Designing Boost Inductors for Power Factor Correction (PFC)

By Colonel Wm. T. McLyman

Historically, the standard power supplies designed for electronic equipment have had a notoriously poor power factor in the area of (0.5-0.6), and a correspondingly, high, harmonic current content. This design approach utilizes a simple rectifier capacitor input filter that results in large current pulses drawn from the line, that cause distorting of the line voltage and create large amounts of EMI and noise.

The regulating bodies, IEC in Europe and IEEE in the USA, have been working to develop a standard for limiting harmonic current, in off-line equipment. The German standardization bodies have established IEC 1000-2, and it is generally accepted as the standard for limiting harmonic currents in off-line equipment.

Many new electronic products are required to have a near unity power factor and a distortion free, current input waveform. The conventional ac-dc converters usually employ a full wave, rectifier bridge, with a simple filter to draw power from the ac line. The typical, rectifier capacitor, input bridge filter and associated waveforms, as shown in Figure 1, is no longer good enough.

![Figure 1 Typical, Capacitor Input Bridge Rectifier Filter.](image)

The line current waveform for equipment that utilizes off-line rectifier capacitor input filter, is shown in Figure 1. The line current is supplied in narrow pulses. Consequently, the power factor is poor (0.5 – 0.6), due to a high harmonic distortion of the current waveform. The power supply can be designed with a power factor approaching unity, by the addition of an input inductor, as shown in Figure 2. The reasons that the input inductors are not designed into power supplies is very simple: cost, weight and bulk. The inductance equation for L1 is shown below.

\[ L_1 = \frac{0.333V_i}{2\pi f_{(line)} f_{(min)}} \text{ [henrys]} \]
Standard Boost Flyback Converter

The standard dc-to-dc boost flyback converter is shown in Figure 3, along with the voltage and current waveforms, shown in Figure 4. The boost converter has become the choice of many engineers as the power stage in the active power factor corrector design. The basic circuit can be operated in either the continuous or discontinuous mode.
Boost PFC Converter

The boost power factor correction converter is shown in Figure 5. The boost converter is the most popular of the power factor pre-regulators. The boost converter can operate in two modes, continuous and discontinuous. The current through the inductor, L1, is shown in Figure 4 for both continuous and discontinuous operation. After examining the schematic the advantages and disadvantages of the boost converter can readily be seen. The disadvantage is the high output voltage to the load circuit and current limit cannot be implemented. The advantage is that the circuit requires a minimum of parts and the gate drive to Q1 is referenced to ground.

The following pages describe a step-by-step procedure for designing a continuous current boost inductor for a Power Factor Correction (PFC) converter.

For this article, the magnetic core and wire data have been taken from the author's book, *Magnetic Core Selection for Transformers and Inductors, Second Edition*. The author will refer to chapters and page numbers in the book for a quick reference. Some of the design information has been described in past articles in the *Wound Magnetics Journal*.
For a typical design example, assume an output filter circuit, as shown in Figure 5, with the following specifications:

1. Circuit topology will be a continuous current boost.
2. Output power $P_o = 250$ watts
3. Input voltage range $V_{in} = 90 - 270$ volts
4. Line frequency $f_{line} = 47 - 65$ Hz
5. Output voltage $V_o = 400$ volts
6. Switching frequency $f = 100$ kHz
7. Inductor ripple current $\Delta I = 20\%$ of $I_{pk}$
8. Magnetics core ETD, R material
9. Converter efficiency $\eta = 95\%$
10. Inductor regulation $\Delta I = 1\%$
11. Window utilization $K_u = 0.4$
12. Operating Flux $B_m = 0.25$, tesla

Step No. 1 Calculate the input power, $P_{in}$.

$$ P_{in} = \frac{P_o}{\eta}, \text{[watts]} $$

$$ P_{in} = \frac{250}{0.95}, \text{[watts]} $$

$$ P_{in} = 263, \text{[watts]} $$

Step No. 2 Calculate the peak input current, $I_{pk}$.

$$ I_{pk} = \frac{P_{in}\sqrt{2}}{V_{in(min)}}, \text{[amps]} $$

$$ I_{pk} = \frac{(263)(1.41)}{90}, \text{[amps]} $$

$$ I_{pk} = 4.12, \text{[amps]} $$

Step No. 3 Calculate the input ripple current, $\Delta I$.

$$ \Delta I = 0.2I_{pk}, \text{[amps]} $$

$$ \Delta I = 0.2(4.12), \text{[amps]} $$

$$ \Delta I = 0.824, \text{[amps]} $$

Step No. 4 Calculate the maximum duty ratio, $D$.

$$ D = \frac{V_o - (V_{in(min)}\sqrt{2})}{V_o} $$

$$ D = \frac{400 - (90\sqrt{2})}{400} $$

$$ D = 0.683 $$
Step No. 5 Calculate the required boost inductance, \( L \).

\[
L = \frac{\left( V_{\text{in(min)}} \sqrt{2} \right) D}{\Delta f}, \quad \text{[henrys]}
\]

\[
L = \frac{(126.9)(0.683)}{(0.824)(100000)}, \quad \text{[henrys]}
\]

\[
L = 0.00105, \quad \text{[henrys]}
\]

