AN106

Designing a Single-Ended, Forward Converter
Using a CoreMaster E2000Q Core

By
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The single-ended converter shown in Figure 1 has become one of the most popular, and widely-used topology for powers under 200W.

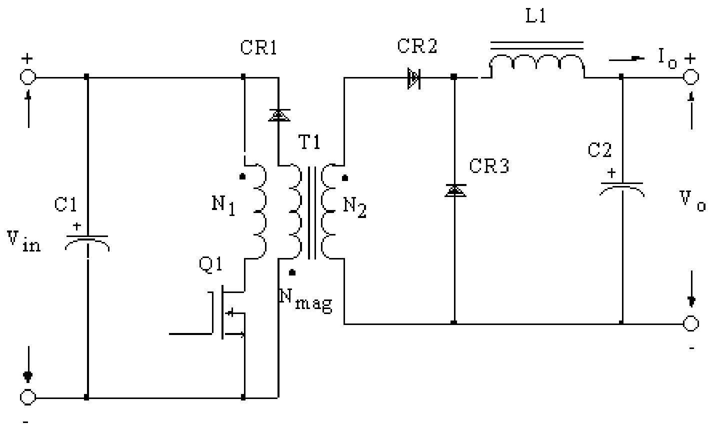


Figure 1. Typical single-ended, forward converter

The dynamic BH loops for the single-ended, forward converter and the push-pull converter are shown in Figure 2.

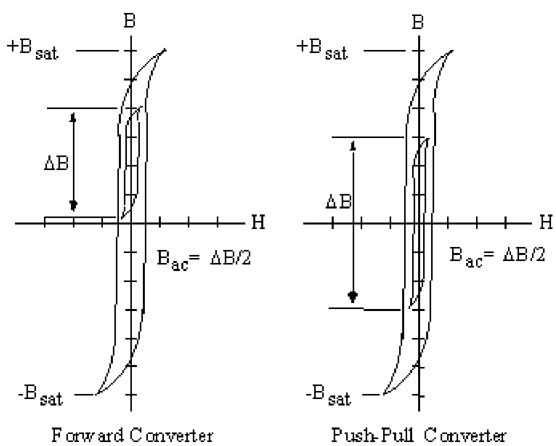


Figure 2. The dynamic BH loop comparison between a single-ended, forward converter and a push-pull converter.

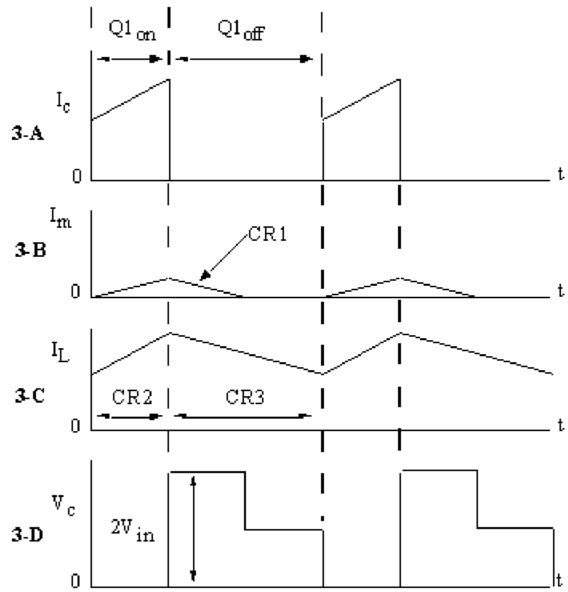


Figure 3. Typical single-ended forward, converter waveforms

The waveforms shown in Figure 3 are typical waveforms of the single-ended forward converter. The collector current I_C is shown in Figure 3-A, and the magnetizing current I_M is shown in Figure 3-B. The inductor L1 current, I_L, made up from the rectifier CR2, and the commutating rectifier, CR3, are shown in Figure 3-C. The collector voltage, V_C, is shown in Figure 3-D.

For a typical design example, assume a single-ended converter circuit, as shown in Figure 1, with the following specification:

1.	Input voltage nominal	$V_{nom} = 28$ V
2.	Input voltage minimum	$V_{min} = 24$ V
3.	Input voltage maximum	$V_{max} = 32$ V
4.	Output voltage	$V_O = 5$ V
5.	Output current	$I_O = 2.5$ A
6.	Frequency	f=100 kHz
7.	Temperature rise	$T_r = 20$ ° C
8.	Efficiency	$\eta = 98$ %
9.	Regulation	$\alpha = 1.0$ %
10.	Diode voltage drop	$V_d = 1$ V
11.	Design flux density	$\Delta B = 0.1$ Tl, $B_{ac} = \Delta B/2$
12.	Use window utilization	$D_{max} = 0.5$
14.	Demag turns ratio	$N_{mag}/N_p = 1$
15.	Demag power	$P_{mag} = 0.1P_O$

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 cm is:

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

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

Then, the wire diameter is:

Wire diameter = 2*d*

Wire diameter = $2 \cdot 0.0209 = 0.0418$ [cm]

