EMI filters for power supplies

Filter designers must consider the actual power supply, power factor correction circuits and power factor correction coils.

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Many EMI filters are used in power supplies. Several problems relating to power supplies are worth investigating. The first involves the design of an EMI filter for a typical linear power supply, or an off-line regulator. The load for these supplies may be a switcher power supply.

Power factor correction circuits are discussed in the next section. These eliminate the need for the critical inductance requirement discussed in the first section.

The power factor correction coil is the last item. This restores the power factor to near unity, allowing the capacitance to increase, and the inductors to decrease in value. This decreases the voltage rise of the 400-Hz filters and reduces the leakage current to ground.

For purposes of consistency, this article will discuss power supplies and the associated EMI filtering in terms of single-phase, 400-Hz power.

POWER SUPPLIES

It is unusual for the load to be correctly specified for the EMI filter designer, especially for power supplies. Engineers frequently work with customers to get this information, but sometimes it is unavailable. As an example of this, consider the power supply as the load for the filter. Figure 1 shows a 120-VAC 400-Hz single-phase line tied to the EMI filter and the filter feeding a power supply either with or without the central transformer.

The purpose of this section is to show the EMI filter design requirements based on two power supply types. The first is the capacitive input power supply filter and the second is the inductive input power supply filter.

Keith Williams, of Grand Transformers in Grand Haven, MI, has developed transcendental functions based on a 1943 article on the capacitive input filter by O. H. Schade. Keith Williams' equations and a basic computer program appeared in *Wound Magnetics Journal* (Volume 3, No. 1, Jan–Mar, 1995).

Williams' Basic computer program gives the start and stop conduction angles of the current pulse. With this knowledge, his listed equations give the minimum voltage angle and value, the peak current angle and value and the peak voltage and angle. Also, his equations provide the voltage and current at any time, t.

Consider an 800-W maximum output power supply with a capacitive input filter (Figure 2). Using Williams' equations and applying some additional Fourier Analysis, the fundamental RMS current is

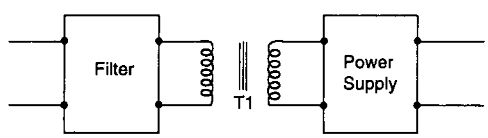

Figure 1. The line, EMI filter and power supply.

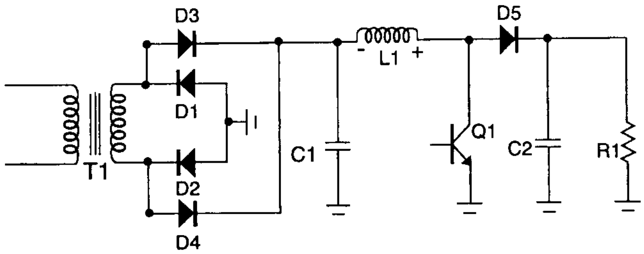

Figure 2. Typical power supply with capacitor storage filter, C1.

8 A. This current value would probably be given to the engineer either verbally or as part of a specification. The full RMS current, which includes all the harmonics, is 10.61 amps. This is based on a DC load of 24 ohms and a 200-µF storage capacitor. If this were the worst error, the EMI filter would function properly. However, the true capacitive charging peak current is 24.2 A. The EMI filter would saturate if designed to the initial specification.

On the other hand, the inductor input filter power supply (Figure 3) would work perfectly with the inductance. This critical inductance (L1 in Figure 3) removes the high peak capacitive charging current. This technique is rarely used because of the inductor's size and weight. Adding to the problem is that its value, and therefore the size, weight and cost, is found by the lowest current value the load requires. The equation for the critical inductance, L_c, is:

$$L_c = \frac{R_o}{6\,\pi\,F} \tag{1}$$

The value of R_o is the highest DC supply voltage divided by the lowest load current. F is the line frequency—in this case, 400 Hz—not the ripple frequency. The inductance value is in Henrys. Clearly, the critical inductance circuitry is best suited for a nearly constant current supply. The inductor value would be greatly reduced. L_c delivers a constant current to the storage capacitor that is equal to the average load current. The line current is a square wave at the line frequency—here again, 400 Hz—but applies equally well to 50- or 60-Hz systems. The EMI filter would remove the upper harmonics making the line current more sinusoidal. 400-Hz EMI filters are notorious for giving higher output voltage, or a voltage rise, at the output at 400 Hz. The design given in this article should be less that 2 percent.

If the customer's EMI test lab listed the requirement for 80-dB insertion loss at 20 kHz, the EMI filter would require a double "Pi" using two 90-µH inductors and three 8-µF capacitors and one tuning capacitor (Figure 4). This insertion loss requirement is demanding, especially at the current required and the 400 Hz. However, this filter will saturate if the supply is a capacitive input type power supply due to the large current peak. The inductors must be redesigned to handle 25 A.