Step No. 6 Calculate the Energy required, Eng.

\[
\text{Eng} = \frac{L I_{\Delta f}^2}{2}, \quad \text{[watt-seconds]}
\]

\[
\text{Eng} = \frac{(0.00105)(4.12)^2}{2}, \quad \text{[watt-seconds]}
\]

\[
\text{Eng} = 0.00891, \quad \text{[watt-seconds]}
\]

Step No. 7 Calculate the electrical coefficient, \( K_e \).

\[
K_e = 0.145 P_e B_m^2 \left( 10^{-4} \right)
\]

\[
K_e = 0.145 (250)(0.25)^2 \left( 10^{-4} \right)
\]

\[
K_e = 0.000227
\]

Step No. 8 Calculate the core geometry coefficient, \( K_g \).

\[
K_g = \frac{\text{Eng}^2}{K_e \alpha}, \quad \text{[cm}^3\text{]}
\]

\[
K_g = \frac{(0.00891)^2}{(0.000227)(1)}, \quad \text{[cm}^3\text{]}
\]

\[
K_g = 0.35, \quad \text{[cm}^3\text{]}
\]

Step No. 9 From Chapter 8, select an ETD ferrite core, comparable in core geometry, \( K_g \).

Core number .......................................................... ETD-4444
Manufacturer .......................................................... Magnetics
Magnetic path length .......................................................... MPL = 10.4 cm
Core weight .......................................................... \( W_{\text{fe}} = 94 \text{ grams} \)
Copper weight .......................................................... \( W_{\text{cu}} = 100 \text{ grams} \)
Mean length turn .......................................................... MLT = 9.4 cm
Iron area .......................................................... \( A_c = 1.72 \text{ cm}^2 \)
Window Area .......................................................... \( W_a = 2.98 \text{ cm}^2 \)
Area Product .......................................................... \( A_p = 5.13 \text{ cm}^4 \)
Core geometry .......................................................... \( K_g = 0.374 \text{ cm}^3 \)
Surface area .......................................................... \( A_s = 87.3 \text{ cm}^2 \)
Step No. 10 Calculate the current density, $J$.

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

$$J = \frac{2(0.00891)(10^4)}{(0.25)(5.13)(0.4)}, \quad \text{[amps/cm}^2\text{]}$$

$$J = 347, \quad \text{[amps/cm}^2\text{]}$$

Step No. 11 Calculate the rms current, $I_{rms}$.

$$I_{rms} = \frac{I_{pk}}{\sqrt{2}}, \quad \text{[amps]}$$

$$I_{rms} = \frac{4.12}{\sqrt{2}}, \quad \text{[amps]}$$

$$I_{rms} = 2.91, \quad \text{[amps]}$$

Step No. 12 Calculate the required bare wire area, $A_{w(B)}$.

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

$$A_{w(B)} = \frac{2.91}{347}, \quad \text{[cm}^2\text{]}$$

$$A_{w(B)} = 0.00839, \quad \text{[cm}^2\text{]}$$

Step No. 13 Select a wire size with the required area from the Wire Table and the micro-ohm per centimeter.

$$AWG = \#18$$

$$A_{w(B)} = 0.00823$$

$$\frac{\mu \Omega}{\text{cm}} = 209$$

Step No. 14 Calculate the required number of turns, $N$.

$$N = \frac{W_K}{A_{w(B)}}, \quad \text{[turns]}$$

$$N = \frac{(2.982)(0.4)}{0.00823}, \quad \text{[turns]}$$

$$N = 145, \quad \text{[turns]}$$
Step No. 15 Calculate the required gap, \( l_g \).

\[
l_g = \frac{0.4\pi N^2 A \left(10^{-8}\right)}{L}, \quad [\text{cm}]
\]

\[
l_g = \frac{(1.257)(1.45)^2(1.72)(10^{-8})}{0.00105}, \quad [\text{cm}]
\]

\[
l_g = 0.433, \quad [\text{cm}]
\]

Change the gap to mils: 0.433 x 393.7 = 170 mils center or 85 mils per each outer leg.

Step No. 16 Calculate the fringing flux factor, \( F \).

\[
F = 1 + \left( \frac{l_g}{\sqrt{A}} \right) \ln \left( \frac{2G}{l_g} \right)
\]

\[
F = 1 + \left( \frac{0.433}{1.31} \right) \ln \left( \frac{6.452}{0.433} \right)
\]

\[
F = 1.89
\]

Step No. 17 Calculate the new turns using the fringing flux.

\[
N = \sqrt{\frac{l_g L}{0.4\pi A F \left(10^{-8}\right)}}, \quad [\text{turns}]
\]

\[
N = \sqrt{\frac{(0.433)(0.00105)}{(1.257)(1.72)(1.89)(10^{-8})}}, \quad [\text{turns}]
\]

\[
N = 105, \quad [\text{turns}]
\]

Step No. 18 Calculate the peak flux, \( B_{pk} \).

\[
B_{pk} = F \left( \frac{0.4\pi NI_{pk} \left(10^{-4}\right)}{l_g} \right), \quad [\text{tesla}]
\]

\[
B_{pk} = 1.89 \left( \frac{(1.257)(105)(4.12)(10^{-4})}{0.433} \right), \quad [\text{tesla}]
\]

\[
B_{pk} = 0.237, \quad [\text{tesla}]
\]

Step No. 19 Calculate the winding resistance, \( R \).

