AN EVALUATION OF EMI POWER LINE FILTERS FOR SWITCHING POWER SUPPLIES

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Abstract. *Power line filters are now present in almost all domestic and industrial applications. One major reason for installing a filter directly at the power entry point is the suppression of the conducted emissions that would otherwise be injected directly onto the power lines. Another reason is to suppress noise entering the equipment from the power lines. The continuous development of uninterruptible power supplies implies more efficient and inexpensive line filters. This article presents a detailed description and evaluation of these "ordinary" filters.*

Keywords: *noise, conducted emissions, power line filter, absorption filter*

Introduction

Power line filters, often-called EMI filters, are present in almost all today equipment, and serves two purposes.

The first is to suppress the noise generated by the equipment, conducted emissions, which could otherwise be impressed directly onto the power lines. The intensity of such emissions is regulated by government agencies in most countries in order not to cause interference with other equipment. In the United States, it is the Federal Communications Commission (FCC) which sets the limits for various classifications of equipment as a function if it’s operating environment. The international authority in this filed is the International Electrotechnical Commission – IEC. All manufacturers must respect the rules and standards issued by IEC. The controlled equipment primarily falls into the broad category of digital devices or those that use digital techniques for any purposes.

Another reason for installing a filter directly at the power entry point is to suppress noise entering the equipment from the power line. Such noise can cause malfunctioning of digital or digitally controlled equipment that may be susceptible to the noise frequencies present on the power lines.

Being a bilateral device, the EMI filters serves both of these purposes. The FCC regulates the amplitude of conducted noise frequencies from 450kHz to 30MHz. In Europe, these noise levels are controlled from 10kHz or 150kHz to 30MHz. The range of controlled frequencies is broader for devices used in the general market than those used in specific, singular installations. Also, the limits for industrial applications are less stringent than those for residential usage.

Since almost all today equipment are powered by switching power supplies operating from 20kHz to near 1MHz, the likelihood of superimposing interfering noise frequencies on the power line is very great. Therefore, the need for an EMI filter at the power line entry point is apparent. Although not always recognized in using EMI filters, it also suppresses noise radiated from the power line that acts as an antenna. The performances of most filters are specified only up to 30MHz, but the filter will suppress noise at higher frequencies.

The performance of a filter in a particular application may be better understood from its common mode and differential mode equivalent circuits. The inductors and capacitors used in a filter are complex components with their effectiveness being dependent on material properties, construction, placement, and means of connection. Similar filters may not perform identically in a given application because of subtle component differences and parasitic parameters. The method used to install a filter in the equipment can have a significant effect on its performance.

Characterization of EMI Noise

Any conducted noise spectrum may be resolved into two components, common (asymmetrical) and differential (symmetrical) modes. An understanding of these modes will assist in analyzing the performance of an EMI power line filter. Common mode noise is that noise which is identical on each line with respect to ground. Differential mode noise is that part of the total noise that occurs between the two lines with no reference to ground. The common mode currents, I_{CM}, are identical at any one frequency in both amplitude and phase. The differential mode current, I_{DM}, is a single current in the loop consisting of the power lines.

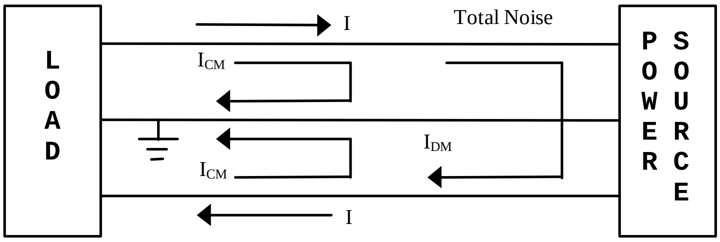

FIGURE 1. Common Mode and Differential Mode Noise Currents

The common mode currents are the same in both lines with their return being the ground connection. The differential mode current does not flow in the ground connection. At any one frequency, the total noise current in one of the lines can be expected to be higher than that in the other line. It depends on the amplitude and phase of the component noise current at that frequency, since the total noise current in one line is the sum of the components in one case and their difference in the other.

There are several reasons, theoretical and practical, why it is difficult to predict conducted EMI.