The filter component values for the 8 A and 25 A would be the same, but the cores used for the inductors will change. Using the 8 A given initially, MPP powder or HF cores may be used. Here MP58930 was used with 24 turns of #14, 6650 Gauss and a reasonable temperature rise of 35° C. The weight would be 0.12 pounds including the copper for each core. Larger cores, such as "C" cores, would be required for 25 A peak current. For the 25 A, a "C" core CH 205 with 9 turns of 5 strands of #15 would be required. The total weight each, with copper, is 0.68 pounds and huge compared to the MPP HF core and wire. The temperature rise was 25° C.

The critical inductance equation gives the minimum inductance as:

$$L_c = \frac{48}{6\,\pi\,400} = 0.0064 \text{ Henrys} \tag{2}$$

Again, a 4-mil "C" CH-47 requires 177 turns of #16 and the weight is 0.79 pounds. The temperature rise is 42° C.

To review, all the filter capacitors are the same.

1) According to the initial design the total inductor weight is 2 x 0.12 = 0.24 pounds, but the inductors will saturate under the 25 A.

2) Redesigned for the 25 A, 2 x 0.68 = 1.35 pounds and much larger.

Using the initial design from 1) above and including the L_c inductor, 2 x 0.12 + 0.79 = 1.03 pounds. A savings of 1/3 pound and the total size of the two areas should be a little smaller. Another savings on weight and size is that the storage capacitor following the L_c inductor should be reduced to less than 50 percent. This is because the critical value inductor supplies constant average current to the capacitor. This technique reduces the output ripple voltage. Therefore, the capacitor value, and size, is smaller.

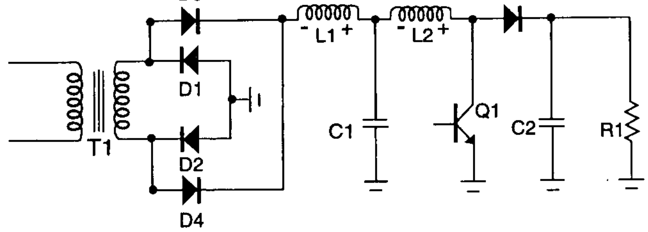

Figure 3. The same power supply with the critical inductance, L1.

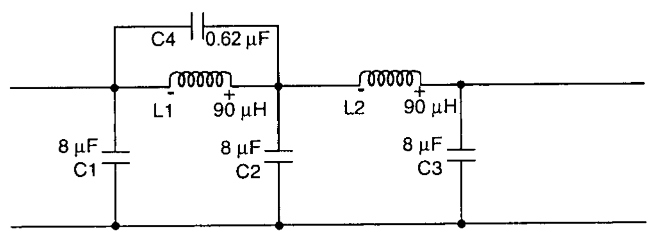

Figure 4. An 8-A filter for the 220-A specification.

The situation just described is a borderline case. As the insertion loss requirement increases, or as the current increases, the solution calls for an inductor designed to meet the critical value. Thus, EMI filters requiring higher currents must be designed. These filters often require insertion loss of 100 dB at 14 kHz. It should be easy to see that the addition of the critical inductance for these power supplies would save space and weight and the cost of the EMI filter would be greatly reduced.

THE POWER FACTOR CORRECTION CIRCUIT

Power factor correction circuits (PFCC) will eliminate the need for the critical inductor in the case discussed if the power requirement is low enough to be practical. At higher currents, the power factor correction coil is used to restore the power factor to near unity, but this technique should be used only at 400 Hz.

Today, power factor correction circuits are essential in many countries (Figure 5). This is a useful technique for lower currents. Power factors as low as 0.43 resulting from the power factor of the power supply and the EMI filter together have been observed. This situation is caused by large EMI filter capacitors followed by the large storage capacitor of the power supply. Power supplies without the power factor correction circuits exhibit power factors as low as 0.7. Improper filtering only adds to the problem. The power factor correction circuits of Figure 5 work by switching the diode output voltage without initially storing the energy in a large filter capacitor. Thus, the switcher current is in phase with, or follows, the line voltage. The switcher creates high frequency pulses that follow the AC voltage sine wave returning the power factor back to near unity. This means that the output impedance of the EMI filter must be very low at the power factor correction circuit switcher frequency. The PFCC inductor conducts current in the same direction while the switch is open and closed. So the current through the diodes is a sine wave at the line frequency plus small steps superimposed on top of it at the switcher frequency. It is the job of the EMI filter to attenuate this switcher frequency without starving the switcher.

