DESIGNING A CONTINUOUS CURRENT BUCK-BOOST CONVERTER USING THE CORE GEOMETRY

Colonel W. T. McLyman
Kg Magnetics, Inc

Abstract- The purpose of this paper is to design a continuous current, Buck-Boost Converter using the core geometry approach. The design will show engineers another method of designing transformers and inductors using this step-by-step approach. There are many advantages of using the core geometry method for designing inductors and transformers over the area product method. The core geometry will give the engineer another tool to better understand transformer and inductor design and therefore, cut the design time way down.

I. INTRODUCTION

The isolated buck-boost flyback converter looks very much like a single-ended forward converter, as shown in Figure 1. The similarity is that the forward converter uses a multi-winding transformer, while the isolated buck-boost uses a multi-winding inductor. 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}.

A. Energy Transfer

There are two distinct modes of operations for the buck-boost converter. The discontinuous current mode is shown in Figure 2, and the continuous current mode is shown in Figure 3. In the discontinuous mode, all energy stored in the primary, during the ON time, is completely delivered to the secondary and its circuits during the OFF time, before another switching period occurs, as shown in Figure 2. In the continuous mode the energy stored in the primary is not completely transferred to the secondary and its circuits during the OFF time before another switching period occurs, as shown in Figure 3.

When designing in the discontinuous mode, a smaller inductor is required, but a smaller inductor results in a higher peak current in the switching transistor, Q1.

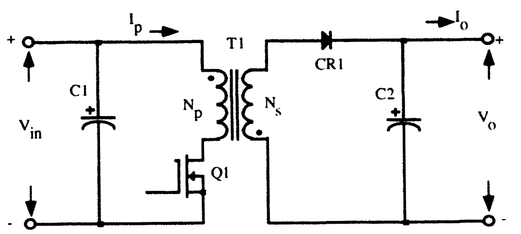

Fig. 1. Energy storage isolated buck-boost converter.

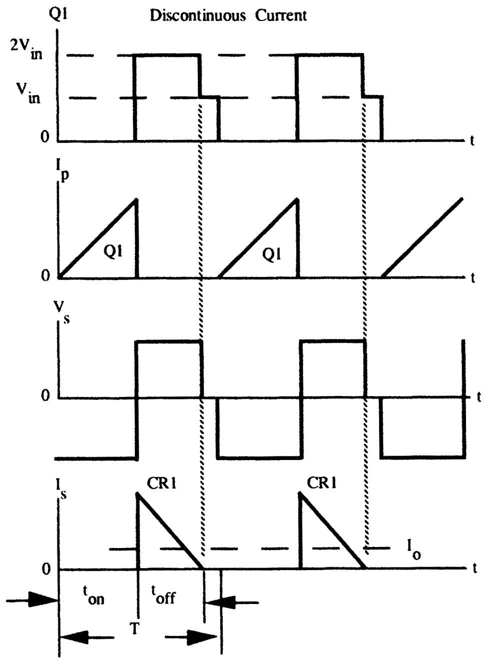

Fig. 2. Discontinuous ideal voltage and current waveforms.

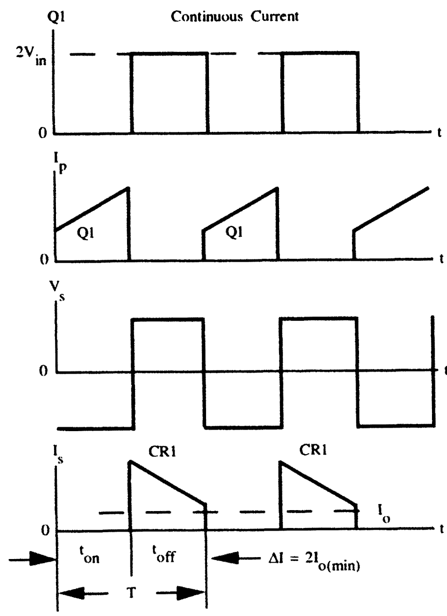

Fig. 3. Continuous ideal voltage and current waveforms.

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The sawtooth waveform has a higher rms to the average than the trapezoidal waveform. A larger inductance results in higher copper losses. The advantage of this circuit, other than having a smaller inductor, is that when the switching is turned on, the initial current is zero. This means the output diode, CR1, has completely recovered, and the switching device does not momentarily turn on into a short. In the continuous mode, a large primary inductance is required. This results in a low peak current at the end of the ON period. The continuous mode requires a higher current through the switch during turn-on. This could lead to higher switch dissipation. The discontinuous current mode B-H loop is shown in Figure 4, and the continuous current mode B-H loop is shown in Figure 5.

