AN115

Designing a Continuous Current 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}.

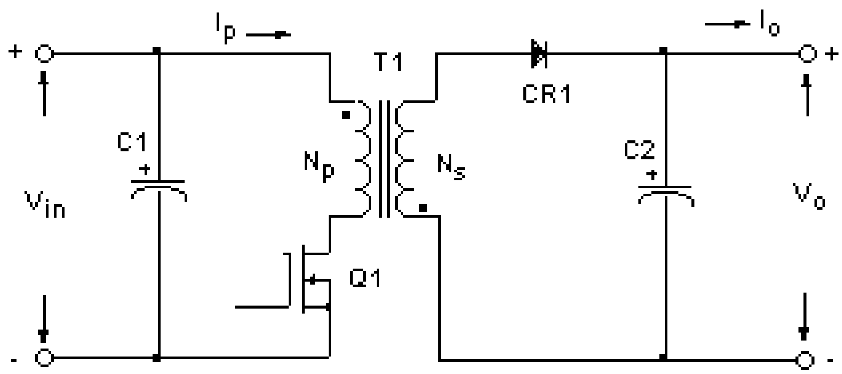

Figure 1. Buck-Boost isolated, continuous, current converter.

Energy Transfer
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 2. The continuous current B-H is shown in Figure 3.

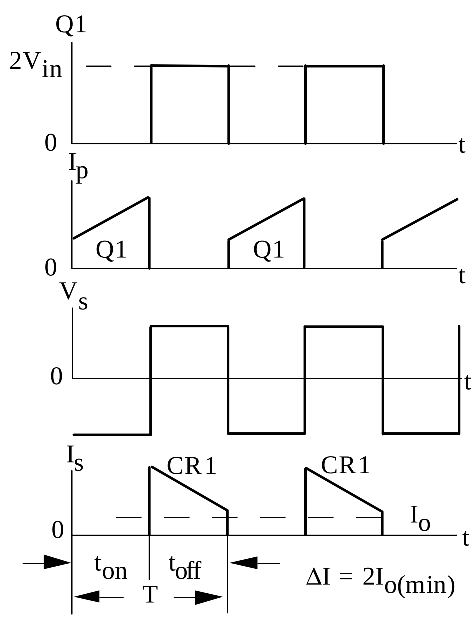

Figure 2. Isolated, buck-boost, ideal voltage and current waveforms.

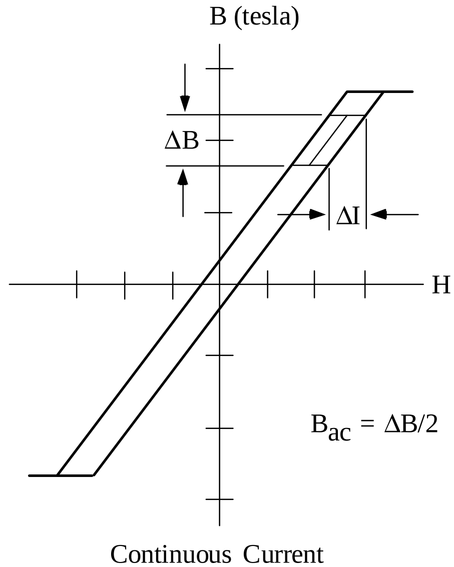

Figure 3. B-H loop for the continuous current buck-boost converters.

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.

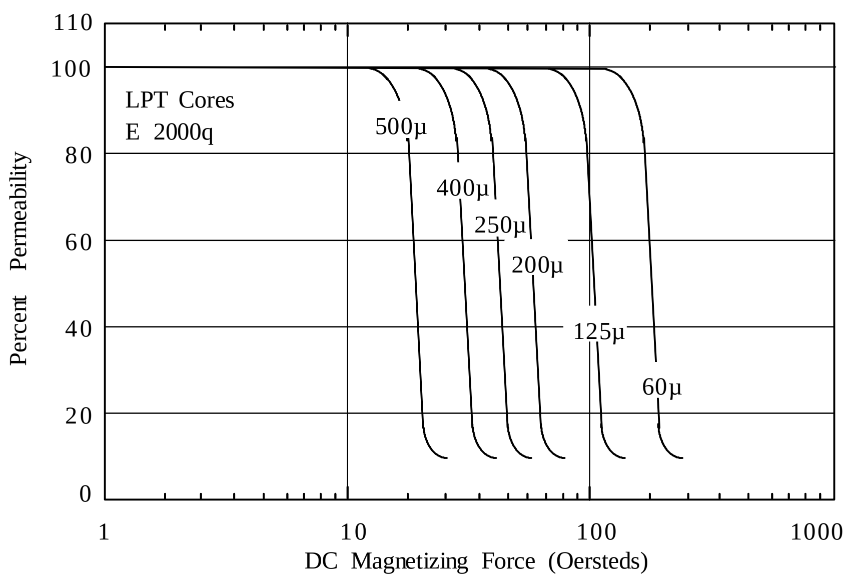

Figure 4. DC magnetization curves for LPT cores.

