

## **Chapter 15**

### **Input Filter Design**

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## Introduction

Today, almost all modern equipment uses some sort of power conditioning. There are a lot of different circuit topologies used. When you get to the bottom line, all power conditioning requires some kind of an input filter. The input LC filter has become very critical in its design and must be designed not only for EMI, but also for system stability, and for the amount of ac ripple current drawn from the source.

The input voltage supplied to the equipment is also supplied to other users. For this reason, there is a specification requirement regarding the amount of ripple current seen at the source, as shown in Figure 15-1. Ripple currents generated by the user induce a ripple voltage,  $V_z$ , across the source impedance. This ripple voltage could impede the performance of other equipment connected to the same bus.

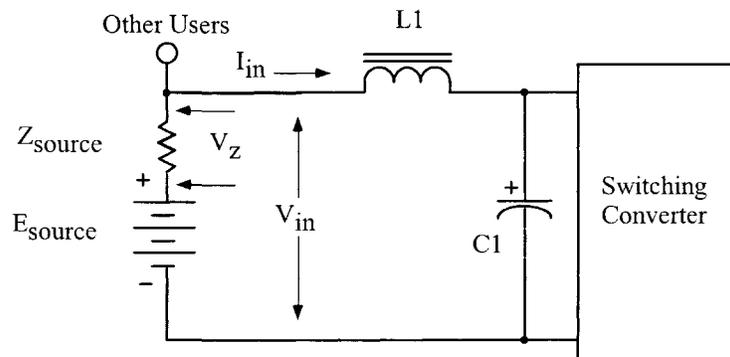


Figure 15-1. Simple, LC, Input Filter.

## Capacitor

Switching regulators have required the engineer to put a significantly more analytical effort into the design of the input filter. The current pulse, induced by the switching regulator, has had the most impact on the input capacitor. These current pulses required the use of high quality capacitors with low ESR. The waveforms, induced by the switching regulator, are shown in Figure 15-2. In the input inductor,  $L1$ , peak-peak ripple current is  $I_L$ . In the capacitor,  $C1$ , peak-peak, ripple current is  $I_C$ . In the capacitor,  $C1$ , peak-peak, ripple voltage is,  $\Delta V_C$ . The equivalent circuit for the capacitor is shown in Figure 15-3. The voltage,  $\Delta V_C$ , developed across the capacitor, is the sum of two components, the equivalent series resistance, (ESR), and the reactance of the capacitor.

The voltage developed across the equivalent series resistance, (ESR), is:

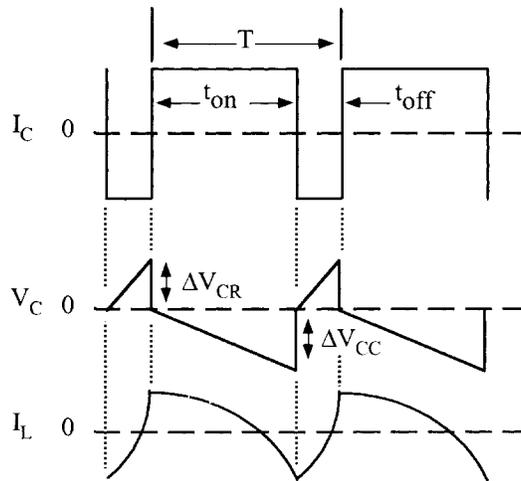
$$V_{CR} = I_C (\text{ESR}), \text{ [volts] [15-1]}$$

The voltage developed across the capacitance is:

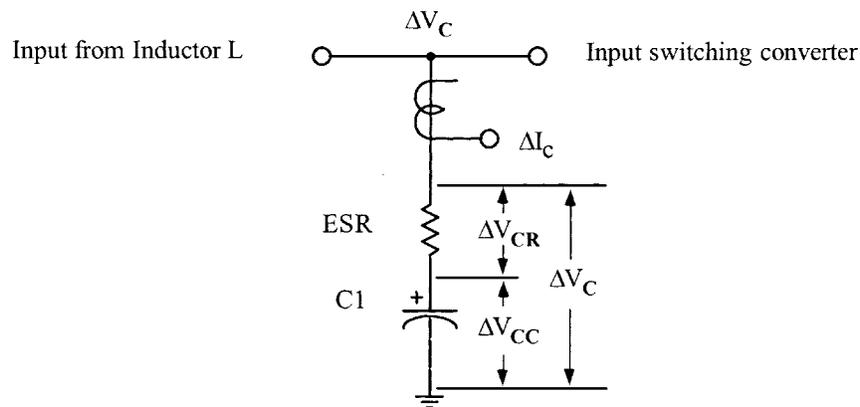
$$\Delta V_{CC} = I_C \left( \frac{(t_{on})(t_{off})}{(C1)(T)} \right), \text{ [volts] [15-2]}$$