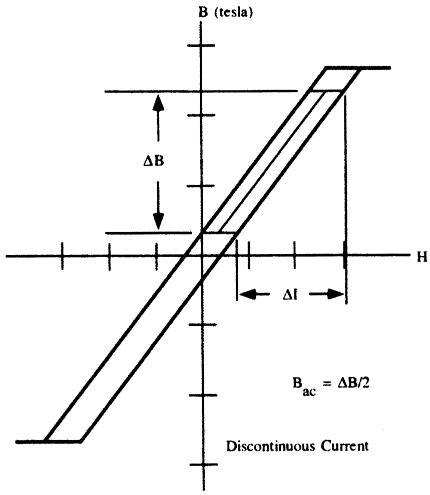

Fig. 4. Discontinuous mode buck-boost converter, B-H loop.

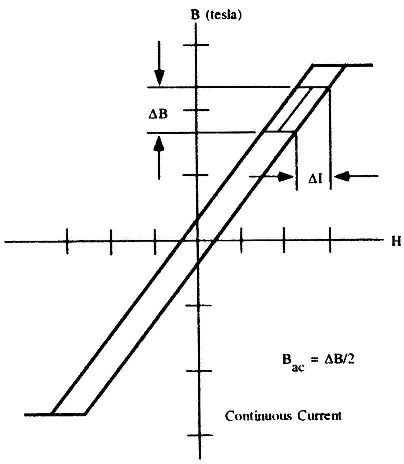

Fig. 5. Continuous mode buck-boost converter, B-H loop.

B. Skin Effect

The skin effect on an inductor is the same as a transformer. The main difference is that the ac flux is much lower and does not require the use of the same maximum wire size.

The ac flux is caused by the delta current, ΔI, and is normally only a fraction of the dc flux. In many cases, the ac current that is riding on top of the dc current, as shown in Figure 5, is small enough that it does not affect the overall current density of the single wire used. There are times when the larger wire is just too difficult to wind on small ferrite cores. Large wire is not only hard to handle, but it does not give a proper lay. It is easier to wind with bi-filar or quad-filar wire with equivalent cross-section.

II. DESIGN PROCEDURE

In this design the wire is selected such that the relationship between the ac resistance and the dc resistance is unity.

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

The skin depth in centimeters is:

$$\varepsilon = \frac{6.62}{\sqrt{f}}, \quad \text{(cm)}$$

$$\varepsilon = \frac{6.62}{\sqrt{100{,}000}}, \quad \text{(cm)}$$

$$\varepsilon = 0.0209, \quad \text{(cm)}$$

The wire diameter is:

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

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

$$\text{Wire Diameter} = 0.0418, \quad \text{(cm)}$$

The bare wire area A_w is

$$A_w = (\pi D^2)/4 = [(3.14)(0.0418)^2]/4 = 0.00137 \quad (\text{cm}^2)$$

The wire gauge chosen is a Number 26 AWG; bare area of 0.00128 cm^2; and a resistance of 1345 μΩ/cm.

Buck-Boost Isolated Continuous Current Design Specification

1. Input voltage max .... V_{max} = 32 volts
2. Input voltage nom .... V_{nom} = 28 volts
3. Input voltage min .... V_{min} = 24 volts
4. Output voltage .... V_o = 5 volts
5. Output current max .... $I_{o(max)}$ = 10 amps
6. Output current min .... $I_{o(min)}$ = 2 amps
7. Window utilization .... K_u = 0.4
8. Frequency .... f = 100 kHz
9. Transformer efficiency .... η_T = 98 %
10. Converter efficiency .... η = 92 %
11. Maximum duty ratio .... D_{max} = 0.5
12. Regulation (copper loss) .... α = 0.5 %
13. Operating flux density .... B_m = 0.25
14. Diode voltage drop .... V_d = 1.0
15. Temperature Rise .... T_r = < 25° C

Step 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 2. Calculate the maximum transistor on time, t_{on}.