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

Buck-Boost Isolated Continuous Current Design Specification

1. Input voltage max .... V_{max} = 32 V
2. Input voltage nom .... V_{nom} = 28 V
3. Input voltage min .... V_{min} = 24 V
4. Output voltage .... V_o = 5 V
5. Output current .... I_o = 10 A
6. Output current .... $I_{o(min)}$ = 2 A
7. Window utilization .... K_u = 0.4
8. Frequency .... f = 100 kHz
9. Transformer efficiency .... η = 98 %
10. Maximum duty ratio.. D_{max} = 0.5
11. Regulation .... α = 0.5 %
12. Operating flux density .... B_m = 0.8 T
13. Diode voltage .... V_d = 1.0 V
14. Temperature rise .... T_r = < 30°C

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, DI, and is normally only a fraction of the dc flux. In this design of a continuous current buck-boost converter, both the dc current density and the high frequency ac current density, will be calculated. In many cases, the ac current that is riding on top of the dc current is small enough that it does not effect the overall current density of the single wire used. 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.

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

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

$$T = \frac{1}{100000} = 10[ms]$$

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

$$t_{on} = TD_{max}$$

$$t_{on} = 10 \cdot 10^{-6} \cdot 0.5 = 5 \ [ms]$$

Step No. 3. Calculate the minimum duty ratio, D_{min}.

$$D_{min} = \frac{V_{min}}{V_{max}} D_{max}$$

$$D_{min} = \frac{24}{32} \cdot 0.5 = 0.375$$

Step No. 4. Calculate the secondary, maximum load power, $P_{o(max)}$.

$$P_{o(\max)} = I_o \left(V_o + V_d\right)$$

$$P_{o(\max)} = 10 \cdot (5+1) = 60 \text{ [W]}$$

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

$$P_{o(\min)} = I_{o(\min)} \left(V_o + V_d\right)$$

$$P_{o(\min)} = 2 \cdot (5+1) = 12 \text{ [W]}$$

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

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

$$I_{in(\max)} = \frac{60}{24 \cdot 0.98} = 2.55 \text{ [A]}$$

Step No. 7. Calculate the minimum, input power, P $_{in(min)}$.

$$P_{in(\min)} = \frac{P_o}{h}$$

$$P_{in(\min)} = \frac{12}{0.98} = 12.2 \text{ [W]}$$

Step No. 8. Calculate the required, primary inductance, L_p.

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

$$L_p = \frac{32 \cdot 0.375^2 \cdot 10 \cdot 10^{-6}}{2 \cdot 12.2} = 59 \text{ [}m\text{H]}$$

Step No. 9. Calculate the primary, delta current, I $_p$.

$$\Delta I_p = \frac{D_{\max} T V_{\min}}{L_p}$$

$$\Delta I_p = \frac{0.5 \cdot 10 \cdot 10^{-6} \cdot 24}{59 \cdot 10^{-6}} = 2.03 \text{ [A]}$$

Step No. 10. Calculate the primary, delta rms current, I $_{p(rms)}$.

$$\Delta I_{p(\mathrm{rms})} = \Delta I_p \sqrt{\frac{t_{on}}{3T}}$$

$$\Delta I_{p(\mathrm{rms})} = 2.03 \cdot \sqrt{\frac{5}{3 \cdot 10}} = 0.829 \text{ [A]}$$

Step No. 11. Calculate the primary, peak current, I_{pk}

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

$$I_{in(\max)} = \frac{60}{24 \cdot 0.98} = 2.55 \text{ [A]}$$

Step No. 12. Calculate the primary, rms current, I_{rms}.

$$I_{rms} = \sqrt{\left(I_{pk}^2 - I_{pk} \cdot \Delta I + \frac{(\Delta I)^2}{3}\right) \cdot D_{max}}$$

$$I_{rms} = \sqrt{\left(6.12^2 - 6.12 \cdot 2.03 + \frac{2.03^2}{3}\right) \cdot 0.5} = 3.63 \text{ [A]}$$

Step No. 13. Calculate the energy-handling capability in Watt-seconds, W-s.

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

$$\text{Energy} = \frac{59 \cdot 10^{-6} \cdot 6.12^2}{2} = 0.0011 \text{ [W-s]}$$

Step No. 14. Calculate the electrical conditions, K_e.