1) Differential mode and common mode noises are coupled through different paths to the measured EMI. Equipment package and component layout all affect the coupling paths, but the effects are very difficult to quantify. Often, a seemingly small change in layout could lead to significant change in EMI performance.

2) The effectiveness of an EMI filter depends not only on the filter itself but also on the noise source impedance.

3) Beyond a certain frequency, the effects of parasitic elements start to surface. This frequency is the border between “high frequency” and “low frequency”. High-frequency effects include permeability reduction of choke core, parasitic capacitance effect of the inductor and the parasitic inductance effect of filter capacitors.

Low Cost Power Line Filter

A typical power line filter is a simply low-pass filter that provides no attenuation to the power frequency but provides large (ideal infinite) attenuation to RF energy. Consequently, an EMI power line filter consists of series of inductors and shunt capacitors.

The inductors may take two forms. The most common inductor found in almost all low-cost filters is a single magnetic core structure wound with two coupled windings, one in series in one line and the other in series in the other line. A filter may also contain independent, single winding inductors in either or both lines.

In the case of multiphase or split phase filters, the common core inductors must have identical windings connected in each power current carrying line. Similarly, the independent inductors would appear in each of these lines. The principles will be discussed for single-phase filters in this paper.

In order to increase the effectiveness, filters often include capacitors connected from line-to-line and others connected from line-to-ground.

A simple but representative EMI power filter circuit diagram is shown in Figure 1:

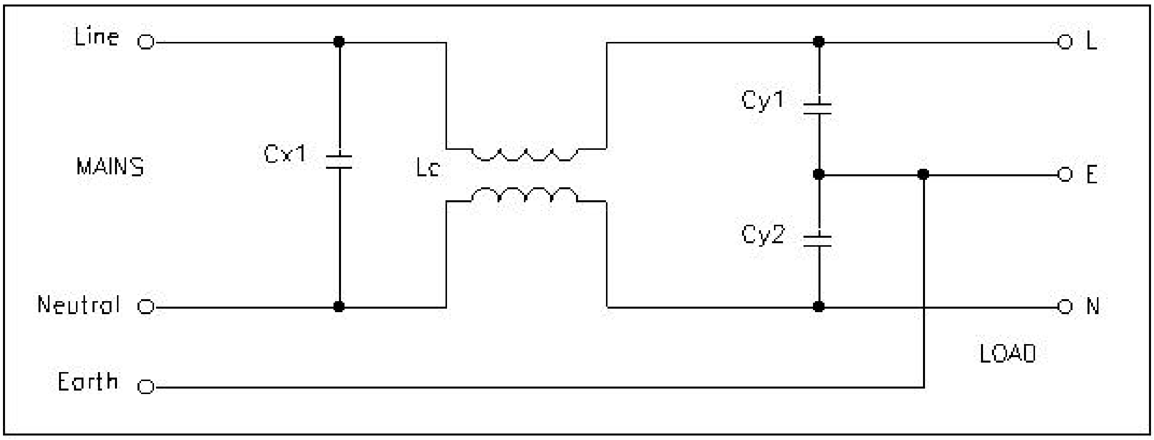

FIGURE 2. A Simple Low Cost EMI Power Line Filter
C_{x1} - Line to Line Capacitor
$C_{y1,2}$ – Line to Ground Capacitor
L_c – Common Core Inductors

On notice the presence of only one inductor (L_c) and a single line-to-line capacitor (C_{x1}). Line-to-line capacitors are usually made of metal vaporized film or film and foil. Such capacitors have a relatively high value 0.1µF to 1.0µF, for example, along with high reliability. Their self-resonant frequency is of the order of 1MHz to 2MHz. Thus, they are more effective against lower frequency differential-mode noise. Line to ground capacitors must be of very low value, in the range of 1.0nF to 10nF. Therefore, they are more effective against higher frequency common mode noise. Because of their superior, high self-resonant frequencies of ceramic capacitors over that of wound film capacitors, the former are usually used for this purpose. Ceramic capacitors with very short leads resonate at 50MHz or more, generally, depending on their geometry. Film capacitors even with short leads will resonate around 10MHz or nearby.

