# Chapter 14

## Forward Converter, Transformer Design, and Output Inductor Design

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# Introduction

When speaking of a forward converter, the circuit that comes to mind is the single-ended, forward converter circuit, as shown in Figure 14-1. This single-ended, forward converter was developed about 1974 and has become one of the most popular and widely-used topology for powers under 200 W. The single-ended, forward converter gets its name from a family of converters. A description of a forward converter is that when current is flowing in the primary, there is current flowing in the secondary, and in the load. The push-pull converter, full-bridge converter, and half-bridge converter are all, basically, forward converters. The voltage stress on the single-forward converter is the same as it is on the push-pull converter, $2V_{in}$. This circuit's main advantage, that is so appealing to engineers is its simplicity and parts' count.
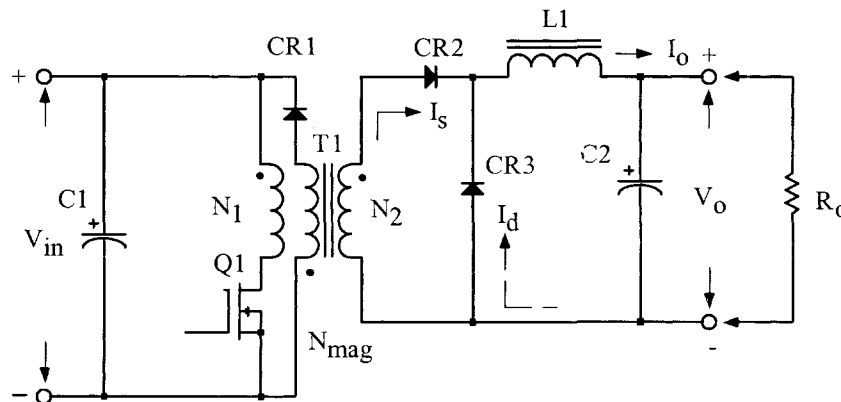


**Figure 14-1.** Schematic of a Single-Ended Forward Converter.

# Circuit Operation

The basic circuit operation of this single-ended, forward converter is as follows: When the drive is applied to, Q1, the secondary current, $I_s$, will flow through, CR2, and, L1, and into the load. This process is due to transformer action, (T1). At the same time, the magnetizing current begins to build up in the transformer primary. When the base drive to, Q1, is removed, then, Q1, turns off the magnetizing current that has built up in the primary. The magnetizing current continues to flow through the demagnetizing winding, $N_{mag}$ and CR1. The demagnetizing winding, $N_{mag}$, has the same number of turns as the primary winding. So, when the magnetizing field collapses, when Q1 is turned off, diode CR1 is clamped to the same voltage as the applied voltage during the $t_{on}$ time. This means the transistor on time, $t_{on}$, divided by the total time, T, must not exceed 0.5 or 50%. Otherwise, the forward volt-seconds will exceed the reset volt-second

capability and the transformer will saturate. To ensure smooth transfer of the magnetizing current, the primary and demagnetizing winding must be tightly coupled (bifilar). In a push-pull converter, the reset of the core occurs naturally on each alternate half cycle.

## Comparing the Dynamic B-H Loops

One of the main reasons for engineers to use the single-ended, forward converter circuit is the problem they have with the push-pull converter core-saturating. The core saturation can be due to an imbalance of the primary or secondary. The dynamic BH loops for the single-ended, forward converter and the push-pull converter are shown in Figure 14-2.



Single-Ended, Forward Converter        Push-Pull Converter
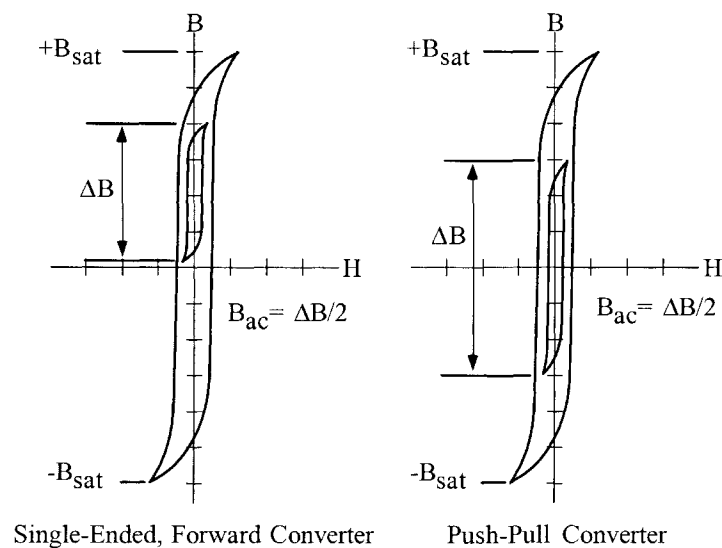
**Figure 14-2.** The dynamic BH loop comparison.

The average input current for the single-ended, forward converter is about the same as the push-pull converter, but the peak current is always greater than twice the average current. Operating the single-ended, forward converter at low input voltages, the high peak currents could be a component problem. The input filter and output filter for the single-ended, forward converter are always larger than the push-pull converter, because it is operating at the fundamental frequency.

The waveforms shown in Figure 14-3 are typical waveforms of the single-ended forward converter. The collector current, $I_c$, is shown in Figure (14-3-A), and the magnetizing current, $I_m$, is shown in Figure (14-3-B). The inductor, L1, current, $I_L$, made up from the rectifier, CR2, and the commutating rectifier, CR3, are shown in Figure (14-3-C). The collector voltage, $V_c$, is shown in Figure (14-3-D).

