AN120

Discontinuous Current Inverted Buck-Boost Converter
Using a LPT E2000Q Core

By
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The principle behind flyback converters is based on the storage of energy in the inductor during the charging, or on period, t_{on}, and the discharge of energy to the load during the off period, t_{off}.

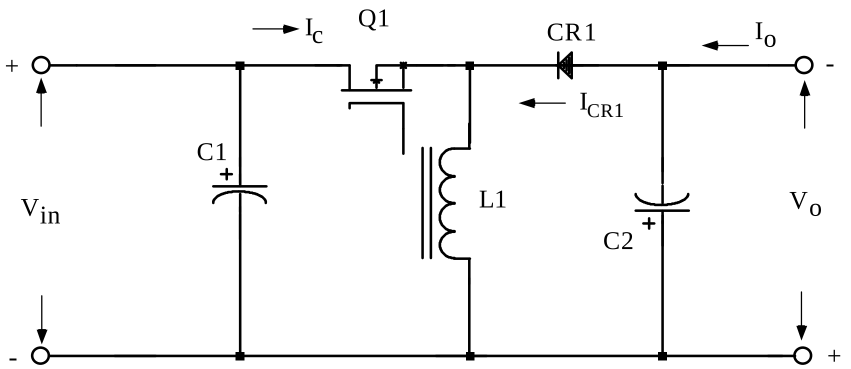

Figure 1. Inverted buck-boost converter, discontinuous current.

Energy Transfer
In the discontinuous mode the energy, stored in the inductor, is completely transferred to the load circuits, during the off time, before another switching period occurs, as shown in Figure 2. The discontinuous current B-H loop is shown in Figure 3.

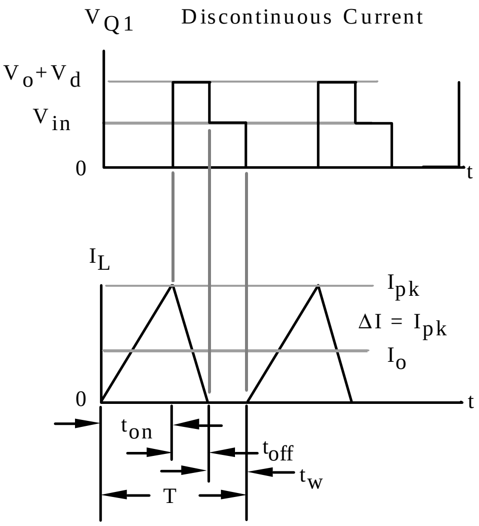

Figure 2. Inverted buck-boost converter discontinuous current, ideal voltage and current waveforms.

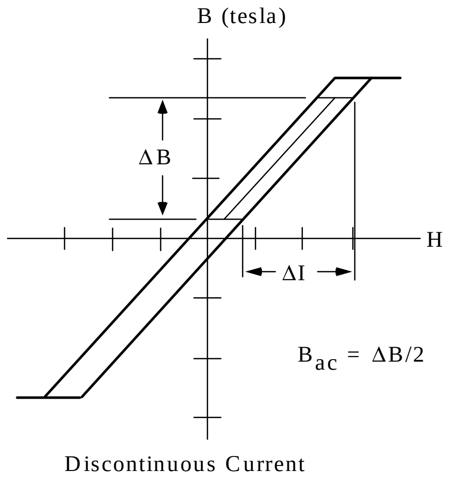

Figure 3. B-H loop for the continuous current inverted buck-boost converters.

When designing a LPT inductor, and after the core geometry (size) has been selected, then, the correct core permeability can be calculated. Care must be used in selecting the right permeability so the core does not saturate at the maximum amp-turns to which it will be subjected. The dc magnetizing curves for LPT cores are shown in Figure 4. The permeabilities for LPT cores range from 60 to 500 perm. The engineer will select a core with the highest permeability that will not saturate at maximum load current. This core will produce an inductor with the smallest size.