$$t_{on} = TD_{\max}, \quad (\mu\text{sec})$$

$$t_{on} = (10)(0.5), \quad (\mu\text{sec})$$

$$t_{on} = 5, \quad (\mu\text{sec})$$

Step 3. Calculate the minimum duty ratio, D_{min}.

$$D_{\min} = \frac{V_{in(\min)}}{V_{in(\max)}}(D_{\max})$$

$$D_{\min} = \frac{24}{32}(0.5)$$

$$D_{\min} = 0.375$$

Step 4. Calculate the sec., maximum load power, $P_{o(max)}$.

$$P_{o(\max)} = I_{o(\max)}(V_o + V_d), \quad \text{(watts)}$$

$$P_{o(\max)} = 10(5+1), \quad \text{(watts)}$$

$$P_{o(\max)} = 60, \quad \text{(watts)}$$

Step 5. Calculate the sec., minimum load power, $P_{o(min)}$.

$$P_{o(\min)} = I_{o(\min)}(V_o + V_d), \quad \text{(watts)}$$

$$P_{o(\min)} = 2(5+1), \quad \text{(watts)}$$

$$P_{o(\min)} = 12, \quad \text{(watts)}$$

Step 6. Calculate the maximum, input current, $I_{in(max)}$.

$$I_{in(\max)} = \frac{P_{o(\max)}}{V_{in(\min)}\eta}, \quad \text{(amps)}$$

$$I_{in(\max)} = \frac{60}{(24)(0.92)}, \quad \text{(amps)}$$

$$I_{in(\max)} = 2.72, \quad \text{(amps)}$$

Step 7. Calculate the minimum, input power, $P_{in(min)}$.

$$P_{in(\min)} = \frac{P_{o(\min)}}{\eta}, \quad \text{(watts)}$$

$$P_{in(\min)} = \frac{12}{0.92}, \quad \text{(watts)}$$

$$P_{in(\min)} = 13.0, \quad \text{(watts)}$$

Step 8. Calculate the required, primary inductance, L_p.

$$L_p = \frac{\left(V_{in(\max)}D_{(\min)}\right)^2 T}{2P_{in(\min)}}, \quad \text{(henrys)}$$

$$L_p = \frac{\left((32)(0.375)\right)^2 \left(10x10^{-6}\right)}{2(13)}, \quad \text{(henrys)}$$

$$L_p = 55.4, \quad (\mu\text{h})$$

Step 9. Calculate the primary, delta current, ΔI_p.

$$\Delta I_p = \frac{D_{\max} T V_{in(\min)}}{L_p}, \quad \text{(amps)}$$

$$\Delta I_p = \frac{(0.5)\left(10x10^{-6}\right)(24)}{55.4x10^{-6}}, \quad \text{(amps)}$$

$$\Delta I_p = 2.17, \quad \text{(amps)}$$

Step 10. Calculate the primary, delta rms current, $\Delta I_{p(rms)}$.

$$\Delta I_{p(rms)} = \Delta I_p \sqrt{\frac{t_{on}}{3T}}, \quad \text{(amps)}$$

$$\Delta I_{p(rms)} = (2.17)\sqrt{\frac{5}{3(10)}}, \quad \text{(amps)}$$

$$\Delta I_{p(rms)} = 0.886, \quad \text{(amps)}$$

Step 11. Calculate the primary, peak current, $I_{p(pk)}$.

$$I_{p(pk)} = \frac{I_{in(\max)}}{D_{\max}} + \frac{\Delta I_p}{2}, \quad \text{(amps)}$$

$$I_{p(pk)} = \frac{2.72}{0.5} + \frac{2.17}{2}, \quad \text{(amps)}$$

$$I_{p(pk)} = 6.53, \quad \text{(amps)}$$

Step 12. Calculate the primary, rms current, $I_{p(rms)}$.

$$I_{p(rms)} = \sqrt{\left(\left(I_{p(pk)}\right)^2 - \left(I_{p(pk)}\right)\left(\Delta I_p\right) + \frac{\Delta I_p^2}{3}\right)\left(D_{\max}\right)}, \quad \text{(amps)}$$

$$I_{p(rms)} = \sqrt{\left((6.53)^2 - (6.53)(2.17) + \frac{(2.17)^2}{3}\right)(0.5)}, \quad \text{(amps)}$$

$$I_{p(rms)} = 3.88, \quad \text{(amps)}$$

Step 13. Calculate the required energy-handling capability in watt-seconds, w-s.

$$\text{Energy} = \frac{L_p I_{p(pk)}^2}{2}, \quad \text{(w-s)}$$

$$\text{Energy} = \frac{\left(55.4x10^{-6}\right)(6.53)^2}{2}, \quad \text{(w-s)}$$

$$\text{Energy} = 0.00118, \quad \text{(w-s)}$$

Step 14. Calculate the electrical conditions, K_e.

$$K_e = 0.145\, P_o B_m^2 x10^{-4}$$

$$K_e = 0.145\,(60)(0.25)^2 x10^{-4}$$

$$K_e = 0.0000544$$

Step 15. Calculate the core geometry, K_g.