# Forward Converter Waveforms
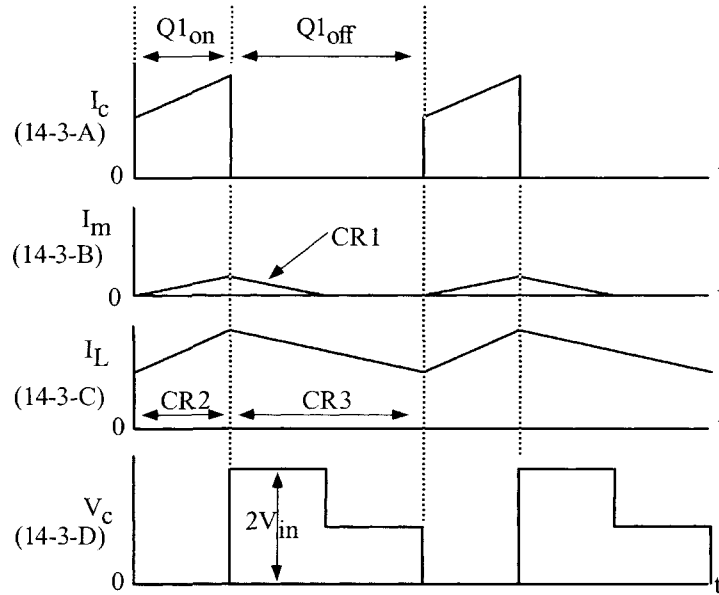


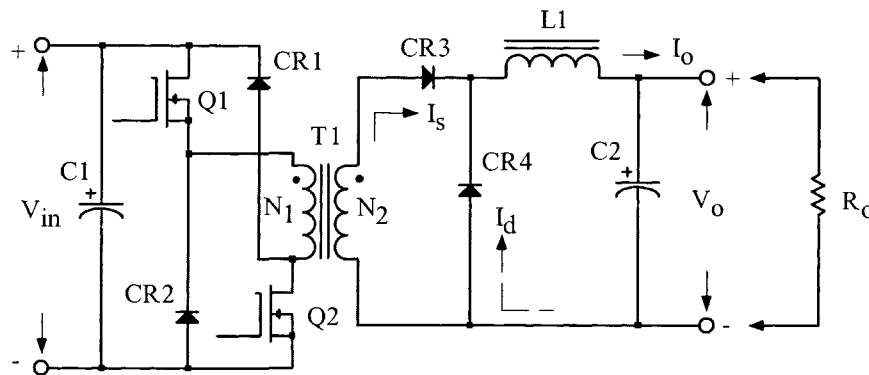**Figure 14-3.** Typical Single-Ended Forward, Converter Waveforms.

Another version of the classic, forward converter is the double-ended, forward converter, shown in Figure 14-4. The double-ended, forward converter has two transistors rather than one, compared to the single-ended, forward converter, shown in Figure 14-1. The double-ended forward converter is more complicated than the single-ended forward converter because one of the transistors is on the high side of the input voltage, but it has some significant advantages. The series switching transistors are subjected to only the input voltage, $(V_{in})$, rather than twice the input voltage, $(2V_{in})$. It also removes the need for a demagnetizing winding. The demagnetizing current now flows through the primary, through, CR1, and CR2, and back to the source, as shown in Figure 14-5. This demagnetizing path also provides a path for the energy stored in the leakage inductance. The resulting spiking voltage, caused from the leakage inductance, is now clamped to the input voltage, plus the two diode drops $(V_{in} + 2V_d)$.



**Figure 14-4.** Schematic of a Double-Ended Forward Converter.
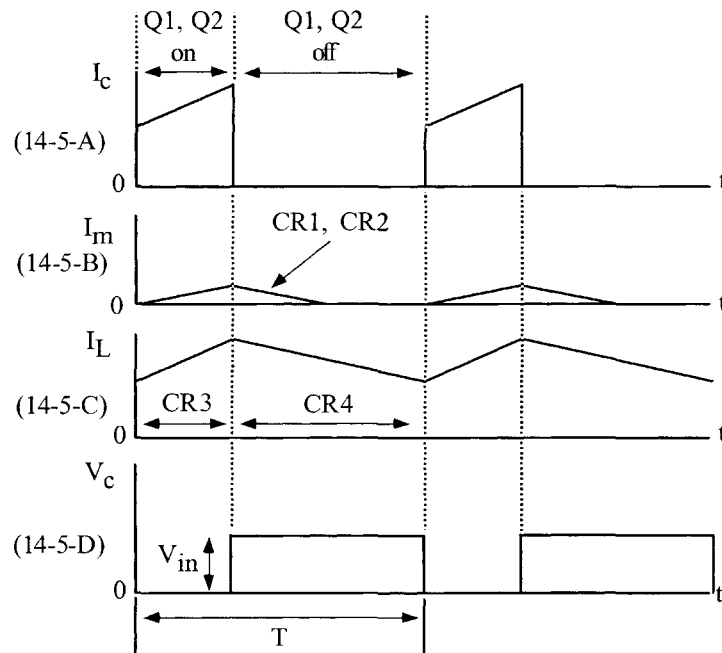
**Figure 14-5.** Typical Double-Ended Forward, Converter Waveforms.

**Note:**

The design equations are from communication and work with the late Dr. J. K. Watson, Professor of Electrical Engineering at the University of Florida.