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

\[
R = (9.4)(105)(209)\left(10^{-6}\right), \quad [\text{ohms}]
\]

\[
R = 0.206, \quad [\text{ohms}]
\]
Step No. 20 Calculate the winding copper loss, \( P_{cu} \).

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

\[
P_{cu} = (2.91)^2 (0.206), \quad \text{[watts]}
\]

\[
P_{cu} = 1.74, \quad \text{[watts]}
\]

Step No. 21 Calculate the regulation, \( \alpha \).

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

\[
\alpha = \left( \frac{1.74}{250} \right) 100, \quad \%
\]

\[
\alpha = 0.696, \quad \% \]

Step No. 22 Calculate the ac flux density, \( B_{ac} \).

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

\[
B_{ac} = \left( \frac{1.257}{105} \right) (0.412) \left( 10^{-4} \right), \quad \text{[tesla]}
\]

\[
B_{ac} = 0.0125, \quad \text{[tesla]}
\]

Step No. 23 Calculate the watts per kilogram, \( W/K \), using 2300 perm material, as shown on page 170 in the author's book.

\[
W/K = 3.18 \left( 10^{-7} \right) \left( f \right)^{1.979} \left( B_{ac} \right)^{2.628}, \quad \text{[watts per kilogram]}
\]

\[
W/K = 3.18 \left( 10^{-7} \right) (100000)^{1.979} \left( 0.0125 \right)^{2.628}, \quad \text{[watts per kilogram]}
\]

\[
W/K = 0.0245, \quad \text{[watts per kilogram]}
\]

Step No. 24 Calculate the core loss, \( P_{fe} \).

\[
P_{fe} = W_{fe} \left( 10^{-3} \right) (W/K), \quad \text{[watts]}
\]

\[
P_{fe} = (94) \left( 10^{-3} \right) (0.0245), \quad \text{[watts]}
\]

\[
P_{fe} = 0.0023, \quad \text{[watts]}
\]

Step No. 25 Calculate the total loss core loss, \( P_{fe} \) and copper loss, \( P_{cu} \).

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

\[
P = (1.74) + (0.0023), \quad \text{[watts]}
\]

\[
P = 1.742, \quad \text{[watts]}
\]
Step No. 26 Calculate the watt density, $\psi$. 

$$\psi = \frac{P}{A}, \text{ [watts per cm}^2\text{]}$$

$$\psi = \frac{1.742}{87.3}, \text{ [watts per cm}^2\text{]}$$

$$\psi = 0.02, \text{ [watts per cm}^2\text{]}$$

Step No. 27 Calculate the temperature rise, $T_r$.

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

$$T_r = 450 (0.02)^{0.826}, \text{ [°C]}$$

$$T_r = 17.8, \text{ [°C]}$$

**Conclusion:**

When designing boost inductors for power factor correction, the author hopes that this article with its step-by-step approach helps the reader understand the design of a boost inductor. The above example of this boost inductor was built, and tested. It meets the intent of the specification and shows the reader a typical design.

The simplicity of the boost converter and parts count gives this circuit advantages over other power converters.

I would like to thank Richard Ozenbaugh who has reviewed the math and the step-by-step approach of this design.

The Author would like to thank Steve Freeman at Rodon Product, Inc. for building the inductor to prove form, fit and function.

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The information in the book, Magnetic *Core Selection for Transformers and Inductors, Second Edition*, is an invaluable reference enabling engineers to quickly compare components and select the one best suited to their needs in a minimum amount of time.

The author is now serving as a power supply consultant for the Space Instruments Implementation Section at the Jet Propulsion Laboratory, in Pasadena, California. He is working on ultra low noise power supply design.

**PFC References**

1. Unitode Application Note U-132, Power Factor Correction Using The UC3852 Controller on-time zero current Switching Technique.

2. Unitode Application Note U-134, UC3854 Controlled Power Factor Correction Circuit Design

4. **PCIM August 1990, Active Power Factor Correction Using a Flyback Topology, James LoCascio and Mehmet Nalbant/ Micor Linear Corporation.**

5. **Silicon General Application SG3561A Power Factor Controller.**

6. **SGS Thomson Application Note AN628/0593 Designing a High Power Factor Pre-regulator with the L4981 Continuous Current.**

7. **IEEE, A Comparison Between Hysteretic and Fixed Frequency Boost Converter Used for Power Factor Correction, James J. Spanger Motorola and Anup K. Behera Illinois Institute Technology.**

**BIBLIOGRAPHY**


**Software**

For information regarding the above Books and Companion Software in Windows 95', 98', NT, or to order the books and software, contact:

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