The sum of the two voltages,  $\Delta V_{CR}$  and  $\Delta V_{CC}$ , is:

$$\Delta V_C = \Delta V_{CR} + \Delta V_{CC}, \text{ [volts] [15-3]}$$



**Figure 15-2.** Typical Voltage, Current Waveforms.



**Figure 15-3.** Capacitor, Individual Ripple, Components.

## Inductor

The input filter inductor is basically a straight-forward design. There are four parameters required to achieve a good design: (1) required inductance, (2) dc current, (3) dc resistance, and (4) temperature rise. The requirement for the input inductor is to provide a low ac ripple current to the source. The low ac ripple current in the inductor produces an ac flux at a magnitude of about 0.025 tesla. This resulting low ac flux will keep the core loss to a minimum. The input inductor losses will normally be 80 to 90% copper. A high flux magnetic material is ideally suited in this application. Operating with a high dc flux and a low ac flux, silicon, with its high flux density of 1.6 teslas, will produce the smallest size, as shown in Table 15-1.

**Table 15-1.** Most Commonly Used Input Filter Material.

Magnetic Material Properties		
Material	Operating Flux, B, tesla	Permeability $\mu_i$
Silicon	1.5-1.8	1.5K
Permalloy Powder	0.3	14-550
Iron Power	1.2-1.4	35-90
Ferrite	0.3	1K-15K

## Oscillation

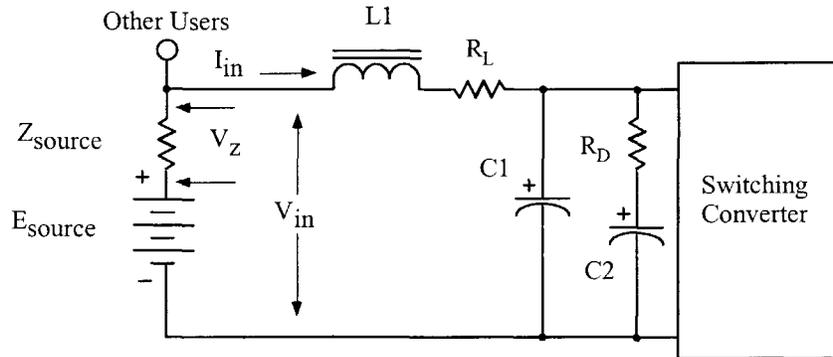
The input filter can affect the stability of the associated switching converter. The stability problem results from an interaction between the output impedance of the input filter and the input impedance of the switching converter. Oscillation occurs when the combined positive resistance of the LC filter, and power source exceed the negative dynamic resistance of the regulator's dc input. To prevent oscillation, the capacitor's ESR, and the inductor's resistance must provide sufficient damping. Oscillation will not occur when:

$$\left( \frac{\eta (V_{in})^2}{P_o} \right) > \left( \frac{L}{C + (R_L + R_s)(ESR)} \right) \left( \frac{R_L + R_s}{(R_L + R_s) + (ESR)} \right) \quad [15-4]$$