Electrical coefficient is:

$$K_e = 0.145 f^2 \Delta B^2 \left(10^{-4}\right) \quad [14\text{-}1]$$

Core geometry is:

$$K_g = \frac{P_{in} D_{(max)}}{\alpha K_e}, \quad [\text{cm}^5] \quad [14\text{-}2]$$

Current density is:

$$J = \frac{2 P_{in} \sqrt{D_{(max)}} \left(10^4\right)}{f \Delta B A_c W_a K_u}, \quad [\text{amps per cm}^2] \quad [14\text{-}3]$$

Primary current is:

$$I_p = \frac{P_{in}}{V_{in(min)} \sqrt{D_{(max)}}}, \quad [\text{amps}] \quad [14\text{-}4]$$

# Transformer Design Using the Core Geometry, $K_g$, Approach

The following information is the Design specification for a 30 watts, single-ended transformer, operating at 100kHz, using the, $K_g$, core geometry approach. For a typical design example, assume a single-ended converter circuit, as shown in Figure 14-1, with the following specification:

1.  Input voltage, $V_{(min)}$ ........................................................ = 22 volts
2.  Input voltage, $V_{(nom)}$ ........................................................ = 28 volts
3.  Input voltage, $V_{(max)}$ ........................................................ = 35 volts
4.  Output voltage, $V_o$ ........................................................ = 5.0 volts
5.  Output current, $I_o$ ........................................................ = 5.0 amps
6.  Frequency, f ........................................................ = 100kHz
7.  Efficiency, $\eta$ ........................................................ = 98%
8.  Regulation, $\alpha$ ........................................................ = 0.5%
9.  Diode voltage drop, $V_d$ ........................................................ = 1.0 volt
10. Operating flux density, $\Delta B$, $(B_{ac} = \Delta B/2)$ ........................................................ = 0.1 tesla
11. Core Material ........................................................ = ferrite
12. Window utilization, $K_u$ ........................................................ = 0.3
13. Temperature rise goal, $T_r$ ........................................................ = 30°C
14. Maximum duty ratio, $D_{max}$ ........................................................ = 0.5
15. Notes:

       Demag turns ratio, $N_{mag}/N_p$ ........................................................ = 1

       Demag power, $P_{mag}$ ........................................................ = (0.1)$P_o$

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 centimeters is:

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

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

$$\varepsilon = 0.0209, \quad [cm]$$

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 0.001280 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. | $\mu\Omega$/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 transformer output power, $P_o$.

$$P_o = I_o(V_o + V_d), \quad [\text{watts}]$$
$$P_o = 5(5 + 1), \quad [\text{watts}]$$
$$P_o = 30, \quad [\text{watts}]$$

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

$$P_{in} = \frac{P_o(1.1)}{\eta}, \quad [\text{watts}]$$
$$P_{in} = \frac{30(1.1)}{(0.98)}, \quad [\text{watts}]$$
$$P_{in} = 33.67, \quad [\text{watts}]$$

Step No. 3 Calculate the electrical coefficient, $K_e$.

$$K_e = 0.145 f^2 \Delta B^2 (10^{-4})$$
$$K_e = 0.145(100,000)^2(0.1)^2(10^{-4})$$
$$K_e = 1450$$

Step No. 4 Calculate the core geometry, $K_g$.

$$K_g = \frac{P_{in} \, D_{max}}{\alpha K_e}, \quad [cm^5]$$

$$K_g = \frac{(33.67)(0.5)}{(0.5)(1450)}, \quad [cm^5]$$

$$K_g = 0.0232, \quad [cm^5]$$

When operating at high frequencies, the engineer has to review the window utilization factor, $K_u$. When using small bobbin ferrites, 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 to the total area is 0.78. Therefore, the overall window utilization, $K_u$, is reduced. 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.

$$K_g = 0.0232 (1.35), \quad [cm^5]$$

$$K_g = 0.0313, \quad [cm^5]$$

Step No. 5 Select a EPC core from Chapter 3, comparable in core geometry $K_g$.

Core number ................................................................................................ EPC-30

Manufacturer ............................................................................................... TDK

Magnetic material ...................................................................................... PC44

Magnetic path length , MPL........................................................................ 8.2 cm

Window height, G ....................................................................................... 2.6 cm

Core weight, $W_{tfe}$ ....................................................................................... 23 grams

Copper weight, $W_{tcu}$ ................................................................................. 22 grams

Mean length turn, MLT .............................................................................. 5.5 cm

Iron area, $A_c$ .............................................................................................. 0.61 cm$^2$

Window area, $W_a$ ...................................................................................... 1.118 cm$^2$

Area product, $A_p$ ...................................................................................... 0.682 cm$^4$

Core geometry, $K_g$.................................................................................... 0.0301 cm$^5$

Surface area, $A_t$ ........................................................................................ 31.5 cm$^2$

Millihenrys per 1000 turns, AL ................................................................. 1570

Step No. 6 Calculate the number of primary turns, $N_p$.

$$N_p = \frac{V_{in(min)} D_{(max)} (10^4)}{f A_c \Delta B}, \quad [\text{turns}]$$

$$N_p = \frac{(22)(0.5)(10^4)}{(100,000)(0.61)(0.1)}, \quad [\text{turns}]$$

$$N_p = 18.0, \quad [\text{turns}]$$

Step No. 7 Calculate the current density, J, using a window utilization, $K_u = 0.29$.

$$J = \frac{2P_{in} \sqrt{D_{(max)}} (10^4)}{f A_c \Delta B W_a K_u}, \quad [\text{amps} / \text{cm}^2]$$

$$J = \frac{2(33.67)(0.707)(10^4)}{(100,000)(0.61)(0.1)(1.118)(0.29)}, \quad [\text{amps} / \text{cm}^2]$$

$$J = 241, \quad [\text{amps} / \text{cm}^2]$$

Step No. 8 Calculate the primary rms current, $I_p$.

