x}100, \quad [\%]$$

$$\alpha = \frac{(0.302)}{(50)}\text{x}100, \quad [\%]$$

$$\alpha = 0.604, \quad [\%]$$

Step No. 27 Calculate the ac flux density in tesla, B_{ac}.

$$B_{ac} = \frac{0.4\pi N_n F\left(\frac{\Delta I}{2}\right)\left(10^{-4}\right)}{l_g + \left(\frac{\text{MPL}}{\mu_m}\right)}, \quad \text{[tesla]}$$

$$B_{ac} = \frac{(1.26)(23)(1.66)(3.24)\left(10^{-4}\right)}{(0.179) + \left(\frac{2.86}{2500}\right)}, \quad \text{[tesla]}$$

$$B_{ac} = 0.0869, \quad \text{[tesla]}$$

Step No. 28 Calculate the watts per kilogram, WK.

$$WK = 4.855\left(10^{-5}\right)(f)^{(1.63)}\left(B_{ac}\right)^{(2.62)}, \quad \text{[watts/kilogram]}$$

$$WK = 4.855\left(10^{-5}\right)(100000)^{(1.63)}(0.0869)^{(2.62)}, \quad \text{[watts/kilogram]}$$

$$WK = 11.39, \quad \text{[watts/kilogram] or [milliwatts/gram]}$$

Step No. 29 Calculate the core loss, P_{fe} .

$$P_{fe} = \left(\frac{\text{milliwatts}}{\text{gram}}\right) W_{tfe} \text{x} 10^{-3}, \quad \text{[watts]}$$

$$P_{fe} = (11.39)(5.5)\text{x}10^{-3}, \quad \text{[watts]}$$

$$P_{fe} = 0.0626, \quad \text{[watts]}$$

Step No. 30 Calculate the total loss, P_Σ, core, P_{fe}, and copper, P_{cu}.

$$P_\Sigma = P_{fe} + P_{cu}, \quad \text{[watts]}$$

$$P_\Sigma = (0.0626) + (0.302), \quad \text{[watts]}$$

$$P_\Sigma = 0.365, \quad \text{[watts]}$$

Step No. 31 Calculate the watt density, ψ.

$$\psi = \frac{P_\Sigma}{A_t}, \quad \text{[watts/cm}^2\text{]}$$

$$\psi = \frac{0.365}{11.3}, \quad \text{[watts/cm}^2\text{]}$$

$$\psi = 0.0323, \quad \text{[watts/cm}^2\text{]}$$

Step No. 32 Calculate the temperature rise, T_r in, °C.

$$T_r = 450(\psi)^{(0.826)}, \quad [^\circ\text{C}]$$

$$T_r = 450(0.0323)^{(0.826)}, \quad [^\circ\text{C}]$$

$$T_r = 26.4, \quad [^\circ\text{C}]$$

Designing Boost Inductors for Power Factor Correction (PFC)

Historically, the standard power supplies designed for electronic equipment have had a notoriously poor power factor in the area of (0.5-0.6), and a correspondingly, high, harmonic current content. This design approach utilizes a simple rectifier capacitor input filter that results in large current pulses drawn from the line, that cause distorting of the line voltage and create large amounts of EMI and noise.

The regulating bodies, IEC in Europe and IEEE in the United States, have been working to develop a standard for limiting harmonic current, in off-line equipment. The German standardization bodies have established IEC 1000-2, and it is generally accepted as the standard for limiting harmonic currents in off-line equipment.

Many new electronic products are required to have a near unity power factor and a distortion free, current input waveform. The conventional ac-dc converters usually employ a full wave, rectifier-bridge, with a simple filter to draw power from the ac line. The typical, rectifier capacitor, input bridge filter and associated waveforms, as shown in Figure 13-15, are no longer good enough.