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

$$K_e = 0.145 \cdot 60 \cdot 0.8^2 \cdot 10^4 = 0.000557$$

Step No. 15. Calculate the core geometry, K_g.

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

$$K_g = \frac{0.0011^2}{0.00057 \cdot 0.5} = 0.00435 \text{ [cm}^5\text{]}$$

Step No. 16. Select, from the data sheet, a LPT core, comparable in core geometry, K_g.

Core number.. GC60112Q
Manufacturer .... CMI
Magnetic path length .... MPL = 5.11 cm
Core weight .... W_{tfe} = 9.5 g
Copper weight .... W_{tcu} = 10.3 g
Mean length turn .... MLT = 3.4 cm
Window Area .... W_a = 0.849 cm^2
Area Product .... A_p = 0.204 cm^4
Core geometry... K_g = 0.005938 cm^5
Surface area .... A_t = 25.6 cm^2
Core Permeability.. μ = 250
Millihenrys per 1000 turns .... mH = 151

Step No. 17. Calculate the current density, J, using a window utilization K_u = 0.4.

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

$$J = \frac{2 \cdot 0.0011 \cdot 10^4}{0.204 \cdot 0.8 \cdot 0.4} = 387 \text{ [A/cm}^2\text{]}$$

Step No. 18. Calculate the required permeability, Δμ.

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

$$\Delta m = \frac{0.8 \cdot 5.11 \cdot 10^4}{0.4 \cdot 3.14 \cdot 0.849 \cdot 387 \cdot 0.4} = 248 \text{ use } 250$$

Step No. 19. Calculate the number of turns, N.

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

$$N = 1000 \cdot \sqrt{\frac{0.059}{151}} = 19.8 \text{ use } 20 \text{ [turns]}$$

Step No. 20. Calculate the peak flux density, B_m.

$$B_m = \frac{0.4p\,(N)(I_{pk})(m_r)\,\text{x}10^{-4}}{MPL}$$

$$B_m = \frac{1.256 \cdot 20 \cdot 6.12 \cdot 250 \cdot 10^{-4}}{5.11} = 0.752 \text{ [T]}$$

Step No. 21. Calculate the primary wire area, $A_{pw(B)}$, using a window utilization, $K_{pu} = 0.2$.

$$A_{pw(B)} = \frac{W_a \cdot K_{pu}}{N_p}$$

$$A_{pw(B)} = \frac{0.849 \cdot 0.2}{20} = 0.00849 \text{ [cm}^2\text{]}$$

Step No. 22. 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.

$$\text{AWG} = \#18$$

$$A_{w(B)} = 0.00823 \quad \text{[cm}^2\text{]}$$

$$m\Omega / cm = 210$$

Step No. 23. Calculate the primary, current density, wire area, J_p.

$$J_p = \frac{I_{prms}}{A_{pw(B)}}$$

$$J_p = \frac{3.63}{0.00849} = 428 \text{ [A/cm}^2\text{]}$$

Step No. 24. Calculate the skin depth, ε. The skin depth will be the radius of the wire.

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

$$e = \frac{6.62}{\sqrt{100 \cdot 10^3}} = 0.0209 \text{ [cm]}$$

Step No. 25 Calculate the diameter of the primary wire, AWG 18, from Step 22.

$$D = \sqrt{\frac{4 \cdot A_{W(B)}}{p}}$$

$$D = \sqrt{\frac{4 \cdot 0.00823}{3.14}} = 0.102 \text{ [cm]}$$

Step No. 26. Subtract two times the skin depth, ε from the diameter, and calculate the new area.

$$D_n = D - 2e$$

$$D_n = 0.102 - 2 \cdot 0.0209 = 0.0602 \text{ [cm]}$$

$$A_n = \frac{p\,D_n^2}{4}$$

$$A_n = \frac{3.14 \cdot 0.0602^2}{4} = 0.00285 \text{ [cm}^2\text{]}$$

Step No. 27. Take the difference between area, $A_{w(B)}$, and the new area, A_n. This will be the area for the ΔI current.

$$A_{\Delta I} = A_{w(B)} - A_n$$

$$A_{\Delta I} = 0.00823 - 0.00241 = 0.00402 \text{ [cm}^2\text{]}$$

Step No. 28. Calculate the primary delta current $\Delta I_{p(rms)}$, current density, J.