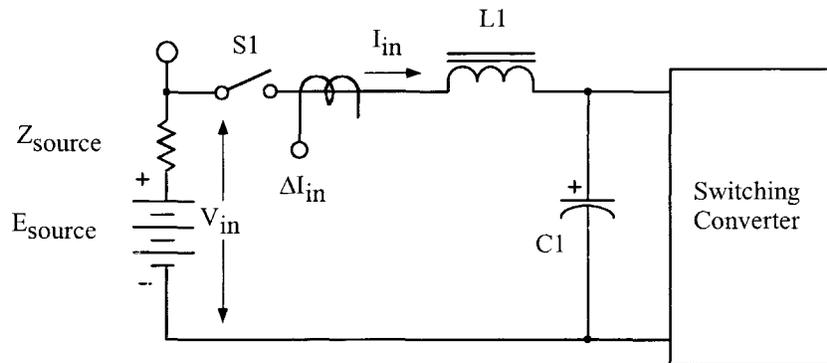
Where  $\eta$  is the switching converter efficiency,  $V_{in(max)}$  is the input voltage;  $P_o$  is the output power in watts,  $L$  is the input inductor in henrys; where,  $C$ , is the filter capacitor in farads,  $R_L$  is inductor series resistance in ohms;  $R_s$  is the source resistance in ohms, and  $R_d$  (ESR), is the equivalent series resistance in ohms. If additional damping is required, it can be done, by increasing the  $R_d$  (ESR), and/or  $R_L$ . See Figure 15-4. The series resistance,  $R_d$ , lowers the Q of the filter and kills the potential Oscillation.

## Applying Power

The inrush current has always been a problem with this simple LC input filter. When a step input is applied, such as a relay or switch S1 as shown in Figure 15-5, there is always a high inrush current.



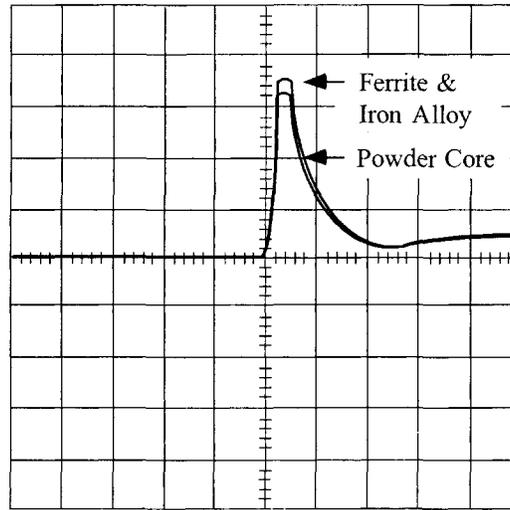
**Figure 15-4.** Input Filter, with Additional Damping.



**Figure 15-5.** Input Filter Inrush Current Measurement.

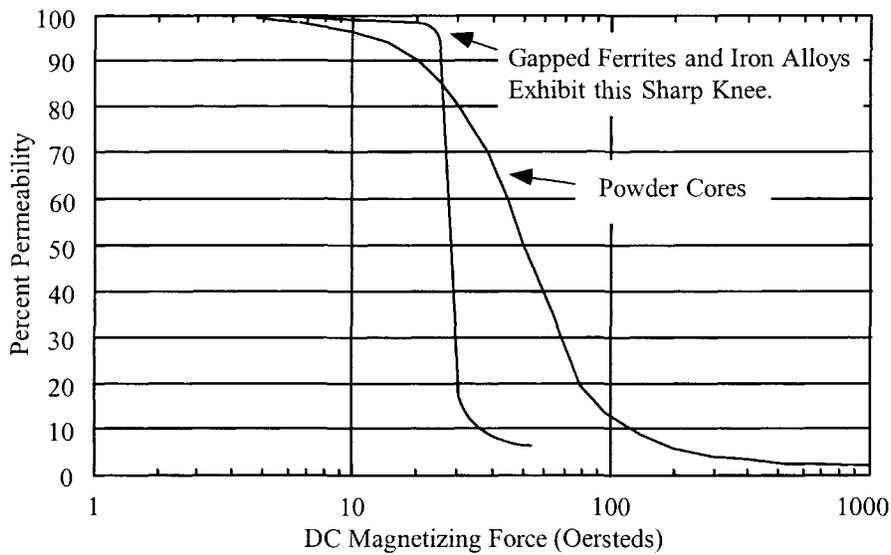
When S1 is closed, the full input voltage,  $V_{in}$ , is applied directly across the input inductor, L1, because C1 is discharged. The applied input voltage,  $V_{in}$ , (volt-seconds), to the input inductor, L1, and the dc current, (amp-turns), flowing through it is enough to saturate the core. The inductor, L1, is normally designed, using the upper limits of the flux density for minimum size. There are two types of core configurations commonly used for input inductor design: powder cores and gapped cores. Some engineers prefer to design around powder cores because they are simple and less hassle, while others design using gapped cores. It is strictly a game of trade-offs. Tests were performed using three different core materials: (1) powder core, (2) ferrite core, and (3) iron alloy. All three materials were designed to have the same inductance and the same dc resistance. The three-inductor designs were tested to compare the inrush current under the same conditions. The inrush current,  $\Delta I$ , for all three materials is shown in Figure 15-6, using the test circuit, shown in Figure 15-5.