$$I_p = \frac{P_{in}}{V_{in(min)} \sqrt{D_{(max)}}}, \quad [\text{amps}]$$

$$I_p = \frac{(33.67)}{(22)(0.707)}, \quad [\text{amps}]$$

$$I_p = 2.16, \quad [\text{amps}]$$

Step No. 9 Calculate the primary bare wire area, $A_{wp(B)}$.

$$A_{wp(B)} = \frac{I_p}{J}, \quad [\text{cm}^2]$$

$$A_{wp(B)} = \frac{2.16}{241}, \quad [\text{cm}^2]$$

$$A_{wp(B)} = 0.00896, \quad [\text{cm}^2]$$

Step No. 10 Calculate the required number of primary strands, $NS_p$.

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

$$NS_p = \frac{0.00896}{0.00128}$$

$$NS_p = 7$$

Step No. 11 Calculate the primary new $\mu\Omega$ per centimeter.

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

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

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

Step No. 12 Calculate the primary resistance, $R_p$.

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

$$R_p = (5.5)(18)(192)\left(10^{-6}\right) \quad [\text{ohms}]$$

$$R_p = 0.0190, \quad [\text{ohms}]$$

Step No. 13 Calculate the primary copper loss, $P_p$.

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

$$P_p = (2.16)^2(0.019), \quad [\text{watts}]$$

$$P_p = 0.0886, \quad [\text{watts}]$$

Step No. 14 Calculate the secondary turns, $N_s$.

$$N_s = \frac{N_p\left(V_o + V_d\right)}{D_{(\max)}V_{in(\min)}}\left(1 + \frac{\alpha}{100}\right), \quad [\text{turns}]$$

$$N_s = \frac{(18)(5+1)}{(0.5)(22)}\left(1 + \frac{0.5}{100}\right), \quad [\text{turns}]$$

$$N_s = 9.87 \text{ use } 10, \quad [\text{turns}]$$

Step No. 15 Calculate the secondary rms current, $I_s$.

$$I_s = \frac{I_o}{\sqrt{2}}, \quad [\text{amps}]$$

$$I_s = \frac{5}{1.41}, \quad [\text{amps}]$$

$$I_s = 3.55, \quad [\text{amps}]$$

Step No. 16 Calculate the secondary bare wire area, $A_{ws(B)}$.

$$A_{ws(B)} = \frac{I_s}{J}, \quad [\text{cm}^2]$$

$$A_{ws(B)} = \frac{3.55}{241}, \quad [\text{cm}^2]$$

$$A_{ws(B)} = 0.0147, \quad [\text{cm}^2]$$

Step No. 17 Calculate the required number of secondary strands, $NS_s$.

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

$$NS_s = \frac{0.0147}{0.00128}$$

$$NS_s = 11.48 \text{ use } 11$$

Step No. 18 Calculate the secondary, new $\mu\Omega$ per centimeter.

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

$$(\text{new})\mu\Omega/\text{cm} = \frac{1345}{11}$$

$$(\text{new})\mu\Omega/\text{cm} = 122$$

Step No. 19 Calculate the secondary winding resistance, $R_s$.

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

$$R_s = (5.5)(10)(122)(10^{-6}) \quad [\text{ohms}]$$

$$R_s = 0.00671, \quad [\text{ohms}]$$

Step No. 20 Calculate the secondary copper loss, $P_s$.

$$P_s = I_s^2 R_s, \quad [\text{watts}]$$

$$P_s = (3.55)^2(0.00671), \quad [\text{watts}]$$

$$P_s = 0.0846, \quad [\text{watts}]$$

Step No. 21 Calculate the total primary and secondary copper loss, $P_{cu}$.

$$P_{cu} = P_p + P_s, \quad [\text{watts}]$$

$$P_{cu} = 0.0886 + 0.0846, \quad [\text{watts}]$$

$$P_{cu} = 0.173, \quad [\text{watts}]$$

Step No. 22 Calculate the transformer regulation, $\alpha$.

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

$$\alpha = \frac{(0.173)}{(30)}(100), \quad [\%]$$
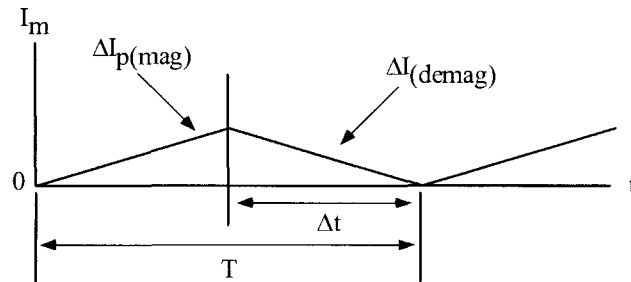
$$\alpha = 0.576, \quad [\%]$$

Step No. 23 Calculate the demag winding inductance, $L_{demag}$.

$$L_{demag} = L_{1000} N_{demag}^2 (10^{-6}), \quad [mh]$$

$$L_{demag} = (1570)(18)^2 (10^{-6}), \quad [mh]$$

$$L_{demag} = 0.509, \quad [mh]$$

Step No. 24 Calculate the time of, $\Delta t$. See Figure 14-6.