This is another reason filters designed for very similar specifications may work well for one group and fail for the next. The first group could be using an off-line regulator for their application and the last group a power factor correction circuit for the same power range. The output impedance of the filter may be inductive (such as a "T"). The inductive reactance would be fine for the first application for the off-line regulator, but be too high for the power factor correction circuit. This would starve the power factor correction circuit and could damage the switcher circuitry. This demands a high quality capacitor at the output of the filter facing the switcher with a self-resonance well above the 10th harmonic of the switcher.

The disadvantage of power factor correction circuits is that they are not 100-percent efficient. The main reason for their development is to reduce the stress of the power source. However, the power factor efficiency is improving with time. Originally, users did not account for the lower efficiencies of these circuits. The power required to drive the equipment using the power factor correction circuits is now lower. The efficiencies were around 70 percent but are close to 90 percent today.

To review, the power factor correction circuit is a good addition to power supplies for the low- to medium-size power supplies. This reduces the size of the inductors in the same way as the critical inductor, but has an added feature of a sinusoidal current. Frequently, the weight and volume is also less than the L_c inductor. The filter manufacturer should be informed that this circuit is part of the input circuitry of the power supply. This will insure a low output impedance of the EMI filter at, and above, the switcher frequency.

POWER FACTOR CORRECTION COIL

A shunt power factor correction coil (Figure 6) is often supplied along with EMI filters. In most designs, the EMI filter looks very capacitive at the power line frequency, and some specifications demand near unity power factor for the filter for three reasons: maximum power efficiency; lower capacitor reactive current, also called leakage current; and the 400 Hz voltage rise.

At the line frequency, the impedance of the inductors in the EMI filter are lower than the capacitor impedance. So, the capacitors add in parallel, as in Figure 6, to a value of 3 x C1. The inductive reactance of the power factor correction coil must be equal to the total capacitive reactance across the line to ground.

This returns the power factor back to near unity by canceling the capacitive reactance current removing the

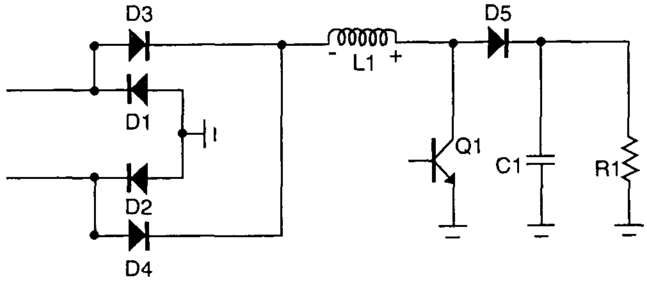

Figure 5. Power factor correction circuit.

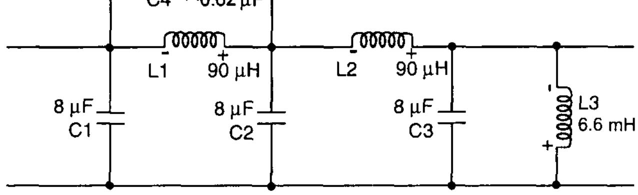

Figure 6. Power factor correction coil.

ground current. If the capacitors from line to ground are equal to 8 μF each, then the total is 24 μF. Then Equation 3 will give the inductance as 6.6 mH.

$$X_L = X_C$$

$$L_c = \frac{1}{4\,\pi^2\,F^2\,C} = \frac{1}{4\,\pi^2\,400^2\,24\cdot10^{-6}} = 6.6\ \text{mH} \quad (3)$$

This is a large inductor and the current through it is the same as the capacitor reactive current of the total capacitance (but 180° out-of-phase). This technique converts the capacitor reactive current of the EMI filter to circulating current in this newly-formed, parallel tank circuit. There are two conflicting factors to consider dealing with the Q of this tank circuit, which is really the Q of the inductor. To reduce the capacitor reactive current as much as possible, the highest value of Q is required. On the other hand, due to aging of the filter components and working stresses on the filter over time, a lower Q is needed. This is also true in installations where the power line frequency drifts over a wide range, such as remote power generators. The frequency drift would cause the network to be off-tuned from the center frequency, and be operating on the side skirts of the impedance curve of the parallel tank circuit. Whatever the Q, high or low, the equation is:

$$I_{circ} = Q \cdot I_{line} \quad (4)$$

Where I_{circ} is the circulating current in this tank, the same as the leakage current before addition of the power factor correction coil, and I_{line} is the new leakage current. The reason for the concern about leakage current is the danger to anyone touching the filter if the safety ground has been removed. This could be lethal due to electric shock when this ground is cut. Equation 4 shows that the leakage current has been reduced by a factor of Q. As already stated, this technology should be used only on 400-Hz systems. The reason is apparent when comparing the required inductance values for 50 or 60 Hz.

To review, the power factor correction coil helps to remove the 400-Hz voltage rise by reducing the total line inductance; providing a safety factor by reducing the current on the ground return; and bringing back the power factor of the filter to unity.

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