Any capacitor at a frequency higher that its self-resonant frequency is an inductor and is, therefore, a less effective EMI filter component because its impedance now increases with frequency. This fact is important in selecting the type of capacitor and in its method of assembly into the filter.

Inductors, like capacitors, are not purely inductive. The windings by their very nature are shunted by distributed capacitance. Therefore, inductors also suffer from self-resonant characteristics. Above their self-resonant frequency, the capacitance dominates so that they are less effective at higher frequencies. Depending on value of the inductance, the geometry of the windings, and the care material, coil self-resonance typically occurs in the range of 150kHz to 2MHz.

High Efficiency Passive Power Line Filter

A more complex filter is presented in Figure 4. It is often called the “total EMI filter”. The basic structure is similar with that of the simple EMI filter. There are some extra elements, two inductors, L_{d1} and L_{d2} and one condenser C_{x2} connected in a low pass configuration.

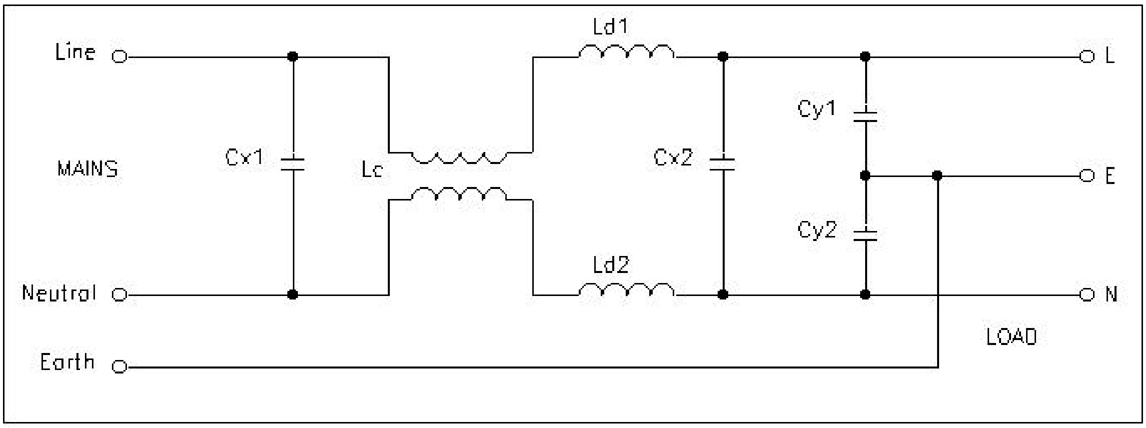

FIGURE 3. A Complete EMI Power Line Filter
C_{x1} - Line to Line Capacitor
C_{x2} – Line to Ground Capacitor
$C_{y1,2}$ - Line to Ground Capacitor
L_c - Common Core Inductors
$L_{d1,2}$ – Independent inductors

The design of the independent inductors L_{d1} and L_{d2} must take into account the saturation characteristics of the core material relative to the rated current of the filter and the turns required on that core to achieve the desired inductance. Otherwise, the core would be saturated under normal operating conditions and be ineffective as a filter component. Saturation is a very important factor in the design of common core inductors. The two windings of such a component are designed with equal number of turns, so that the magnetic force around the core due to the power current in these windings cancel.

An EMI filter will most often contain a bleeder resistor to discharge the line-to-line capacitors when power is interrupted (R_{x1}, $R_{y1,2}$ in Figure 5). They have no effect in filter performance. If a ground choke is included in the filter, it will suppress common, not differential, mode noise.
One solution is to put in parallel with each condenser a varistor. This can be helpful in reducing the over-voltages injected by the source itself in the power lines.

A practical approach

We made some tests using a standard forward switching power supply. The load was a 10 ohms resistor in series with a 10mH inductance. The electrical diagram of the source is presented in Figure 4.