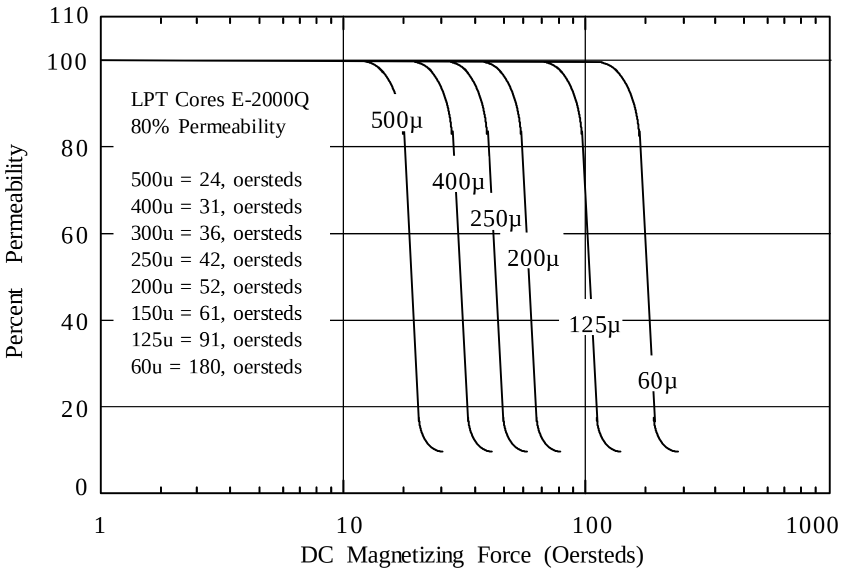

Figure 4. DC magnetization curves for LPT cores.

For a typical design example, assume a inverted buck-boost converter, as shown in Figure 1, with the following specifications:

Discontinuous Current Inverted Buck-Boost Converter

Inductor Design specification

1.	Input voltage	$V_{nom} = 15$ V
2.	Input voltage	$V_{min} = 12$ V
3.	Input voltage	$V_{max} = 18$ V
4.	Output voltage	$V_o = -12$ V
5.	Output current	$I_o = 2$ A
6.	Dwell time duty ratio	$D_w = 0.1$
7.	Frequency	f = 100 kHz
8.	Efficiency	= 90%
9.	Regulation	= 1 %
10.	Operating flux density	$B_m = 0.4$ T
11.	Window utilization	$K_u = 0.4$
12.	Diode voltage drop	$V_d = 1.0$ V

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.

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:

$$e = \frac{6.62}{\sqrt{f}}$$

$$e = \frac{6.62}{\sqrt{100{,}000}} = 0.0209 \text{ [cm]}$$

Then, the wire diameter is:

$$\text{Wire Diameter} = 2(e)$$

$$\text{Wire Diameter} = 2 \cdot 0.0209 = 0.0418 \text{ [cm]}$$

Then, the bare wire area A_W is:

$$A_w = \frac{p D^2}{4}$$

$$A_w = \frac{3.14 \cdot 0.0418^2}{4} = 0.00137 \text{ [cm}^2\text{]}$$

From the Wire Table, 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	0.00128	0.001603	0.798	1345
#27	0.001021	0.001313	0.778	1687
#28	0.000804	0.000105	0.765	2142

Step No. 1. Calculate the total period, T.

$$T = \frac{1}{f}$$

$$T = \frac{1}{100{,}000} = 10 \text{ [}ms\text{]}$$

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

$$P_o = I_o (V_o + V_d)$$

$$P_o = 2.0 \cdot (12 + 1) = 26 \text{ [W]}$$

Step No. 3. Calculate the maximum input current, I_{max}.

$$I_{in(\max)} = \frac{P_o}{V_{in(\min)} \cdot h}$$

$$I_{in(\max)} = \frac{26}{12 \cdot 0.9} = 2.407 \text{ [A]}$$

Step No. 4. Calculate the minimum duty ratio, D_{min}.

$$D_{\min} = \frac{V_{in(\min)} \cdot (1 - D_w)}{V_{in(\min)} + (V_o + V_d)}$$

$$D_{\min} = \frac{12(1 - 0.1)}{12 + (12 + 1.0)} = 0.432$$

Step No. 5. Calculate the maximum duty ratio, D_{max}.