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

$$K_g = \frac{(0.00118)^2}{(0.0000544)(0.5)}, \quad (\text{cm}^5)$$

$$K_g = 0.0512, \quad (\text{cm}^5)$$

Core Geometry

$$K_g = \frac{W_a A_c^2 K_u}{\text{MLT}}, \quad (\text{cm}^5)$$

When operating at 100kHz and having to use #26 wire, because of the skin effect, the overall window utilization, K_u, is reduced. The core data is taken from the author's handbook [1]. The core geometry, K_g was developed using a window utilization of 0.4. To return the design back to the norm, the calculated 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.

Step 16. Calculate the new core geometry, K_g.

$$K_g = 0.0512(1.35) = 0.0691) \quad (\text{cm}^2)$$

Step 17. Select a core that has a core geometry, K_g, as close as possible to 0.0691 cm^5.

Selected Core

1. Magnetics Core number	PQ 42620
2. Magnetic path length	MPL = 4.63 cm
3. Core weight	W_{tfe} = 31 grams
4. Mean length turn	MLT = 5.6 cm
5. Window area	$W_a = 0.604$ cm^2
6. Iron area	$A_c = 1.19$ cm^2
7. Area product	$A_p = 0.718$ cm^4
8. Core Geometry	$K_g = 0.0613$ cm^5
9. Surface Area	$A_t = 28.4$ cm^2
10. Winding length	G = 1.15 cm
11. Magnetic material	P
12. Material permeability	$\mu_m = 2500$
13. Window Utilization	$K_u = 0.4$

Step 18. Calculate the current density, J, using a window utilization, $K_u = 0.29$.

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

$$J = \frac{2(0.00118)(10^4)}{(0.25)(0.718)(0.29)}, \quad [\text{amps/cm}^2]$$

$$J = 453, \quad [\text{amps/cm}^2]$$

Step 19. Calculate the required primary wire area, $A_{wp(B)}$.

$$A_{wp(B)} = \frac{I_{p(rms)}}{J}, \quad (\text{cm}^2)$$

$$A_{wp(B)} = \frac{3.82}{453}, \quad (\text{cm}^2)$$

$$A_{wp(B)} = 0.00843, \quad (\text{cm}^2)$$

Step 20. Calculate the number of primary strands, S_{np}.

$$S_{np} = \frac{A_{wp}}{\#26\ (\text{bare area})}$$

$$S_{np} = \frac{0.00843}{0.00128}$$

$$S_{np} = 6.59 \text{ use } 7$$

Step 21. Calculate the number of primary turns, N_p. Half of the available window is primary, $W_a/2$. Using the number strands, S_{np}, and the wire area for #26.

$$W_{ap} = \frac{W_a}{2} = \frac{0.604}{2} = 0.302, \quad (\text{cm}^2)$$

$$N_p = \frac{K_u W_{ap}}{7(\#26(\text{bare area}))}, \quad (\text{turns})$$

$$N_p = \frac{(0.29)(0.302)}{7(0.00128)}, \quad (\text{turns})$$

$$N_p = 9.77 \text{ use } 10, \quad (\text{turns})$$

Step 22. Calculate the required total gap, l_g.

$$l_g = \frac{0.4\pi N^2 A_c (10^{-8})}{L_p} + \frac{\text{MPL}}{\mu_m}, \quad (\text{cm})$$

$$l_g = \frac{(1.257)(10)^2(1.19)(10^{-8})}{(55.4(10^{-6}))} + \frac{4.63}{2500}, \quad (\text{cm})$$

$$l_g = 0.0289, \quad (\text{cm})$$

Step 23. Calculate the equivalent gap in mils.