**Figure 14-6.** Magnetizing Current Waveform.

$$\Delta t = T D_{(max)}, \quad [seconds]$$

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

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

$$T = 10(10^{-6}) \quad [seconds]$$

$$\Delta t = (10(10^{-6}))(0.5), \quad [seconds]$$

$$\Delta t = 5(10^{-6}) \quad [seconds]$$

Step No. 25 Calculate the demag, winding delta current, $\Delta I_{demag}$.

$$\Delta I_{demag} = \frac{V_{in} \Delta t}{L_{demag}}, \quad [\text{amps}]$$

$$\Delta I_{demag} = \frac{(22)\left(5\left(10^{-6}\right)\right)}{\left(509\left(10^{-6}\right)\right)}, \quad [\text{amps}]$$

$$\Delta I_{demag} = 0.217, \quad [\text{amps}]$$

Step No. 26 Calculate the demag, winding rms current, $I_{demag}$. This is the rms equation for a saw tooth current.

$$I_{demag} = \Delta I \sqrt{\frac{D_{(max)}}{3}}, \quad [\text{amps}]$$

$$I_{demag} = (0.217)(0.408), \quad [\text{amps}]$$

$$I_{demag} = 0.089, \quad [\text{amps}]$$

Step No. 27 Calculate the required demag, wire area, $A_{w(demag)}$.

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

$$A_{w(demag)} = \frac{0.089}{241}, \quad [\text{cm}^2]$$

$$A_{w(demag)} = 0.000369, \quad \approx \#31 \text{ use a } \#26$$

Step No. 28 Calculate the window utilization, $K_u$.

$$K_u = \frac{N A_{w(B)(\#26)}}{W_a}$$

$$N = \left(N_p NS_p\right) + \left(N_s NS_s\right) + \left(N_{demag} NS_{demag}\right)$$

$$N = (18)(7) + (10)(11) + (18)(1)$$

$$N = 254$$

$$K_u = \frac{(254)(0.00128)}{1.118}$$

$$K_u = 0.291$$

Step No. 29 Calculate the milliwatts per gram, mW/g.

$$mW/g = 0.000318(f)^{1.51}(B_{ac})^{2.747}$$
$$mW/g = 0.000318(100000)^{1.51}(0.05)^{2.747}$$
$$mW/g = 3.01$$

Step No. 30 Calculate the core loss, $P_{fe}$.

$$P_{fe} = (mW \ / \ g)(W_{tfe})(10^{-3}) \quad [\text{watts }]$$
$$P_{fe} = (3.01)(23)(10^{-3}) \quad [\text{watts }]$$
$$P_{fe} = 0.069, \quad [\text{watts }]$$

Step No. 31 Calculate the total loss, $P_{\Sigma}$.

$$P_{\Sigma} = P_{cu} + P_{fe}, \quad [\text{watts }]$$
$$P_{\Sigma} = (0.173) + (0.069), \quad [\text{watts }]$$
$$P_{\Sigma} = 0.242, \quad [\text{watts }]$$

Step No. 32 Calculate the watts per unit area, $\psi$.

$$\psi = \frac{P_{\Sigma}}{A_t}, \quad [\text{watts } / \text{cm}^2]$$
$$\psi = \frac{(0.242)}{(31.5)}, \quad [\text{watts } / \text{cm}^2]$$
$$\psi = 0.0077, \quad [\text{watts } / \text{cm}^2]$$

Step No. 33 Calculate the temperature rise, $T_r$.

$$T_r = 450(\psi)^{(0.826)}, \quad [°C]$$
$$T_r = 450(0.0077)^{(0.826)}, \quad [°C]$$
$$T_r = 8.08, \quad [°C]$$

## Forward Converter Output Inductor Design

Part 2 is designing the output inductor, L1, as shown in Figure 14-7. The output filter inductor for switch-mode power supplies, (SMPS), probably has been designed more times than any other single component. Presented here is a straight-forward approach for selecting the core and the proper wire size to meet the specification.

The losses in the magnetic material will increase significantly when the converter is operating at a higher frequency. However, the core loss in the output inductor of a switching regulator is much lower compared to the core loss in the main converter transformer. The core loss in the output inductor is caused by the change in current or $\Delta I$, which induces a change in flux, as shown in Figure 14-7.
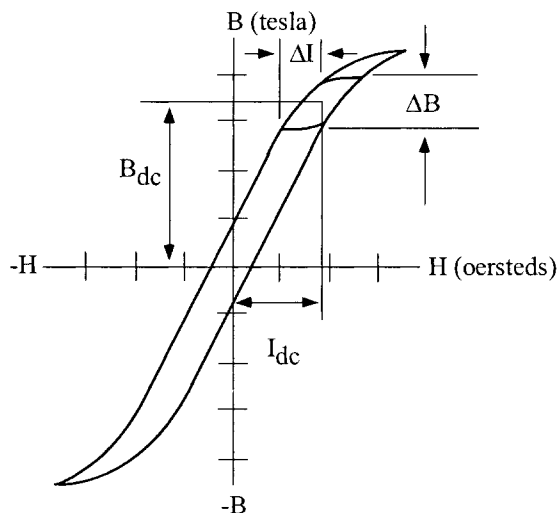


Figure 14-7. Typical output inductor BH Loop.

The single-ended, forward converter schematic is shown in Figure 14-8. This topology is appealing to engineers for it simplicity and parts' count. The output filter circuit, shown in Figure 14-8, has three current probes. These current probes monitor the three basic currents in a switch mode, converter output filter. Current probe A monitors the transformer's secondary current. Current probe B monitors the commutating current through CR3. Current probe C monitors the current through the output inductor, L1.