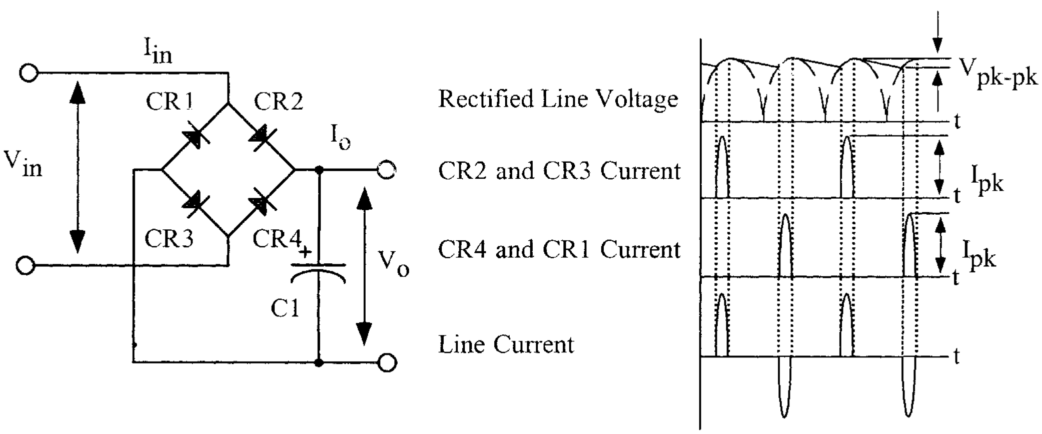

Figure 13-15. Typical, Capacitor Input Bridge Rectifier Filter.

The line current waveform for equipment that utilizes off-line rectifier capacitor input filter, is shown in Figure 13-15. The line current is supplied in narrow pulses. Consequently, the power factor is poor (0.5 – 0.6), due to a high harmonic distortion of the current waveform. The power supply can be designed with a power factor approaching unity, by the addition of an input inductor, as shown in Figure 13-16. The reasons why the input inductors are not designed into power supplies is very simple: cost, weight and bulk. The inductance equation for, L1, is shown below.

$$L1 = \frac{V_o}{3\omega I_{o(\min)}}, \quad \text{[henrys]} \quad [13\text{-}56]$$

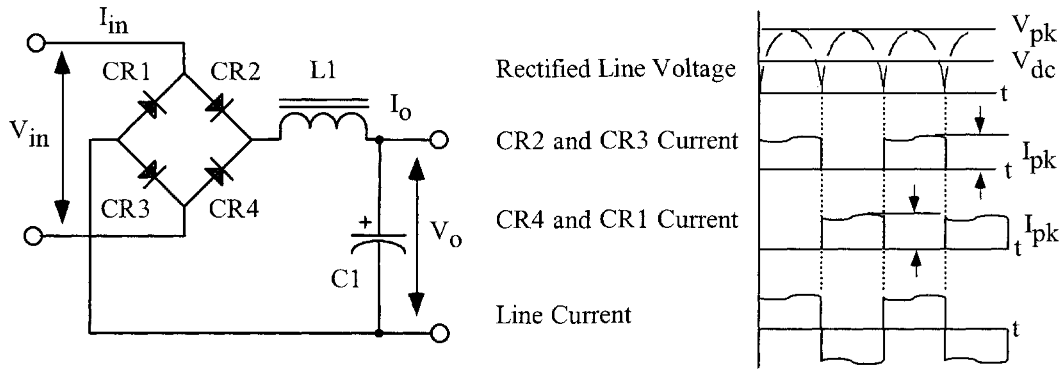

Figure 13-16. A Typical, Inductor Input Bridge Rectifier Filter.

Standard Boost Flyback Converter

The standard dc-to-dc boost flyback converter is shown in Figure 13-6, along with the voltage and current waveforms, shown in Figure 13-7 and 13-8. The boost converter has become the choice of many engineers as the power stage in the active power factor corrector design. The basic circuit can be operated in either the continuous or discontinuous mode.

Boost PFC Converter

The boost power factor correction converter is shown in Figure 13-17. The boost converter is the most popular of the power factor pre-regulators. The boost converter can operate in two modes, continuous and discontinuous. The current through the inductor, L1, is shown in Figure 13-18, for both continuous and discontinuous operation. After examining the schematic, the advantages and disadvantages of the boost converter can readily be seen. The disadvantage is the high output voltage to the load circuit and current limit cannot be implemented. The advantage is that the circuit requires a minimum of parts and the gate drive to, Q1, is referenced to ground.