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

$$\text{mils} = (0.0289)(393.7)$$

$$\text{mils} = 11$$

Step 24. Calculate the fringing flux factor, F.

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

$$F = 1 + \frac{0.0289}{\sqrt{1.19}} \ln\left(\frac{2(1.15)}{0.0289}\right)$$

$$F = 1.116$$

Step 25. Calculate the new primary turns, N_{np}, using the fringing flux, F.

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

$$N_{np} = \sqrt{\frac{(0.0289)\left(55.4\left(10^{-6}\right)\right)}{(1.257)(1.19)(1.116)\left(10^{-8}\right)}}, \quad \text{(turns)}$$

$$N_{np} = 9.79 \text{ use } 10, \quad \text{(turns)}$$

Step 26. Calculate the peak flux density, B_{pk}.

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

$$B_{pk} = \frac{(1.257)(10)(1.116)(6.53)\left(10^{-4}\right)}{0.0289 + \left(\frac{4.63}{2500}\right)}, \quad \text{(tesla)}$$

$$B_{pk} = 0.298, \quad \text{(tesla)}$$

Step 27. Calculate the primary, the new μΩ/cm.

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

$$(\text{new})\,\mu\Omega/\text{cm} = \frac{1345}{7}$$

$$(\text{new})\,\mu\Omega/\text{cm} = 192$$

Step 28. Calculate the primary winding resistance, R_p.

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

$$R_p = (5.6)(10)(192)\left(10^{-6}\right), \quad \text{(ohms)}$$

$$R_p = 0.0108, \quad \text{(ohms)}$$

Step 29. Calculate the primary copper loss, P_p.

$$P_p = I_{p(rms)}^2 R_p, \quad \text{(watts)}$$

$$P_p = (3.88)^2(0.0108), \quad \text{(watts)}$$

$$P_p = 0.162, \quad \text{(watts)}$$

Step 30. Calculate the secondary turns, N_s.

$$N_s = \frac{N_{np}\left(V_o + V_d\right)\left(1 - D_{\max}\right)}{V_{in(\min)} D_{\max}}, \quad \text{(turns)}$$

$$N_s = \frac{(10)(5+1)(1-0.5)}{(24)(0.5)}, \quad \text{(turns)}$$

$$N_s = 2.5 \text{ use } 3, \quad \text{(turns)}$$

Step 31. Calculate the secondary inductance, L_s.

$$L_s = \frac{0.4\pi N_p^2 A_c F\left(10^{-8}\right)}{l_g + \left(\frac{\text{MPL}}{\mu_m}\right)}, \quad \text{(henrys)}$$

$$L_s = \frac{(1.257)(3)^2(1.19)(1.116)\left(10^{-8}\right)}{0.0289 + \left(\frac{4.63}{2500}\right)}, \quad \text{(henrys)}$$

$$L_s = 4.89, \quad (\mu\text{h})$$

Step 32. Calculate the secondary, delta current, ΔI_s.

$$\Delta I_s = \frac{\left(V_o + V_d\right) T D_{\min}}{L_s}, \quad \text{(amps)}$$

$$\Delta I_s = \frac{(5+1)\left(10x10^{-6}\right)(0.375)}{4.89x10^{-6}}, \quad \text{(amps)}$$

$$\Delta I_s = 4.6, \quad \text{(amps)}$$

Step 33. Calculate the secondary, delta rms current, $\Delta I_{\sigma(rms)}$.

$$\Delta I_{s(rms)} = \Delta I_s \sqrt{\frac{T\left(1 - D_{\min}\right)}{3T}}, \quad \text{(amps)}$$

$$\Delta I_{s(rms)} = 4.6\sqrt{\frac{\left(10x10^{-6}\right)(0.625)}{3\left(10x10^{-6}\right)}}, \quad \text{(amps)}$$

$$\Delta I_{s(rms)} = 2.10, \quad \text{(amps)}$$

Step 34. Calculate the secondary, peak current, $I_{s(pk)}$.

$$I_{s(pk)} = \frac{P_o}{\left(V_o + V_d\right)\left(1 - D_{\max}\right)} + \frac{\Delta I_s}{2}, \quad \text{(amps)}$$

$$I_{s(pk)} = \frac{60}{(5+1.0)(0.5)} + \frac{4.6}{2}, \quad \text{(amps)}$$

$$I_{s(pk)} = 22.3, \quad \text{(amps)}$$

Step 35. Calculate the secondary rms current, $I_{s(rms)}$.