Then, the bare wire area A_W is:

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

$$A_W = \frac{3.1416 \cdot 0.0418^2}{4} = 0.00137 [\text{cm}^2]$$

From the Wire Table, number 26 has a bare wire area of 0.001280 cm^2. 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 transformer output power, P_O.

$$P_O = I_O (V_O + V_d)$$

$$P_O = 2.5 \cdot (5+1) = 15 \text{ [W]}$$

Step No. 2. Calculate the input power, P_{IN}.

$$P_{IN} = \frac{P_O \cdot 1.1}{h}$$

$$P_{IN} = \frac{15 \cdot 1.1}{0.98} = 16.8 \text{ [W]}$$

Step No. 3. Calculate the electrical coefficient, K_e

$$K_e = 0.145 f^2 \Delta B^2 \cdot 10^{-4}$$

$$K_e = 0.145 \cdot 100{,}000^2 \cdot 0.1^2 \cdot 10^{-4} = 1450$$

Step No. 4. Calculate the core geometry, K_g

$$K_g = \frac{P_{IN} D_{MAX}}{a K_e}$$

$$K_g = \frac{16.8 \cdot 0.5}{1.0 \cdot 1450} = 0.00579 \text{ [cm}^5]$$

Step No. 6. Select from the data sheet a E 2000Q core comparable in core geometry, K_g.

Core number	TEA0112Q
Manufacturer	CMI
Magnetic material	E2000Q

Magnetic path length, MPL	5.10 cm
Core weight, W_{tfe}	9.50 g
Copper weight, W_{tcu}	10.30 g
Mean length turn, MLT	3.4 cm
Iron area, A_c	0.24 cm^2
Window area, W_a	0.87 cm^2
Area product, A_p	0.2078 cm^4
Core geometry, K_g	0.005937 cm^5
Surface area, A_t	24.9 cm^2

Step No. 7. Calculate the number of primary turns, N_p.

$$N_p = \frac{V_{IN(MIN)} D_{MAX} \cdot 10^4}{f A_c \Delta B}$$

$$N_P = \frac{24 \cdot 0.5 \cdot 10^4}{100{,}000 \cdot 0.24 \cdot 0.1} = 50 \text{ [turns]}$$

Step No. 8. Calculate the current density J using a window utilization, $K_u = 0.4$.

$$J = \frac{2 P_{IN} \sqrt{D_{\max}} \cdot 10^4}{f A_C \Delta B W_a K_u}$$

$$J = \frac{2 \cdot 16.8 \cdot 0.707 \cdot 10^4}{100{,}000 \cdot 0.24 \cdot 0.1 \cdot 0.87 \cdot 0.4} = 284 \text{ [A/cm}^2\text{]}$$

Step No. 9. Calculate the primary rms current, I_P.

$$I_P = \frac{P_{IN}}{V_{IN} \sqrt{D_{MAX}}}$$

$$I_P = \frac{16.8}{24 \cdot 0.707} = 0.99 \text{ [A]}$$

Step No. 10. Calculate the primary bare wire area, $A_{wp(B)}$.

$$A_{wp(B)} = \frac{I_P}{J}$$

$$A_{wp(B)} = \frac{0.99}{284} = 0.00348 \text{ [cm}^2\text{]}$$

Step No. 11. Calculate the required number of primary strands, NS_p.

$$NS_P = \frac{A_{wp(B)}}{\#26}$$

$$NS_P = \frac{0.00348}{0.00128} = 2.72 \text{ use } 3$$

Step No. 12. Calculate the primary new μΩ/cm.

$$new m\Omega / cm = \frac{m\Omega / cm}{NS_p}$$

$$new m\Omega / cm = \frac{1345}{3} = 448$$

Step No. 13. Calculate the primary resistance, R_p.

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

$$R_P = 3.4 \cdot 50 \cdot 448 \cdot 10^{-6} = 0.076 \; [\Omega]$$

Step No. 14. Calculate the primary copper loss, P_P.

$$P_P = I_P{}^2 R_P$$

$$P_P = 0.99^2 \cdot 0.076 = 0.0745 \; [\text{W}]$$

Step No. 15. Calculate the secondary turns, N_S.

$$N_S = \frac{N_P \left(V_O + V_d \right)}{D_{MAX} V_{IN(MIN)}} \left(1 + \frac{a}{100} \right)$$

$$N_S = \frac{50 \cdot (5+1)}{0.5 \cdot 24} \left(1 + \frac{1.0}{100} \right) = 25 \; [\text{turns}]$$

Step No. 16. Calculate the secondary rms current, I_S.

$$I_S = \frac{I_O}{\sqrt{2}}$$

$$I_S = \frac{2.4}{1.41} = 1.77 \; [\text{A}]$$

Step No. 17. Calculate the secondary bare wire area, A_{ws}.

$$A_{ws(B)} = \frac{I_S}{J}$$

$$A_{ws(B)} = \frac{1.77}{284} = 0.00623 \; [\text{cm}^2]$$

Step No. 18. Calculate the required number of secondary strands, NS_s.

$$NS_S = \frac{A_{ws(B)}}{\#26}$$

$$NS_S = \frac{0.00623}{0.00128} = 4.87 \text{ use } 4$$

Step No. 19. Calculate the secondary, new μΩ/cm.

$$(new) m\Omega / cm = \frac{m\Omega / cm}{NS_S}$$

$$(new) m\Omega / cm = \frac{1345}{4} = 336$$

Step No. 20. Calculate the secondary winding resistance, R_S.