$$D_{\max} = 1 - D_{\min} - D_w$$

$$D_{\max} = 1 - 0.432 - 0.1 = 0.468$$

Step No. 6. Calculate the minimum load resistance, R_{min}, (maximum load condition).

$$R_{\min} = \frac{(V_o + V_d)}{I_{o(\max)}}$$

$$R_{\min} = \frac{(12 + 1.0)}{2.0} = 6.5 \text{ [}\Omega\text{]}$$

Step No. 7. Calculate the maximum required inductance, L.

$$L \le \frac{R_{\min} \cdot T \cdot \left(1 - D_{\max} - D_w\right)^2}{2}$$

$$L \le \frac{6.5 \cdot 10 \cdot 10^{-6} \cdot \left(1 - 0.468 - 0.1\right)^2}{2} \le 6.07\ [m\mathrm{H}]$$

Step No. 8. Calculate the delta current, I.

$$\Delta I = \frac{2P_o}{V_{in(\min)} \cdot D_{\max} \cdot h}$$

$$\Delta I = \frac{2 \cdot 26}{12 \cdot 0.468 \cdot 0.9} = 10.23\ [\mathrm{A}]$$

Step No. 9. Calculate the delta rms current, $I_{(rms)}$.

$$\Delta I_{(rms)} = \Delta I \sqrt{\frac{T \cdot D_{(\max)}}{3T}}$$

$$\Delta I_{(rms)} = 10.23 \sqrt{\frac{10 \cdot 0.468}{3 \cdot 10}} = 4.041\ [\mathrm{A}]$$

Step No. 10. Calculate the energy-handling capability in watt-seconds, w-s.

$$\text{Energy} = \frac{L \cdot I_{pk}^2}{2}$$

$$\text{Energy} = \frac{6.07 \cdot 10^{-6} \cdot 10.23^2}{2} = 0.000318\ [\text{W-s}]$$

Step No. 11. Calculate the electrical conditions, K_e.

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

$$K_e = 0.145 \cdot 26 \cdot 0.4^2 \cdot 10^{-4} = 0.0000603$$

Step No. 12. Calculate the core geometry, K_g.

$$K_g = \frac{(\text{Energy})^2}{K_e \cdot a}$$

$$K_g = \frac{0.000318^2}{0.0000603 \cdot 1.0} = 0.00168\ [\mathrm{cm}^5]$$

Step No. 13 Select from Table a LPT E2000Q core comparable in core geometry K_g.

Core number	GC30111Q
Magnetic path length	MPL = 4.1 cm
Core weight	W_{tfe} = 4.3 g
Copper weight	W_{tcu} = 5.6 g
Mean length turn	MLT = 2.7 cm
Iron area	A_c = 0.14 cm^2
Window Area	W_a = 0.581 cm^2
Area Product	A_p = 0.0813 cm^4
Core geometry	K_g = 0.00168 cm^5
Surface area	A_t = 16.3 cm^2

Permeability .... μ = 125
Millihenrys per 1000 turns.. mH = 53.6

Step No. 14. Calculate the current density, J, using a window utilization K_u = 0.4.

$$J = \frac{2(\text{Energy})\cdot 10^4}{A_p \cdot B_m \cdot K_u}$$

$$J = \frac{2\cdot 0.000318\cdot 10^4}{0.0813\cdot 0.4\cdot 0.4} = 489\ [\text{A/cm}^2]$$

Step No. 15. Calculate the required permeability, Δμ.

$$\Delta m = \frac{B_m \cdot (MPL)\cdot 10^4}{0.4p \cdot W_a \cdot J \cdot K_u}$$

$$\Delta m = \frac{0.4\cdot 4.1\cdot 10^4}{1.256\cdot 0.581\cdot 489\cdot 0.4} = 115 \text{use 125 perm}$$

Step No. 16. Calculate the number of turns, N.

$$N = 1000\sqrt{\frac{L_{(new)}}{L_{(1000)}}}$$

$$N = 1000\sqrt{\frac{0.00607}{53.6}} = 10.6 \text{ use 11 [turns]}$$

Step No. 17. Calculate the peak flux density, B_{pk}.

$$B_{pk} = \frac{0.4p \cdot N \cdot I_{pk} \cdot \Delta m \cdot 10^{-4}}{MPL}$$

$$B_{pk} = \frac{1.256\cdot 11\cdot 10.23\cdot 125\cdot 10^{-4}}{4.1} = 0.431\ [\text{T}]$$

Step No. 18. Calculate the required bare wire area, $A_{w(B)}$.