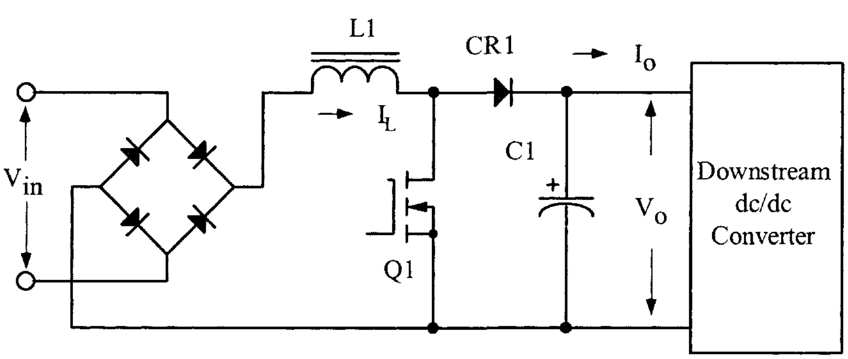

Figure 13-17. Boost PFC Converter.

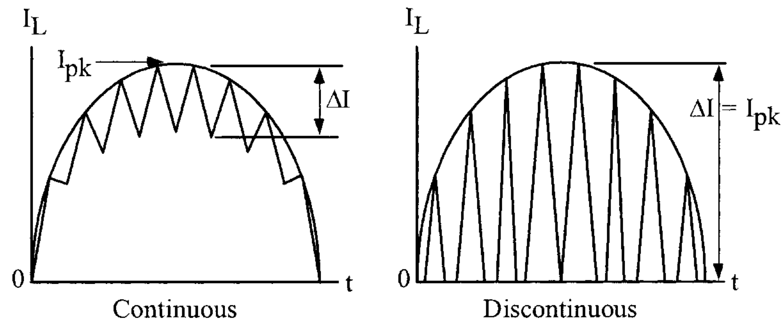

Figure 13-18. Current Through Inductor L1.

Design Example, (PFC) Boost Converter, Continuous Current

The following pages describe a step-by-step procedure for designing a continuous current boost inductor for a Power Factor Correction (PFC) converter, as shown in Figure 13-17, with the following specifications:

1. Output power, P_o .... $= 250$ watts
2. Input voltage range, V_{in} .... $= 90 - 270$ volts
3. Line frequency, $f_{(line)}$ .... $= 47 - 65$ Hz
4. Output voltage, V_o .... $= 400$ volts
5. Switching frequency, f .... $= 100$kHz
6. Inductor ripple current, ΔI .... $= 20\%$ of I_{pk}
7. Magnetic core .... = ETD
8. Magnetic material .... = R
9. Converter efficiency, η .... $= 95\%$
10. Inductor regulation, α .... $= 1\%$
11. *Window utilization, K_u .... $= 0.29$
12. Operating Flux, B_m .... $= 0.25$ tesla

*When operating at high frequencies, the engineer has to review the window utilization factor, K_u. When using a small bobbin ferrite, the ratio of the bobbin winding area to the core window area is only about 0.6. Operating at 100kHz and having to use a #26 wire, because of the skin effect, the ratio of the bare copper area is 0.78. Therefore, the overall window utilization, K_u, is reduced. The core geometries, K_g, in Chapter 3 have been calculated with a window utilization, K_u, of 0.4. To return the design back to the norm, the core geometry, K_g, is to be multiplied by 1.35, and then, the current density, J, is calculated, using a window utilization factor of 0.29. See Chapter 4.

Skin Effect

The skin effect on an inductor is the same as a transformer. In the normal dc inductor, the ac current (ac flux), is much lower, and does not require the use of the same, maximum wire size. This is not the case in the discontinuous, current type, flyback converter, where all of the flux is ac and no dc. In the discontinuous, flyback design, the skin effect has to be treated just like a high frequency transformer.

There are times when the larger wire is just too difficult to wind. Large wire is not only hard to handle, but it does not give the proper lay. It is easier to wind with bi-filar or quad-filar wire, with the equivalent cross-section.