As, shown in Figure 15-6, the inrush current for all three test inductors has about the same general shape and amplitude. The changes in permeability, with dc bias, for both gapped and powder cores are shown in Figure 15-7. Gapped cores have a definitely sharper knee while the powder cores roll off more gradually. The advantage in using a gapped core over the powder core is the ability to use the full flux capacity of the core up to the knee, before the permeability starts to droop.



Vertical 2 amps/Div., Horizontal 500 $\mu$ sec/Div.

**Figure 15-6.** Typical, Inrush Current for a Simple Input.



**Figure 15-7.** Comparing Gapped and Powder Cores, Permeability Change with DC Bias.

## Resonant Charge

Most all types of electronic equipment are energized by either a switch or relay. This type of turn-on goes for spacecraft, aircraft, computer, medical equipment, and automobiles. There are some power sources that require some type of current limiting that does not follow the general rule. If the input voltage is applied via a switch or relay to an input filter, as shown in Figure 15-8, a resonant charge condition will develop with L1 and C1. The resulting resonant charge with L1 and C1 could put a potential on C1 that could be as much as twice the applied input voltage, as shown in Figure 15-9. The voltage rating of C1 must be high enough to sustain this peak voltage without damage. The oscillating voltage is applied to the switching converter.

A simple way to dampen this oscillation is to place one or two diodes across the input choke, as shown in Figure 15-10. The reason for two diodes is the ripple voltage,  $V_c$ , might be greater than the threshold voltage of the diode. As the voltage across C1 rises above the input voltage,  $V_{in}$ , due to the oscillation diodes, CR1 and CR2 will become forward-biased, clamping the voltage across C1 to two diode drops above the input voltage,  $V_{in}$ , as shown in Figure 15-11.

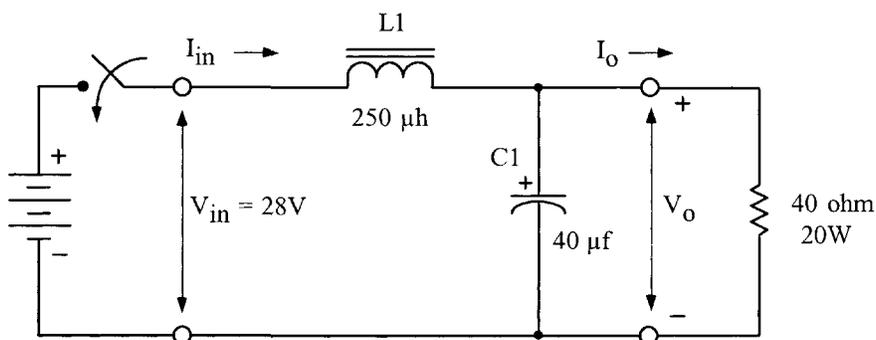


Figure 15-8. Typical, Simple LC, Input Filter.

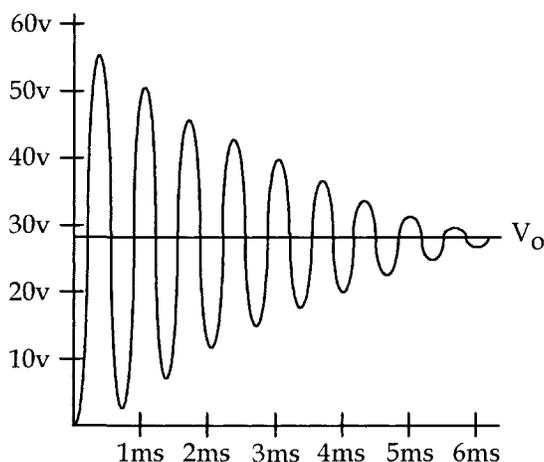


Figure 15-9. Resonating Voltage, across Capacitor, C1.