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

$$A_{w(B)} = \frac{0.581\cdot 0.4}{11} = 0.0211\ [\text{cm}^2]$$

Step No. 19. Select a wire size with the required area from the Wire Table. If the area is not within 10% of the required area, then go to the next smallest size.

$$AWG = \#14$$

$$A_{w(B)} = 0.0208\ [\text{cm}^2]$$

$$m\Omega/\text{cm} = 82.8$$

Step No. 20. Calculate the required number of strands, S_n.

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

$$S_n = \frac{0.0208}{0.00128} = 16.25 \text{ use 16}$$

Step No. 21. Calculate the new µ per centimeter.

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

$$(\text{new})m\Omega/\text{cm} = \frac{1345}{16} = 84$$

Step No. 22. Calculate the winding resistance, R.

$$R = \text{MLT} \cdot \text{N} \cdot \frac{m\Omega}{\text{cm}} \cdot 10^{6}$$

$$R = 2.7 \cdot 11 \cdot 84 \cdot 10^{-6} = 0.0025\ [\Omega]$$

Step No. 23. Calculate the copper loss, P_{cu}.

$$P_{cu} = I_{rms}^{2} \cdot R$$

$$P_{cu} = 4.041^{2} \cdot 0.0025 = 0.0408\ [\text{W}]$$

Step No. 24. Calculate the peak magnetizing force in Oersteds, H.

$$H = \frac{0.4p \cdot N \cdot I_{pk}}{MPL}$$

$$H = \frac{1.256 \cdot 11 \cdot 10.23}{4.1} = 34.5\ [\text{Oe}]$$

Inductance is down 20% at 91 Oersteds

Step No. 25. Calculate the ac flux density in T, B_{ac}.

$$B_{ac} = \frac{0.4p \cdot N \cdot \frac{I_{pk}}{2} \cdot m_{r} \cdot 10^{-4}}{MPL}$$

$$B_{ac} = \frac{1.256 \cdot 11 \cdot 5.12 \cdot 125 \cdot 10^{-4}}{4.1} = 0.216\ [\text{T}]$$

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

$$a = \frac{P_{cu}}{P_{o}} \cdot 100$$

$$a = \frac{0.0408}{26} \cdot 100 = 0.157\ [\%]$$

Step No. 27. Calculate the watts per kilogram, WK.

$$WK = 8.64 \cdot 10^{-7} \cdot f^{1.834} \cdot B_{ac}^{2.112}$$

$$WK = 8.64 \cdot 10^{-7} \cdot 100000^{1.834} \cdot 0.216^{2.112} 50.2\ [\text{W/kg}] \text{ or } [\text{mW/g}]$$

Step No. 28. Calculate the core loss, P_{fe} .

$$P_{fe} = \frac{mW}{g} \cdot W_{tfe} \cdot 10^{-3}$$

$$P_{fe} = 50.2 \cdot 4.3 \cdot 10^{-3} = 0.216\ [\text{W}]$$

Step No. 29. Calculate the total loss P_{Σ}, core P_{fe} and copper P_{cu} .

$$P_{\Sigma} = P_{fe} + P_{cu}$$

$$P_{\Sigma} = 0.216 + 0.0408 = 0.257\ [\text{W}]$$

Step No. 30. Calculate the watt density, Ø.

$$y = \frac{P_\Sigma}{A_t}$$

$$y = \frac{0.257}{16.3} = 0.0158 \text{ [W/cm}^2\text{]}$$

Step No. 31. Calculate the temperature rise in °C.

$$T_r = 450 \cdot \Psi^{0.826}$$

$$T_r = 450 \cdot 0.0158^{0.826} = 14.6 \text{ [°C]}$$

BIBLIOGRAPHY

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3. Colonel William T. McLyman, Designing Magnetic Components for High Frequency, dc-dc Converters, Kg Magnetics, Inc., 1993.

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