$$I_{s(rms)}=\sqrt{\left(\left(I_{s(pk)}\right)^2-\left(I_{s(pk)}\right)\left(\Delta I_s\right)+\frac{\Delta I_s^2}{3}\right)\left(1-D_{\min}\right)},\quad \text{(amps)}$$

$$I_{s(rms)}=\sqrt{\left((22.3)^2-(22.3)(4.6)+\frac{(4.6)^2}{3}\right)(0.625)},\quad \text{(amps)}$$

$$I_{s(rms)}=15.8,\quad \text{(amps)}$$

Step 36. Calculate the required secondary wire area, $A_{ws(B)}$.

$$A_{ws(B)}=\frac{I_{s(rms)}}{J},\quad \left(\text{cm}^2\right)$$

$$A_{ws(B)}=\frac{15.8}{453},\quad \left(\text{cm}^2\right)$$

$$A_{ws(B)}=0.0349,\quad \left(\text{cm}^2\right)$$

Step 37. Calculate the number of secondary strands, S_{ns}.

$$S_{ns}=\frac{A_{ws}}{\#26\text{ (bare area)}}$$

$$S_{ns}=\frac{0.0349}{0.00128}$$

$$S_{ns}=27.2 \text{ use } 27$$

Step 38. Calculate the secondary, the new $\mu\Omega$/cm.

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

$$(\text{new})\,\mu\Omega/\text{cm}=\frac{1345}{27}$$

$$(\text{new})\,\mu\Omega/\text{cm}=49.8$$

Step 39. Calculate the secondary winding resistance, R_s.

$$R_s=\text{MLT}\left(N_s\right)\left(\frac{\mu\Omega}{\text{cm}}\right)\left(10^{-6}\right),\quad \text{(ohms)}$$

$$R_s=(5.6)(3)(49.8)\left(10^{-6}\right),\quad \text{(ohms)}$$

$$R_s=0.000837,\quad \text{(ohms)}$$

Step 40. Calculate the secondary copper loss, P_s.

$$P_s=I_{s(rms)}^2R_s,\quad \text{(watts)}$$

$$P_s=(15.8)^2(0.000837),\quad \text{(watts)}$$

$$P_s=0.209,\quad \text{(watts)}$$

Step 41. Calculate the window utilization, K_u.

$$K_u=\frac{\left(N_{np}S_{np}A_{wp}\right)+\left(N_sS_{ns}A_{ws}\right)}{W_a}$$

$$K_u=\frac{(10)(7)(0.00128)+(3)(27)(0.00128)}{0.604}$$

$$K_u=0.32$$

Step 42. Calculate the total copper loss, P_{cu}.

$$P_{cu}=P_s+P_p,\quad \text{(watts)}$$

$$P_{cu}=0.209+0.162,\quad \text{(watts)}$$

$$P_{cu}=0.371,\quad \text{(watts)}$$

Step 43. Calculate the transformer regulation, α.

$$\alpha=\frac{P_{cu}}{P_o}(100),\quad (\%)$$

$$\alpha=\frac{(0.371)}{(60)}(100),\quad (\%)$$

$$\alpha=0.618,\quad (\%)$$

Step 44. Calculate the ac flux density in tesla, B_{ac}.

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

$$B_{ac}=\frac{(1.257)(10)(1.116)\left(\frac{2.17}{2}\right)\left(10^{-4}\right)}{(0.0289)+\frac{4.63}{2500}},\quad \text{(tesla)}$$

$$B_{ac}=0.0495,\quad \text{(tesla)}$$

Step 45. Calculate the watts per kilogram, WK.

$$WK=Kf^{(m)}B^{(n)},\quad \text{(watt/kg)}$$

$$WK=\left(4.855x10^{-5}\right)(100{,}000)^{(1.64)}(0.0495)^{(2.62)},\quad \text{(watts/kg)}$$

$$WK=2.92,\quad \text{(watts/kg) or (milliwatts/gram)}$$

Step 46. Calculate core loss, P_{fe}.

$$P_{fe}=\left(\frac{\text{milliwatts}}{\text{gram}}\right)W_{tfe}x10^{-3},\quad \text{(watts)}$$

$$P_{fe}=(2.92)(31)x10^{-3},\quad \text{(watts)}$$

$$P_{fe}=0.0905,\quad \text{(watts)}$$

Step 47. Calculate the total loss, P_Σ.