Select a wire so that the relationship between the ac resistance and the dc resistance is 1:

$$\frac{R_{ac}}{R_{dc}} = 1$$

The skin depth in centimeters is:

$$\varepsilon = \frac{6.62}{\sqrt{f}}, \quad [\text{cm}]$$

$$\varepsilon = \frac{6.62}{\sqrt{100,000}}, \quad [\text{cm}]$$

$$\varepsilon = 0.0209, \quad [\text{cm}]$$

Then, the wire diameter is:

$$\text{Wire Diameter} = 2(\varepsilon), \quad [\text{cm}]$$

$$\text{Wire Diameter} = 2(0.0209), \quad [\text{cm}]$$

$$\text{Wire Diameter} = 0.0418, \quad [\text{cm}]$$

Then, the bare wire area, A_w, is:

$$A_w = \frac{\pi D^2}{4}, \quad [\text{cm}^2]$$

$$A_w = \frac{(3.1416)(0.0418)^2}{4}, \quad [\text{cm}^2]$$

$$A_w = 0.00137, \quad [\text{cm}^2]$$

From the Wire Table in Chapter 4, Number 26 has a bare wire area of 0.00128 centimeters. This will be the minimum wire size used in this design. If the design requires more wire area to meet the specification, then, the design will use a multifilar of #26.

Wire AWG	Bare Area	Area Ins.	Bare/Ins.	μΩ/cm
#26	0.001280	0.001603	0.798	1345

Step No. 1 Calculate the input power, P_{in}.

$$P_{in} = \frac{P_o}{\eta}, \quad \text{[watts]}$$

$$P_{in} = \frac{250}{0.95}, \quad \text{[watts]}$$

$$P_{in} = 263, \quad \text{[watts]}$$

Step No. 2 Calculate the peak input current, I_{pk}.

$$I_{pk} = \frac{P_{in}\sqrt{2}}{V_{in(\min)}}, \quad \text{[amps]}$$

$$I_{pk} = \frac{(263)(1.41)}{90}, \quad \text{[amps]}$$

$$I_{pk} = 4.12, \quad \text{[amps]}$$

Step No. 3 Calculate the input ripple current, ΔI.

$$\Delta I = 0.2 I_{pk}, \quad \text{[amps]}$$

$$\Delta I = 0.2(4.12), \quad \text{[amps]}$$

$$\Delta I = 0.824, \quad \text{[amps]}$$

Step No. 4 Calculate the maximum duty ratio, $D_{(\max)}$.

$$D_{(\max)} = \frac{\left(V_o - \left(V_{in(\min)}\sqrt{2}\right)\right)}{V_o}$$

$$D_{(\max)} = \frac{\left(400 - \left(90\sqrt{2}\right)\right)}{400}$$

$$D_{(\max)} = 0.683$$

Step No. 5 Calculate the required boost inductance, L.

$$L = \frac{\left(V_{in(\min)}\sqrt{2}\right) D_{(\max)}}{\Delta I f}, \quad \text{[henrys]}$$

$$L = \frac{(126.9)(0.683)}{(0.824)(100000)}, \quad \text{[henrys]}$$

$$L = 0.00105, \quad \text{[henrys]}$$

Step No. 6 Calculate the Energy required, Eng.

$$\text{Eng} = \frac{L I_{pk}^2}{2}, \quad \text{[watt-seconds]}$$

$$\text{Eng} = \frac{(0.00105)(4.12)^2}{2}, \quad \text{[watt-seconds]}$$

$$\text{Eng} = 0.00891, \quad \text{[watt-seconds]}$$

Step No. 7 Calculate the electrical coefficient, K_e.

$$K_e = 0.145 P_o B_m^2 \left(10^{-4}\right)$$
$$K_e = 0.145(250)(0.25)^2 \left(10^{-4}\right)$$
$$K_e = 0.000227$$

Step No. 8 Calculate the core geometry coefficient, K_g.

$$K_g = \frac{(\text{Eng})^2}{K_e \alpha}, \quad [\text{cm}^5]$$
$$K_g = \frac{(0.00891)^2}{(0.000227)(1)}, \quad [\text{cm}^5]$$
$$K_g = 0.35, \quad [\text{cm}^5]$$
$$K_g = 0.35(1.35), \quad [\text{cm}^5] \text{ Corrected}$$
$$K_g = 0.47, \quad [\text{cm}^5]$$

Step No. 9 From Chapter 3, select an ETD ferrite core, comparable in core geometry, K_g.