$$J = \frac{\Delta I_{p(\text{rms})}}{A_{\Delta I}}$$

$$J = \frac{0.829}{0.00402} = 206 \text{ [A/cm}^2\text{]}$$

$\Delta I_{p(rms)}$ current density J = 206 A / cm^2

I_{dc} current density J = 428 A / cm^2

$\Delta I_{p(rms)}$ current density < I_{dc} current density

Step No. 29. Calculate the primary, winding resistance, R_p.

$$R_p = MLT \cdot N_p \cdot \left(\frac{m\Omega}{cm}\right) \cdot 10^{-6}$$

$$R_p = 3.4 \cdot 20 \cdot 210 \cdot 10^{-6} = 0.0143 \text{ [}\Omega\text{]}$$

Step No. 30. Calculate the primary, copper loss, P_p.

$$P_p = I_{p(rms)}^2 \cdot R_p$$

$$P_p = 3.63^2 \cdot 0.0143 = 0.188 \text{ [W]}$$

Step No. 31. Calculate the secondary turns, N_s.

$$N_s = \frac{N_p \cdot (V_o + V_d) \cdot (1 - D_{\max})}{V_p \cdot D_{\max}}$$

$$N_s = \frac{20 \cdot (5+1) \cdot (1-0.5)}{24 \cdot 0.5} = 5 \text{ [turns]}$$

Step No. 32. Calculate the secondary inductance, L_s.

$$L_s = N_s^2 \cdot (LMT) \cdot 10^{-9}$$

$$L_s = 5^2 \cdot 151 \cdot 10^{-9} = 3.78 \cdot 10^{-6} \text{ [H]}$$

Step No. 33. Calculate the secondary, delta current, I .

$$\Delta I_s = \frac{(V_o + V_d) \cdot T \cdot D_{\min}}{L_s}$$

$$\Delta I_s = \frac{(5+1.0) 10 \cdot 10^{-6} \cdot 0.375}{3.78 \cdot 10^{-6}} = 5.95 \text{ [A]}$$

Step No. 34. Calculate the secondary, delta rms current, $I_{p(rms)}$.

$$\Delta I_{s(\mathrm{rms})} = \Delta I_p \cdot \sqrt{\frac{T \cdot (1 - D_{\min})}{3 \cdot T}}$$

$$\Delta I_{s(\mathrm{rms})} = 5.95 \cdot \sqrt{\frac{10 \cdot 0.625}{3 \cdot 10}} = 2.72 \text{ [A]}$$

Step No. 35. Calculate the secondary, peak current, $I_{s(pk)}$.

$$I_{s(pk)} = \frac{P_o}{(V_o + V_d) \cdot (1 - D_{\max})} + \frac{\Delta I}{2}$$

$$I_{s(pk)} = \frac{60}{6.0 \cdot (1-0.5)} + \frac{5.95}{2} = 23 \text{ [A]}$$

Step No. 36. Calculate the peak flux, density, B_m.

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

$$B_m = \frac{1.256 \cdot 20 \cdot 6.12 \cdot 250 \cdot 10^{-4}}{5.11} = 0.752 \text{ [T]}$$

Step No. 37. Calculate the secondary, rms current, $I_{s(rms)}$.

$$I_{s(rms)} = \sqrt{\left(I_{pk}^2 - I_{pk} \cdot \Delta I + \frac{\Delta I^2}{3}\right) \cdot (1 - D_{\min})}$$

$$I_{s(rms)} = \sqrt{\left(23^2 - 23 \cdot 5.95 + \frac{5.95^2}{3}\right) \cdot 0.625} = 15.8 \text{ [A]}$$

Step No. 38 Calculate the secondary, wire area, $A_{sw(B)}$, using a window utilization, $K_{su} = 0.2$.

$$A_{sw(B)} = \frac{W_a \cdot K_{su}}{N_s}$$

$$A_{sw(B)} = \frac{0.849 \cdot 0.2}{5} = 0.034 \text{ [cm}^2\text{]}$$

Step No. 39 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.

$$AWG = \#12$$

$$A_{sw} = 0.0331 \text{ [cm}^2\text{]}$$

$$m\Omega / cm = 52.1$$

Step No. 40. Calculate the secondary $I_{s(rms)}$, current density, wire area, J_S.

$$J_s = \frac{I_{srms}}{A_{sw(B)}}$$

$$J_s = \frac{15.3}{0.0331} = 477 \text{ [A/cm}^2\text{]}$$

Step No. 41. Calculate the diameter of the secondary wire, AWG 12, from Step 39.

$$D = \sqrt{\frac{4 \cdot A_{w(B)}}{p}}$$

$$D = \sqrt{\frac{4 \cdot 0.0331}{3.1416}} = 0.205 \text{ [cm]}$$

Step No. 42. Subtract two times the skin depth, ε from the diameter, and calculate the new area.