$$P_\Sigma = P_{fe} + P_{cu}, \quad (\text{watts})$$
$$P_\Sigma = 0.0905 + 0.371, \quad (\text{watts})$$
$$P_\Sigma = 0.462, \quad (\text{watts})$$

Step 48. Calculate the watt density, ψ.

$$\psi = \frac{P_\Sigma}{A_t}, \quad (\text{watts/cm}^2)$$
$$\psi = \frac{0.462}{28.4}, \quad (\text{watts/cm}^2)$$
$$\psi = 0.0163, \quad (\text{watts/cm}^2)$$

Step 49. Calculate the temperature rise, T_r, in degrees C.

$$T_r = 450(\psi)^{(0.826)}, \quad (\text{degrees C})$$
$$T_r = 450(0.0163)^{(0.826)}, \quad (\text{degrees C})$$
$$T_r = 15, \quad (\text{degrees C})$$

ACKNOWLEDGEMENT

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REFERENCE

[1] McLyman, C., "Transformer and Inductor Design Handbook," 3rd ed., Marcel Dekker, New York, 2000

APPENDIX

Glossary of Terms

α = regulation (copper loss), [%]
A_c = core iron area, [cm^2]
A_p = area product, [cm^4]
A_t = surface area, [cm^2]
A_w = wire area, [cm^2]
$A_{wp(B)}$ = primary bare wire area, [cm^2]
$A_{ws(B)}$ = secondary bare wire area, [cm^2]
B_{ac} = ac flux density, [tesla]
B_m = operating flux density, [tesla]
B_{pk} = peak flux density, [tesla]
D_{max} = maximum duty ratio
D_{min} = minimum duty ratio
ε = skin depth, [cm]
Energy = energy-handling, [watt-second]
η = converter efficiency, [%]
η_T = transformer efficiency, [%]
F = fringing flux factor
f = frequency, [hertz]
G = winding length, [cm]
ΔI_p = primary delta current, [amps]
ΔI_s = secondary delta current, [amps]
$\Delta I_{p(rms)}$ = primary delta rms current, [amps]
$\Delta I_{s(rms)}$ = secondary delta rms current, [amps]
$I_{in(max)}$ = input current maximum, [amps]
$I_{o(max)}$ = output current maximum, [amps]
$I_{o(min)}$ = output current minimum, [amps]
$I_{p(pk)}$ = primary peak current, [amps]
$I_{s(pk)}$ = secondary peak current, [amps]
$I_{p(rms)}$ = primary rms current, [amps]
$I_{s(rms)}$ = secondary rms current, [amps]
J = current density, [amps/cm^2]
K_e = electrical conditions
K_g = core geometry, [cm^5]
K_u = window utilization
l_g = total gap, [cm]
L_p = primary inductance, [henrys]
L_s = secondary inductance, [henrys]
MLT = mean length turn, [cm]
MPL = magnetic path length, [cm]
N_{np} = new primary turns, [turns]
N_p = primary turns, [turns]
N_s = secondary turns, [turns]
P_{cu} = total copper loss, [watts]
P_{fe} = core loss, [watts]
$P_{in(min)}$ = input power minimum, [watts]
$P_{o(max)}$ = output power maximum, [watts]
$P_{o(min)}$ = output power minimum, [watts]
P_p = primary copper loss, [watts]
ψ = watt density, [watts/cm^2]
P_s = secondary copper loss, [watts]
P_Σ = total loss, [watts]
R_{ac} = ac resistance, [ohms]
R_{dc} = dc resistance, [ohms]
R_p = primary resistance, [ohms]
R_s = secondary resistance, [ohms]
S_{np} = number of primary strands
S_{ns} = number of secondary strands
T = total period, [seconds]
t_{off} = transistor off time, [µsec]
t_{on} = transistor on time, [µsec]
T_r = temperature rise, [°C]
μ_m = material permeability
V_d = diode voltage drop, [volts]
V_{max} = input voltage maximum, [volts]
V_{min} = input voltage minimum, [volts]
V_{nom} = input voltage nominal, [volts]
V_o = output voltage, [volts]
W_a = window area, [cm^2]
W_{ap} = primary window area, [cm^2]
WK = watts per kilogram, [watt/kg]
W_{tfe} = core weight, [grams]