Core number	= ETD-44
Manufacturer	= Ferroxcube
Magnetic path length, MPL	= 10.3 cm
Core weight, W_{tfe}	= 93.2 grams
Copper weight, W_{tcu}	= 94 grams
Mean length turn, MLT	= 9.4 cm
Iron area, A_c	= 1.74 cm^2
Window Area, W_a	= 2.79 cm^2
Area Product, A_p	= 4.85 cm^4
Core geometry, K_g	= 0.360 cm^5
Surface area, A_t	= 87.9 cm^2
Permeability, μ_m	= 2000
Millihenrys per 1000 turns, AL	= 3365
Winding Length, G	= 3.22

Step No. 10 Calculate the current density, J.

$$J = \frac{2(\text{Eng})\left(10^4\right)}{B_m A_p K_u}, \quad [\text{amps/cm}^2]$$
$$J = \frac{2(0.00891)\left(10^4\right)}{(0.25)(4.85)(0.29)}, \quad [\text{amps/cm}^2]$$
$$J = 507, \quad [\text{amps/cm}^2]$$

Step No. 11 Calculate the rms current, I_{rms}.

$$I_{rms} = \frac{I_{pk}}{\sqrt{2}}, \quad \text{[amps]}$$

$$I_{rms} = \frac{4.12}{\sqrt{2}}, \quad \text{[amps]}$$

$$I_{rms} = 2.91, \quad \text{[amps]}$$

Step No. 12 Calculate the required bare wire area, $A_{w(B)}$.

$$A_{w(B)} = \frac{I_{rms}}{J}, \quad [\text{cm}^2]$$

$$A_{w(B)} = \frac{2.91}{507}, \quad [\text{cm}^2]$$

$$A_{w(B)} = 0.00574, \quad [\text{cm}^2]$$

Step No. 13 Calculate the required number of strands, S_n.

$$S_n = \frac{A_{w(B)}}{\#26(\text{bare area})}, \quad [\text{cm}^2]$$

$$S_n = \frac{(0.00574)}{(0.00128)}, \quad [\text{cm}^2]$$

$$S_n = 4.48 \text{ use } 5, \quad [\text{cm}^2]$$

Step No. 14 Calculate the required number of turns, N, using the number of strands, S_n, and the area for #26.

$$N = \frac{W_a K_u}{S_n \, \#26}, \quad \text{[turns]}$$

$$N = \frac{(2.79)(0.29)}{5(0.00128)}, \quad \text{[turns]}$$

$$N = 126, \quad \text{[turns]}$$

Step No. 15 Calculate the required gap, l_g.

$$l_g = \left(\frac{0.4\pi N^2 A_c \left(10^{-8}\right)}{L}\right), \quad \text{[cm]}$$

$$l_g = \left(\frac{(1.257)(126)^2(1.74)\left(10^{-8}\right)}{0.00105}\right), \quad \text{[cm]}$$

$$l_g = 0.331, \quad \text{[cm]}$$

Change the gap to mils: 0.331 x 393.7 = 130 mils center or 65 mils per each outer leg.

Step No. 16 Calculate the fringing flux factor, F.

$$F=\left(1+\left(\frac{l_g}{\sqrt{A_c}}\right)\ln\left(\frac{2G}{l_g}\right)\right)$$
$$F=\left(1+\left(\frac{0.331}{1.32}\right)\ln\left(\frac{6.44}{0.331}\right)\right)$$
$$F=1.74$$

Step No. 17 Calculate the new turns using the fringing flux.

$$N=\sqrt{\frac{l_g L}{0.4\pi A_c F\left(10^{-8}\right)}},\quad \text{[turns]}$$
$$N=\sqrt{\frac{(0.331)(0.00105)}{(1.257)(1.74)(1.74)\left(10^{-8}\right)}},\quad \text{[turns]}$$
$$N=96,\quad \text{[turns]}$$

Step No. 18 Calculate the peak flux, B_{pk}.