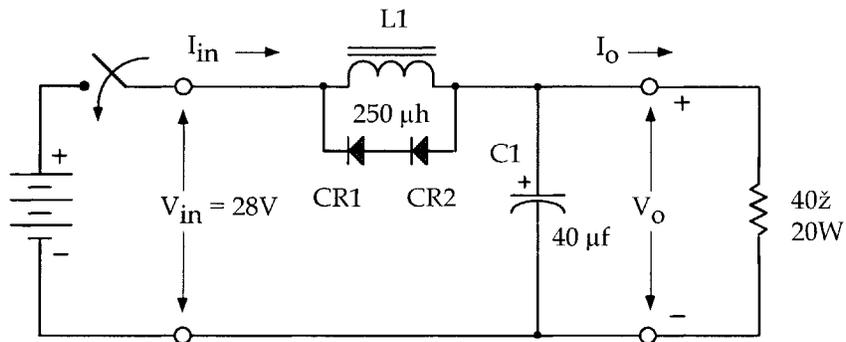


Figure 15-10. Input Inductor with Clamp Diodes.

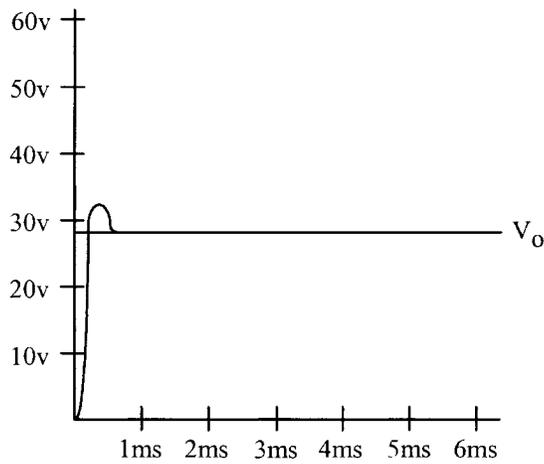


Figure 15-11. DC Voltage Across C1, with the Clamp Diodes.

### Input Filter Inductor Design Procedure

The input filter inductor, L1, for this design is shown in Figure 15-12.

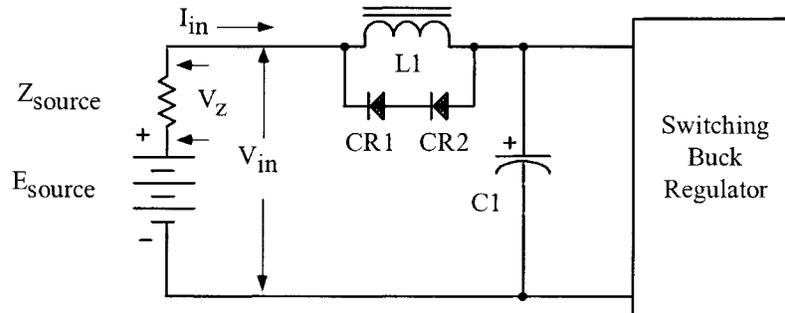
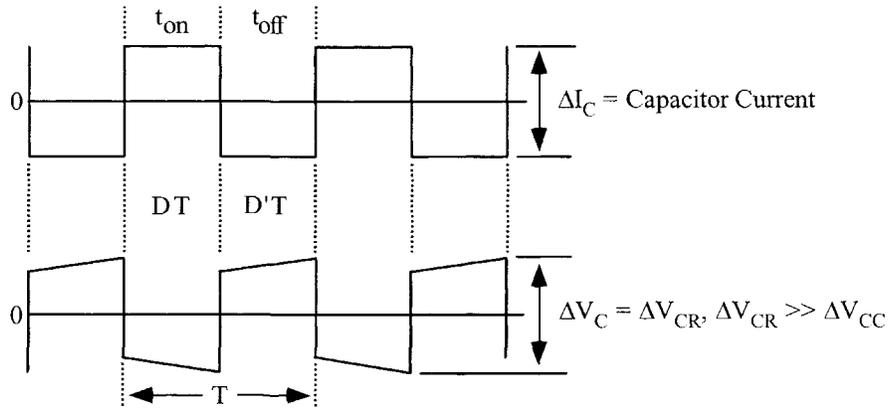