The typical secondary and filter waveforms of the forward converter are shown in Figure 14-8. The waveforms are shown with the converter operating at a 0.5 duty ratio. The applied voltage, $V_1$, to the filter, is shown in Figure (14-9-A). The transformer's secondary current is shown in Figure (14-9-B). The commutating current flowing through, CR3, is shown in Figure (14-9-C). The commutating current is the result of Q1 being turned off, and the field in, L1, collapsing, producing the commutating current. The current flowing through L1 is shown in Figure (14-9-D). The current flowing through L1 is the sum of the currents in Figure (14-9-B) and (14-9-C).
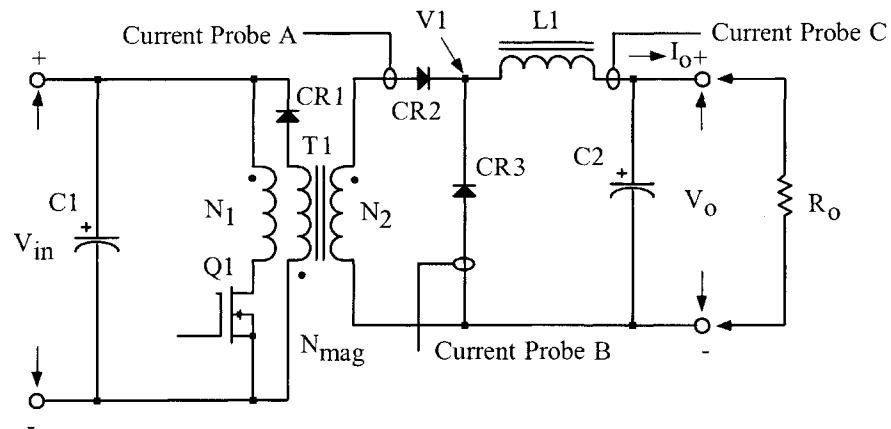
**Figure 14-8.** Typical single-ended, forward converter.
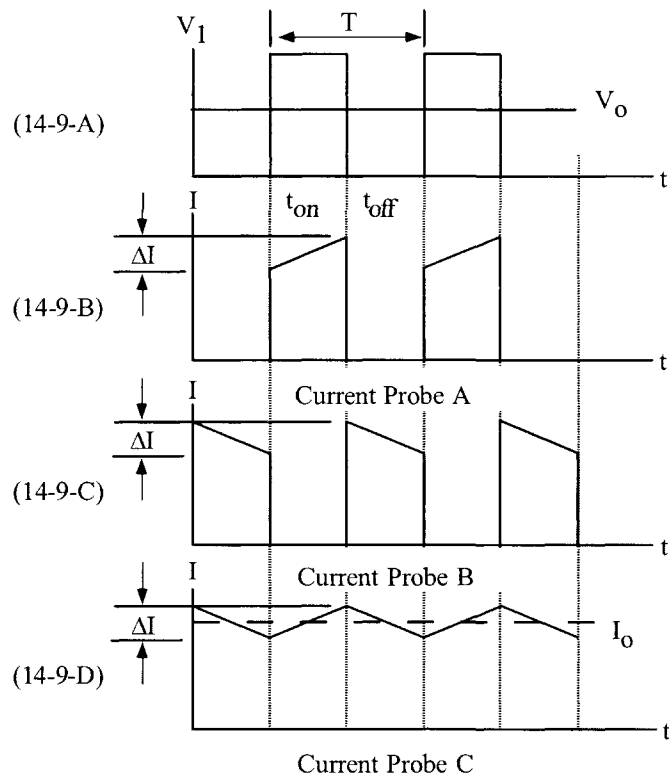


**Figure 14-9.** Typical forward converter waveforms, operating at a 0.5 duty ratio.

The critical inductance current is shown in Figure (14-10-B). The critical inductance current is when the ratio of the delta current to the output load current is equal to $2 = \Delta I / I_o$. If the output load current is allowed to go beyond this point, the current will become discontinuous, as shown in Figure (14-10-D). The applied voltage, $V_1$, will have ringing at the level of the output voltage, as shown in Figure (14-10-C). When the current in the output inductor becomes discontinuous, as shown in Figure (14-10-D), the response time for a step load becomes very poor.

When designing multiple output converters, the slaved outputs should never have the current in the inductor go discontinuous or to zero. If the current goes to zero, a slaved output voltage will rise to the value of $V_1$. If the current is allowed to go to zero, then, there is not any potential difference between the input and output voltage of the filter. Then the output voltage will rise to equal the peak input voltage.
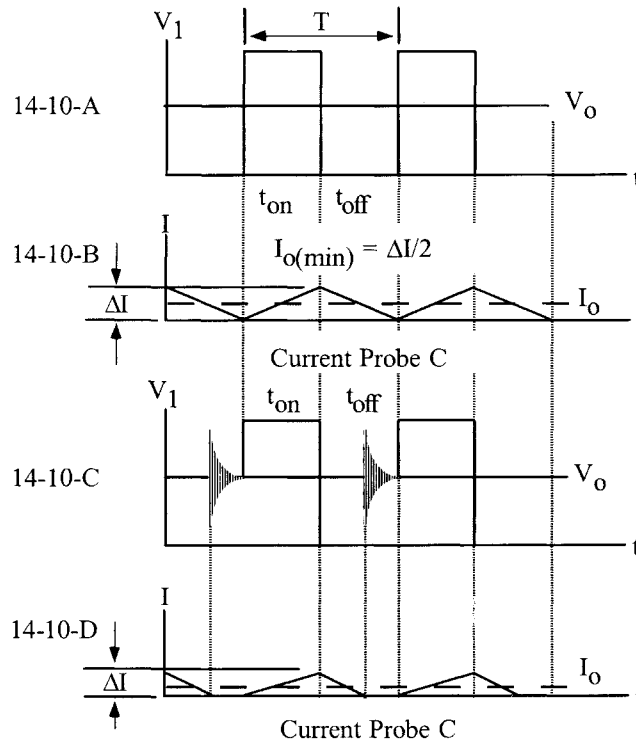