$$B_{pk}=F\left(\frac{0.4\pi N I_{pk}\left(10^{-4}\right)}{l_g}\right),\quad \text{[tesla]}$$
$$B_{pk}=1.74\left(\frac{(1.257)(96)(4.12)\left(10^{-4}\right)}{0.331}\right),\quad \text{[tesla]}$$
$$B_{pk}=0.261,\quad \text{[tesla]}$$

Step No. 19 Calculate the new, μΩ/cm.

$$(\text{new})\mu\Omega/\text{cm}=\frac{\mu\Omega/\text{cm}}{S_n}$$
$$(\text{new})\mu\Omega/\text{cm}=\frac{1345}{5}$$
$$(\text{new})\mu\Omega/\text{cm}=269$$

Step No. 20 Calculate the winding resistance, R.

$$R=(\text{MLT})N\left(\frac{\mu\Omega}{\text{cm}}\right)\left(10^{-6}\right),\quad \text{[ohms]}$$
$$R=(9.4)(96)(269)\left(10^{-6}\right),\quad \text{[ohms]}$$
$$R=0.243,\quad \text{[ohms]}$$

Step No. 21 Calculate the winding copper loss, P_{cu}.

$$P_{cu} = I_{rms}^2 R, \quad \text{[watts]}$$
$$P_{cu} = (2.91)^2 (0.243), \quad \text{[watts]}$$
$$P_{cu} = 2.06, \quad \text{[watts]}$$

Step No. 22 Calculate the regulation, α.

$$\alpha = \frac{P_{cu}}{P_o} 100, \quad [\%]$$
$$\alpha = \frac{(2.06)}{(250)} 100, \quad [\%]$$
$$\alpha = 0.824, \quad [\%]$$

Step No. 23 Calculate the ac flux density, B_{ac}.

$$B_{ac} = \frac{0.4\pi N\left(\frac{\Delta I}{2}\right)(10^{-4})}{l_g}, \quad \text{[tesla]}$$
$$B_{ac} = \frac{(1.257)(96)(0.412)(10^{-4})}{0.331}, \quad \text{[tesla]}$$
$$B_{ac} = 0.0150, \quad \text{[tesla]}$$

Step No. 24 Calculate the watts per kilogram, W/K, using R material in Chapter 2.

$$W/K = 4.316(10^{-5})(f)^{1.64}(B_{ac})^{2.68}, \quad \text{[watts per kilogram]}$$
$$W/K = 4.316(10^{-5})(100000)^{1.64}(0.0150)^{2.68}, \quad \text{[watts per kilogram]}$$
$$W/K = 0.0885, \quad \text{[watts per kilogram]}$$

Step No. 25 Calculate the core loss, P_{fe}.

$$P_{fe} = W_{tfe}(10^{-3})(W/K), \quad \text{[watts]}$$
$$P_{fe} = (93.2)(10^{-3})(0.0885), \quad \text{[watts]}$$
$$P_{fe} = 0.0082, \quad \text{[watts]}$$

Step No. 26 Calculate the total loss core loss, P_{fe} and copper loss, P_{cu}.

$$P = P_{cu} + P_{fe}, \quad \text{[watts]}$$
$$P = (2.03) + (0.0082), \quad \text{[watts]}$$
$$P = 2.04, \quad \text{[watts]}$$

Step No. 27 Calculate the watt density, ψ.

$$\psi = \frac{P}{A_t}, \quad [\text{watts per cm}^2]$$

$$\psi = \frac{2.04}{87.9}, \quad [\text{watts per cm}^2]$$

$$\psi = 0.023, \quad [\text{watts per cm}^2]$$

Step No. 28 Calculate the temperature rise, T_r.

$$T_r = 450(\psi)^{0.826}, \quad [^\circ\text{C}]$$

$$T_r = 450(0.023)^{0.826}, \quad [^\circ\text{C}]$$

$$T_r = 19.9, \quad [^\circ\text{C}]$$

Step No. 29 Calculate the window utilization, K_u.

$$K_u = \frac{NS_n A_{w(B)}}{W_a}$$

$$K_u = \frac{(95)(5)(0.00128)}{(2.79)}$$

$$K_u = 0.218$$

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