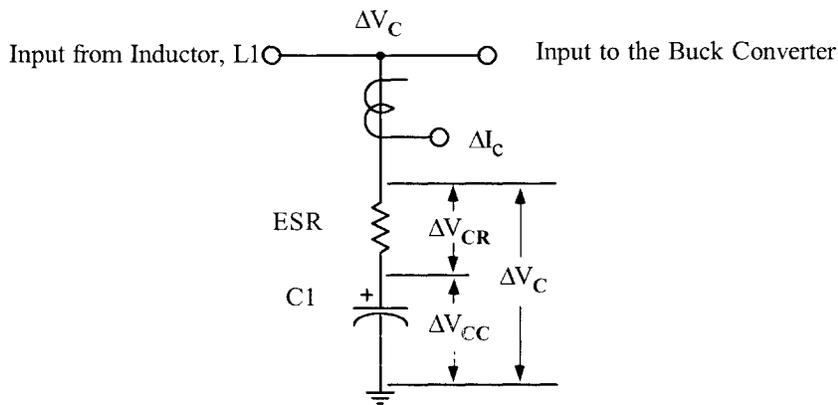
Figure 15-12. Input Filter Circuit.

The ac voltages and currents associated with the input capacitor, C1, are shown in Figure 15-13.



**Figure 15-13.** Input Capacitor Voltage and Current Ripple.

The ac voltages and currents impressed on the input capacitor, C1, are defined in Figure 15-14.



**Figure 15-14.** Defining the Input Capacitor Voltage and Current Ripple.

The components of the inductor current, due to,  $\Delta V_{CR}$  and  $\Delta V_{CC}$ , are:

$\Delta V_{CR}$  = Peak to Peak component due to capacitor, ESR.

$\Delta V_{CC}$  = Peak to Peak component due to capacitor.

$\Delta I_{LR}$  = Component of the inductor ripple current developed by  $\Delta V_{CR}$ .

$\Delta I_{LC}$  = Component of the inductor ripple current developed by  $\Delta V_{CC}$ .

$$\Delta I_{LR} = \left( \frac{\Delta V_{CR}}{L} \right) (DD'T), \quad [\text{amps}] \quad [15-5]$$

$$\Delta I_{LC} = \left( \frac{\Delta V_{CC}}{2L} \right) \left( \frac{T}{4} \right), \quad [\text{amps}]$$

It will be considered that,  $\Delta I_{LR}$ , dominates because of the capacitor, ESR, so:

$$\Delta I_{LR} = \left( \frac{\Delta V_{CR}}{L} \right) (DD'T), \quad [\text{amps}] \quad [15-6]$$

## Input Filter Design Specification

1. Peak-Peak ripple voltage,  $\Delta V_{cr}$  ..... = 0.5 volts
2. Peak-Peak ripple current to the source,  $\Delta I_L$  ..... = 0.010 amps
3. Period, T ..... = 10  $\mu$ sec
4. \*Converter on-time duty cycle,  $D = t_{on}/T$  ..... = 0.5
5. \*Converter off-time duty cycle,  $D' = t_{off}/T$  ..... = 0.5
6. Regulation,  $\alpha$  ..... = 0.5%
7. Output power drawn from the filter network,  $P_o$  ..... = 50 watts
8. Maximum current to the load,  $\Delta I_c$  ..... = 4 amps
9. Average input current,  $I_{in} = I_{av} = \Delta I_c D$  ..... = 2 amps
10. The ripple frequency, f ..... = 100kHz
11. The core RM ferrite, gapped,  $B_{max}$  ..... = 0.25 tesla

\* The worse case time domain is where D and D' = 0.5

Step No. 1 Calculate the required inductance, L.

$$L = \frac{\Delta V_{CR}}{\Delta I_L} (DD'T), \text{ [henrys]}$$

$$L = \frac{0.5}{0.01} (0.5)(0.5)(10(10^{-6})), \text{ [henrys]}$$

$$L = 0.000125, \text{ [henrys]}$$

Step No. 2 Calculate the energy-handling capability.

$$\text{Energy} = \frac{L(I_{av})^2}{2}, \text{ [watt-second]}$$

$$\text{Energy} = \frac{125(10^{-6})(2.0)^2}{2}, \text{ [watt-second]}$$

$$\text{Energy} = 0.000250, \text{ [watt-second]}$$

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

$$K_e = 0.145 P_o B_m^2 (10^{-4})$$

$$K_e = 0.145(50)(0.25)^2 (10^{-4})$$

$$K_e = 0.0000453$$

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

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

$$K_g = \frac{(0.00025)^2}{(0.0000453)(0.5)}, \quad [\text{cm}^5]$$

$$K_g = 0.00275, \quad [\text{cm}^5]$$

Step No. 5 Select the comparable core geometry from the RM ferrite cores.