$$D_n = D - 2e$$

$$D_n = 0.205 - 2 \cdot 0.0209 = 0.163 \text{ [cm]}$$

$$A_n = \frac{p\, D_n^2}{4}$$

$$A_n = \frac{3.14 \cdot 0.163^2}{4} = 0.209 \text{ [cm}^2\text{]}$$

Step No. 43. Take the difference between area, $A_{w(B)}$, and the new area, A_n. This will be the area for the ΔI current.

$$A_{\Delta I} = A_{w(B)} - A_n$$

$$A_{\Delta I} = 0.034 - 0.0209 = 0.0131 \text{ [cm}^2\text{]}$$

Step No. 44. Calculate the secondary delta current $\Delta I_{s(rms)}$, current density, J.

$$J = \frac{\Delta I_{s(\mathrm{rms})}}{A_{\Delta I}}$$

$$J = \frac{2.72}{0.0131} = 208 \text{ [A/cm}^2\text{]}$$

$\Delta I_{s(rms)}$ current density J = 208 A / cm^2

I_{dc} current density J = 477 A / cm^2

$\Delta I_{s(rms)}$ current density < I_{dc} current density

Step No. 45. Calculate the winding resistance, R_s.

$$R_s = MLT \cdot N_s \cdot \left(\frac{m\Omega}{cm}\right) \cdot 10^{-6}$$

$$R_s = 3.4 \cdot 5 \cdot 52.1 \cdot 10^{-6} = 0.000886 \ [\Omega]$$

Step No. 46. Calculate the secondary, copper loss, P_s.

$$P_s = I_s^2 R_s$$

$$P_s = 15.8^2 \cdot 0.000886 = 0.221 \text{ [W]}$$

Step No. 47. Calculate the window utilization, K_u.

$$K_u = \frac{N_p \cdot A_{pw} + N_s \cdot A_{sw}}{W_a}$$

$$K_u = \frac{20 \cdot 0.00823 + 50.0331}{0.849} = 0.389$$

Step No. 48. Calculate the total copper loss, P_{cu}.

$$P_{cu} = P_p + P_s$$

$$P_{cu} = 0.188 + 0.221 = 0.409 \text{ [W]}$$

Step No. 49. Calculate the regulation, α, for this design.

$$a = \frac{P_{cu}}{P_o} \text{x}100$$

$$a = \frac{0.409}{60} \cdot 100 = 0.682 \text{ [\%]}$$

Step No. 50. Calculate the magnetizing force in oersteds, Oe.

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

$$H = \frac{0.4 \cdot 3.14 \cdot 20 \cdot 6.12}{5.11} = 30.1 \text{ [Oe]}$$

Now that the magnetizing force, H, has been calculated, the next step is to see if this magnetizing force could saturate the core. In Figure 4, there is a curve for 250 perm material, located on the horizontal axis of the 30 Oersteds mark. The next step is to see where the 30 oersteds intersect the 250 perm curve. In this design, the inductor still has over 95% of its designed inductance.

Step No. 51. Calculate the ac flux density in tesla, B_{ac}.

$$B_{ac} = \frac{0.4p \cdot N_p \cdot \left(\frac{\Delta I}{2}\right) \cdot m_r \cdot 10^{-4}}{MPL}$$

$$B_{ac} = \frac{1.256 \cdot 20 \cdot 1.01 \cdot 250 \cdot 10^{-4}}{5.11} 0.124 \text{ [T]}$$

Step No. 52. Calculate the watts per kilogram, WK.

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

$$WK = 8.64 \cdot 10^{-7} \cdot 100{,}000^{1.834} \cdot 0.124^{2.112} = 15.6 \text{ [W/kg]}$$

Step No. 53. Calculate the core loss, P_{fe} .

$$P_{fe} = \left(\frac{\text{mW}}{\text{g}}\right) \cdot W_{tfe} \cdot 10^{-3}$$

$$P_{fe} = 15.6 \cdot 9.5 \cdot 10^{-3} = 0.148 \text{ [W]}$$

Step No. 54. Calculate the total loss P_{Σ}, core P_{fe} and copper P_{cu}, in Watts.

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

$$P_{\Sigma} = 0.148 + 0.409 = 0.557 \text{ [W]}$$

Step No. 55. Calculate the watt density, ψ.

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

$$y = \frac{0.557}{25.6} = 0.0217 \text{ [W/cm}^2\text{]}$$

Step No. 56. Calculate the temperature rise in degrees, C.

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

$$T_r = 450 \cdot 0.0217^{0.826} = 19 \text{ [°C]}$$

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