**Figure 14-10.** Forward converter; output filter inductor goes from critical to discontinuous operation.

## Output Inductor Design Using the Core Geometry, $K_g$, Approach

The following information is the design specification for a forward converter, 30 watt output filter design, operating at 100kHz, using the $K_g$ core geometry approach. For a typical design example, assume an output filter circuit, as shown in Figure 14-1, with the following specifications:

1. Frequency, f ................................................................................................................ = 100kHz
2. Output voltage, $V_o$ ..................................................................................................... = 5 volts
3. Output current, $I_{o(max)}$ .......................................................................................... = 5.0 amps
4. Output current, $I_{o(max)}$ .......................................................................................... = 0.5 amps
5. Delta current, $\Delta I$ .................................................................................................. = 1.0 amps
6. Input voltage, $V_{1(max)}$ ........................................................................................... = 19 volts
7. Input voltage, $V_{1(min)}$ ............................................................................................ = 12 volts
8. Regulation, $\alpha$ ........................................................................................................ = 1.0%

9. Output power $(V_o + V_d)$ $(I_{o(max)})$, $P_o$ ................................................ = 30 watts

10. Operating flux density, $B_{pk}$ .......................................................... = 0.3 tesla

11. Window utilization, $K_u$ ................................................................ = 0.4

12. Diode voltage drop, $V_d$ .............................................................. = 1.0 volt

This design procedure will work equally well with all of the various powder cores. Care must be taken regarding maximum flux density with different materials and core loss.

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, $\Delta I$, and is normally only a fraction of the dc flux. In this design the ac current and the dc current will be treated the same.

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, $\varepsilon$, 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, $D_w$, is:

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

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

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

Then, the bare wire area, $A_w$, is:

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

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

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

From the Wire Table in Chapter 4, Number 27 has a bare wire area of 0.001021 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. | $\mu\Omega$/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 minimum duty ratio, $D_{min}$.

$$D_{min} = \frac{V_o}{V_{1\,max}}$$

$$D_{min} = \frac{5}{19}$$

$$D_{min} = 0.263$$

Step No. 3 Calculate the required inductance, L.

$$L = \frac{T(V_o + V_d)(1 - D_{min})}{\Delta I}, \quad [\text{henrys}]$$

$$L = \frac{(10 \times 10^{-6})(5.0 + 1.0)(1 - 0.263)}{(1.0)}, \quad [\text{henrys}]$$

$$L = 44.2, \quad [\mu\text{h}]$$

Step No. 4 Calculate the peak current, $I_{pk}$.

$$I_{pk} = I_{o(max)} + \left(\frac{\Delta I}{2}\right), \quad [\text{amps}]$$

$$I_{pk} = (5.0) + \left(\frac{1.0}{2}\right), \quad [\text{amps}]$$

$$I_{pk} = 5.5, \quad [\text{amps}]$$

Step No. 5 Calculate the energy-handling capability in, watt-seconds.

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

$$Energy = \frac{\left(44.2x10^{-6}\right)\left(5.5\right)^2}{2}, \quad [\text{watt-seconds}]$$

$$Energy = 0.000668, \quad [\text{watt-seconds}]$$

Step No. 6 Calculate the electrical conditions, $K_e$.

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

$$K_e = \left(0.145\right)\left(30\right)\left(0.3\right)^2 x 10^{-4}$$

$$K_e = 0.0000392$$

Step No. 7 Calculate the core geometry, $K_g$.

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

$$K_g = \frac{\left(0.000668\right)^2}{\left(0.0000392\right)\left(1.0\right)} \quad [\text{cm}^5]$$

$$K_g = 0.01138 \quad [\text{cm}^5]$$

Step No. 8 Select, from Chapter 4, a MPP powder core, comparable in core geometry, $K_g$.

Core number .............................................................................. MP-55059-A2

Manufacturer ............................................................................. Magnetics

Magnetic path length, MPL ...................................................... = 5.7 cm

Core weight, $W_{tfe}$ ..................................................................... = 16.0 grams

Copper weight, $W_{tcu}$ ............................................................... = 15.2 grams

Mean length turn, MLT ............................................................. = 3.2 cm

Iron area, $A_c$ ............................................................................. = 0.331 cm$^2$

Window Area, $W_a$ .................................................................... = 1.356 cm$^2$

Area Product, $A_p$ ..................................................................... = 0.449 cm$^4$

Core geometry, $K_g$ ................................................................... = 0.0184 cm$^5$

Surface area, $A_t$ ....................................................................... = 28.6 cm$^2$

Permeability, $\mu$ ........................................................................ = 60

Millihenrys per 1000 turns, AL................................................. = 43

Step No. 9  Calculate the number of turns, N.

$$N = 1000 \sqrt{\frac{L_{(new)}}{L_{(1000)}}}, \quad \text{[turns]}$$

$$N = 1000 \sqrt{\frac{0.0442}{43}}, \quad \text{[turns]}$$

$$N = 32, \quad \text{[turns]}$$

Step No. 10  Calculate the rms current, $I_{rms}$.