1. Core part number ..... = RM-6
2. Core geometry,  $K_g$  ..... = 0.0044  $\text{cm}^5$
3. Core cross-section,  $A_c$  ..... = 0.366  $\text{cm}^2$
4. Window area,  $W_a$  ..... = 0.260  $\text{cm}^2$
5. Area product,  $A_p$  ..... = 0.0953  $\text{cm}^4$
6. Mean length turn, MLT ..... = 3.1 cm
7. Magnetic path length, MPL ..... = 2.86 cm
8. Core weight,  $W_{\text{ife}}$  ..... = 5.5 grams
9. Surface area,  $A_t$  ..... = 11.3  $\text{cm}^2$
10. Winding Length, G ..... = 0.82 cm
11. Permeability,  $\mu_m$  ..... = 2500

Step No. 6 Calculate the current density,  $J$ , using the area product equation,  $A_p$ .

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

$$J = \frac{2(0.00025)(10^4)}{(0.25)(0.0953)(0.4)}, \quad [\text{amps-per-cm}^2]$$

$$J = 525, \quad [\text{amps-per-cm}^2]$$

Step No. 7 Calculate the required bare wire area,  $A_{w(B)}$ .

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

$$A_{w(B)} = \frac{(2.0)}{(525)}, \quad [\text{cm}^2]$$

$$A_{w(B)} = 0.00381, \quad [\text{cm}^2]$$

Step No. 8 Select a wire from the Wire Table in Chapter 4. If the area is not within 10%, take the next smallest size. Also record micro-ohms per centimeter.

$$\text{AWG} = \#21$$

$$\text{Bare, } A_{W(B)} = 0.00411, \text{ [cm}^2\text{]}$$

$$\text{Insulated, } A_W = 0.00484, \text{ [cm}^2\text{]}$$

$$\left(\frac{\mu\Omega}{\text{cm}}\right) = 419, \text{ [micro-ohm/cm]}$$

Step No. 9 Calculate the effective window area,  $W_{a(\text{eff})}$ . Use the window area found in Step 5. A typical value for,  $S_3$  is 0.75, as shown in Chapter 4.

$$W_{a(\text{eff})} = W_a S_3, \text{ [cm}^2\text{]}$$

$$W_{a(\text{eff})} = (0.260)(0.75), \text{ [cm}^2\text{]}$$

$$W_{a(\text{eff})} = 0.195, \text{ [cm}^2\text{]}$$

Step No. 10 Calculate the number turns possible,  $N$ . Use the insulated wire area,  $A_w$ , found in Step 8. A typical value for,  $S_2$ , is 0.6, as shown in Chapter 4.

$$N = \frac{W_{a(\text{eff})} S_2}{A_w}, \text{ [turns]}$$

$$N = \frac{(0.195)(0.60)}{(0.00484)}, \text{ [turns]}$$

$$N = 24, \text{ [turns]}$$

Step No. 11 Calculate the required gap,  $l_g$ .

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

$$l_g = \frac{(1.26)(24)^2 (0.366)(10^{-8})}{(0.000125)} - \left(\frac{2.86}{2500}\right), \text{ [cm]}$$

$$l_g = 0.0201, \text{ [cm]}$$

Step No. 12 Calculate the equivalent gap in mils.

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

$$\text{mils} = (0.0197)(393.7)$$

$$\text{mils} = 7.91 \text{ use } 8$$

Step No. 13 Calculate the fringing flux factor,  $F$ .

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

$$F = 1 + \frac{(0.0201)}{\sqrt{0.366}} \ln \left( \frac{2(0.82)}{0.0201} \right)$$

$$F = 1.146$$

Step No. 14 Calculate the new number of turns,  $N_n$ , by inserting the fringing flux,  $F$ .

$$N_n = \sqrt{\frac{l_g L}{0.4\pi A_c F (10^{-8})}}, \quad [\text{turns}]$$

$$N_n = \sqrt{\frac{(0.0201)(0.000125)}{(1.26)(0.366)(1.146)(10^{-8})}}, \quad [\text{turns}]$$

$$N_n = 22, \quad [\text{turns}]$$

Step No. 15 Calculate the winding resistance,  $R_L$ . Use the, MLT, from Step 5 and the micro-ohm per centimeter, from Step 8.