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

$$R_S = 3.4 \cdot 25 \cdot 336 \cdot 10^{-6} = 0.0252 \; [\Omega]$$

Step No. 21. Calculate the secondary copper loss, P_S.

$$P_S = I_S{}^2 R_S$$

$$P_S = 1.77^2 \cdot 0.0252 = 0.0789 \; [\text{W}]$$

Step No. 22. Calculate the total primary and secondary copper loss, P_{cu}.

$$P_{CU} = P_P + P_S$$

$$P_{CU} = 0.0745 + 0.0789 = 0.153 \; [\text{W}]$$

Step No. 23. Calculate the transformer regulation, α.

$$a = \frac{P_{CU}}{P_O}$$

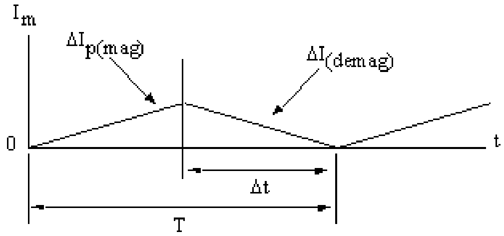
$$a = \frac{0.153}{15} \cdot 100 = 1.02\%$$

Step No. 24. Calculate the demag winding inductance, L_{demag}.

$$L_{demag} = L_{1000} N_{demag}^2 \cdot 10^{-6}$$

$$L_{demag} = 1{,}7731 \cdot 50^2 \cdot 10^{-6} = 44.3 \text{ [mH]}$$

Step No. 25. Calculate the time of, Δt.



$$\Delta t = TD_{MAX}$$

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

$$T = \frac{1}{100{,}000} = 10 \cdot 10^{-6} \text{ [s]}$$

$$\Delta t = 10 \cdot 10^{-6} \cdot 0.5 = 5 \cdot 10^{-6} \text{[s]}$$

Step No. 26. Calculate the demag winding delta current, ΔI.

$$\Delta I_{demag} = \frac{V_{in} \Delta t}{I_{demag}}$$

$$\Delta I_{demag} = \frac{24 \cdot 5 \cdot 10^{-6}}{0.0443} = 0.0027 \text{ [A]}$$

Step No. 27. Calculate the demag winding rms current, I_{demag}. This is the rms equation for a saw tooth current.

$$I_{demag} = \Delta I \sqrt{\frac{D_{MAX}}{3}}$$

$$I_{demag} = 0.0027 \cdot 0.408 = 0.0011 \text{ [A]}$$

Step No. 28. Calculate the required demag wire area, $A_{W(demag)}$.

$$A_{W(demag)} = \frac{I_{demag}}{J}$$

$$A_{W(demag)} = \frac{0.0011}{284} = 0.00000387, \;\; \approx \;\; \text{\#51 use a 26}$$

Step No. 29. Calculate the window utilization K_U.

$$K_U = \frac{NA_{W(\#26)}}{W_a}$$

$$N = N_P \cdot NS_P + N_S \cdot NS_S + N_{demag} \cdot NS_{demag}$$

$$N = 50 \cdot 3 + 25 \cdot 4 + 50 \cdot 1 = 300$$

$$K_U = \frac{300 \cdot 0.00128}{0.87} = 0.441$$

Step No. 30. Calculate the, mW/g.

$$mW/g = 8.64 \cdot 10^{-7} \cdot f^{1.834} \cdot B_{AC}^{2.1122}$$

$$mW/g = 8.64 \cdot 10^{-7} \cdot 100{,}000^{1.834} \cdot 0.05^{2.1122} = 2.27$$

Step No. 31. Calculate the core loss, P_{Fe}.

$$P_{Fe} = (mW/g) \cdot W_{tfe} \cdot 10^{-3}$$

$$P_{Fe} = 2.27 \cdot 9.5 \cdot 10^{-3} = 0.022 \text{ [W]}$$

Step No. 32. Calculate the total loss, P_Σ.

$$P_\Sigma = P_{Cu} + P_{Fe}$$

$$P_\Sigma = 0.153 + 0.022 = 0.175 \text{ [W]}$$

Step No. 33. Calculate the Watts per unit area, Ψ.

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

$$\Psi = \frac{0.175}{24.9} = 0.00703 \text{ [W/cm}^2\text{]}$$

Step No. 34. Calculate the temperature rise, T_r.

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

$$T_r = 450 \cdot 0.00703^{0.826} = 7.49 \text{ [}^\circ\text{C]}$$

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