$$I_{rms} = \sqrt{I_{o(max)}^2 + \Delta I^2}, \quad \text{[amps]}$$

$$I_{rms} = \sqrt{(5.0)^2 + (1.0)^2}, \quad \text{[amps]}$$

$$I_{rms} = 5.1, \quad \text{[amps]}$$

Step No. 11  Calculate the current density, J, using a window utilization, $K_u = 0.4$.

$$J = \frac{NI}{W_a K_u}, \quad \text{[amps-per-cm}^2\text{]}$$

$$J = \frac{(32)(5.1)}{(1.36)(0.4)}, \quad \text{[amps-per-cm}^2\text{]}$$

$$J = 300, \quad \text{[amps-per-cm}^2\text{]}$$

Step No. 12  Calculate the required permeability, $\Delta\mu$.

$$\Delta\mu = \frac{B_{pk}(\text{MPL})(10^4)}{0.4\pi W_a J K_u}, \quad \text{[perm]}$$

$$\Delta\mu = \frac{(0.3)(5.7)(10^4)}{(1.26)(1.36)(300)(0.4)}, \quad \text{[perm]}$$

$$\Delta\mu = 83.1, \quad \text{use 60} \quad \text{[perm]}$$

Step No. 13  Calculate the peak flux density, $B_{pk}$.

$$B_{pk} = \frac{0.4\pi N I_{pk} \mu_r (10^{-4})}{(\text{MPL})}, \quad \text{[tesla]}$$

$$B_{pk} = \frac{(1.26)(32)(5.5)(60)(10^{-4})}{(5.7)}, \quad \text{[tesla]}$$

$$B_{pk} = 0.233, \quad \text{[tesla]}$$

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

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

$$A_{w(B)} = \frac{5.1}{300}, \quad [\text{cm}^2]$$

$$A_{w(B)} = 0.017, \quad [\text{cm}^2]$$

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

$$S_n = \frac{A_{w(B)}}{\#26}, \quad [\text{strands}]$$

$$S_n = \frac{0.017}{0.00128}, \quad [\text{strands}]$$

$$S_n = 13, \quad [\text{strands}]$$

Step No. 16 Calculate the new, $\mu\Omega$, per centimeter.

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

$$(\text{new})\,\mu\Omega/\text{cm} = \frac{1345}{13}$$

$$(\text{new})\,\mu\Omega/\text{cm} = 103$$

Step No. 17 Calculate the winding resistance, R.

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

$$R = (3.2)(32)(103)(10^{-6}), \quad [\text{ohms}]$$

$$R = 0.0105, \quad [\text{ohms}]$$

Step No. 18 Calculate the winding copper loss, $P_{cu}$.

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

$$P_{cu} = (5.1)^2(0.0105), \quad [\text{watts}]$$

$$P_{cu} = 0.273, \quad [\text{watts}]$$

Step No. 19 Calculate the magnetizing force in oersteds, H.

$$H = \frac{0.4\pi N I_{pk}}{\text{MPL}}, \quad [\text{oersteds}]$$

$$H = \frac{(1.26)(32)(5.5)}{5.7}, \quad [\text{oersteds}]$$

$$H = 38.9, \quad [\text{oersteds}]$$

Step No. 20  Calculate the ac flux density in tesla, $B_{ac}$.

$$B_{ac} = \frac{0.4\pi N \left(\dfrac{\Delta I}{2}\right)\mu_r \left(10^{-4}\right)}{\text{MPL}}, \quad [\text{tesla}]$$

$$B_{ac} = \frac{(1.26)(32)(0.5)(60)\left(10^{-4}\right)}{(5.7)}, \quad [\text{tesla}]$$

$$B_{ac} = 0.0212, \quad [\text{tesla}]$$

Step No. 21  Calculate the regulation, $\alpha$, for this design.

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

$$\alpha = \frac{(0.273)}{(30)}(100), \quad [\%]$$

$$\alpha = 0.91, \quad [\%]$$

Step No. 22  Calculate the watts per kilogram, WK, using MPP 60 perm powder cores coefficients, shown in Chapter 2.

$$WK = 0.551\left(10^{-2}\right) f^{(1.23)} B_{ac}^{(2.12)}, \quad [\text{watts-per-kilogram}]$$

$$WK = 0.551\left(10^{-2}\right)(100000)^{(1.23)}(0.0212)^{(2.12)}, \quad [\text{watts-per-kilogram}]$$

$$WK = 2.203, \quad [\text{watts-per-kilogram}]$$

Step No. 23  Calculate the core loss, $P_{fe}$.

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

$$P_{fe} = (2.203)(16)\left(10^{-3}\right), \quad [\text{watts}]$$

$$P_{fe} = 0.0352, \quad [\text{watts}]$$

Step No. 24  Calculate the total loss, $P_\Sigma$, core, $P_{fe}$, and copper, $P_{cu}$, in watts.

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

$$P_\Sigma = (0.0352)+(0.273), \quad [\text{watts}]$$

$$P_\Sigma = 0.308, \quad [\text{watts}]$$

Step No. 25  Calculate the watt density, $\psi$.

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

$$\psi = \frac{(0.308)}{(28.6)}, \quad [\text{watts-per-cm}^2]$$

$$\psi = 0.0108, \quad [\text{watts-per-cm}^2]$$

Step No. 26  Calculate the temperature rise, in °C.

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

$$T_r = 450(0.0108)^{(0.826)}, \quad [°\text{C}]$$

$$T_r = 10.7, \quad [°\text{C}]$$

Step No. 27  Calculate the window utilization, $K_u$.

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

$$K_u = \frac{(32)(13)(0.00128)}{(1.356)}$$

$$K_u = 0.393$$