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

$$R_L = (3.1)(22)(419)(10^{-6}), \quad [\text{ohms}]$$

$$R_L = 0.0286, \quad [\text{ohms}]$$

Step No. 16 Calculate the copper loss,  $P_{cu}$ .

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

$$P_{cu} = (2.0)^2 (0.0286), \quad [\text{watts}]$$

$$P_{cu} = 0.114, \quad [\text{watts}]$$

Step No. 17 Calculate the regulation,  $\alpha$ .

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

$$\alpha = \frac{(0.114)}{(50)} (100), \quad [\%]$$

$$\alpha = 0.228, \quad [\%]$$

Step No. 18 Calculate the ac flux density,  $B_{ac}$ .

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

$$B_{ac} = \frac{(1.26)(22)(1.14) \left(\frac{0.01}{2}\right) (10^{-4})}{(0.0197) + \left(\frac{2.86}{2500}\right)}, \quad [\text{tesla}]$$

$$B_{ac} = 0.000758, \quad [\text{tesla}]$$

Step No. 19 Calculate the watts-per-kilogram, for ferrite,  $P$ , material in Chapter 2. Watts per kilogram can be written in milliwatts-per-gram.

$$\text{mW/g} = k f^{(m)} B_{ac}^{(n)}$$

$$\text{mW/g} = (0.00198)(100000)^{(1.36)} (0.000758)^{(2.86)}$$

$$\text{mW/g} = 0.0000149$$

Step No. 20 Calculate the core loss,  $P_{fe}$ .

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

$$P_{fe} = (0.0000149)(5.5)(10^{-3}), \quad [\text{watts}]$$

$$P_{fe} = 0.082(10^{-6}), \quad [\text{watts}]$$

Step No. 21 Calculate the total loss copper plus iron,  $P_{\Sigma}$ .

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

$$P_{\Sigma} = (0.000) + (0.114), \quad [\text{watts}]$$

$$P_{\Sigma} = 0.114, \quad [\text{watts}]$$

Step No. 22 Calculate the watt density,  $\psi$ . The surface area,  $A_t$ , can be found in Step 5.

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

$$\psi = \frac{(0.114)}{(11.3)}, \quad [\text{watts/cm}^2]$$

$$\psi = 0.010, \quad [\text{watts/cm}^2]$$

Step No. 23 Calculate the temperature rise,  $T_r$ .

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

$$T_r = 450(0.010)^{(0.826)}, \quad [^{\circ}\text{C}]$$

$$T_r = 10.0, \quad [^{\circ}\text{C}]$$

Step No. 24 Calculate the peak flux density,  $B_{pk}$ .

$$B_{pk} = \frac{0.4\pi N_n F \left( I_{dc} + \frac{\Delta I}{2} \right) (10^{-4})}{I_g + \left( \frac{\text{MPL}}{\mu_m} \right)}, \quad [\text{tesla}]$$

$$B_{pk} = \frac{(1.26)(22)(1.14)(2.005)(10^{-4})}{(0.0197) + \left( \frac{2.86}{2500} \right)}, \quad [\text{tesla}]$$

$$B_{pk} = 0.304, \quad [\text{tesla}]$$

Step No. 25 Calculate the window utilization,  $K_u$ .

$$K_u = \frac{A_{v(B)} N_n}{W_u}$$

$$K_u = \frac{(0.00411)(22)}{(0.260)}$$

$$K_u = 0.348$$

## References

1. T. K. Phelps and W. S. Tate, "Optimizing Passive Input Filter Design," (no source).
2. David Silber, "Simplifying the Switching Regulator Input Filter," Solid-State Power Conversion, May/June 1975.
3. Dan Sheehan, "Designing a Regulator's LC Input Filter: 'Ripple' Method Prevents Oscillation Woes," Electronic Design 16, August 2, 1979.

### Note:

I would like to thank Jerry Fridenberg, for modeling the circuits in Figure 15-8 and 15-10, on his SPICE program. The modeling results are shown in Figures 15-9 and 15-11.