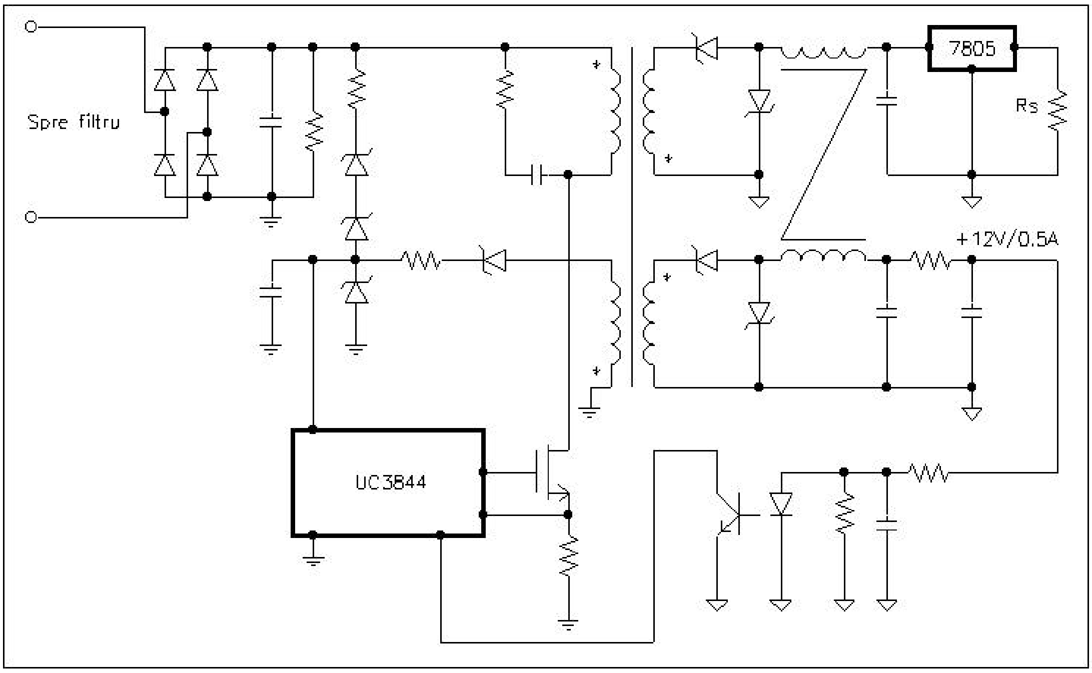

FIGURE 4. Circuit diagram of a 100W forward switching power supply using the specialized IC - UC3844

For the filter we used the more complex one (Figure 5). The condition for the filter is to meet the VDE limit (that is more than 10-dB attenuation for 10Hz to 150kHz frequency range and more than 20dB for 150kHz to 30MHz range).

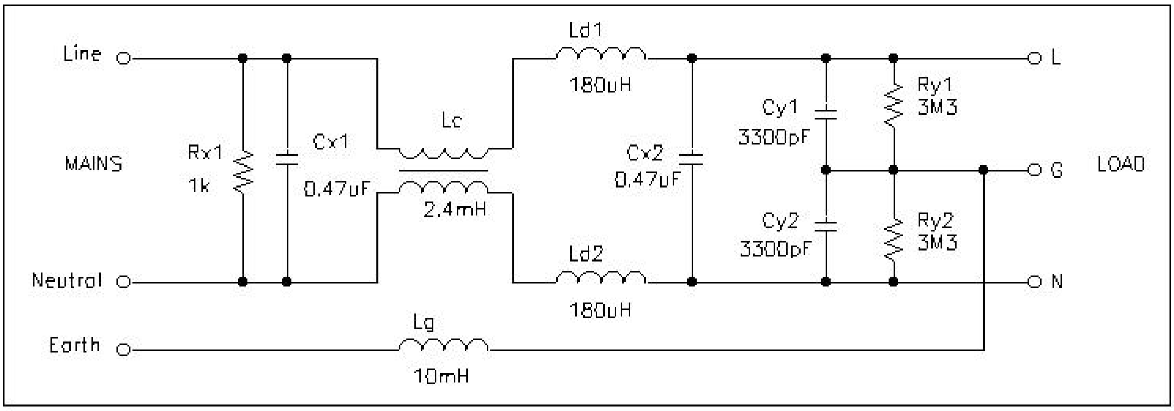

FIGURE 5. The filter used to measure the noise of a 100W forward switching power supply

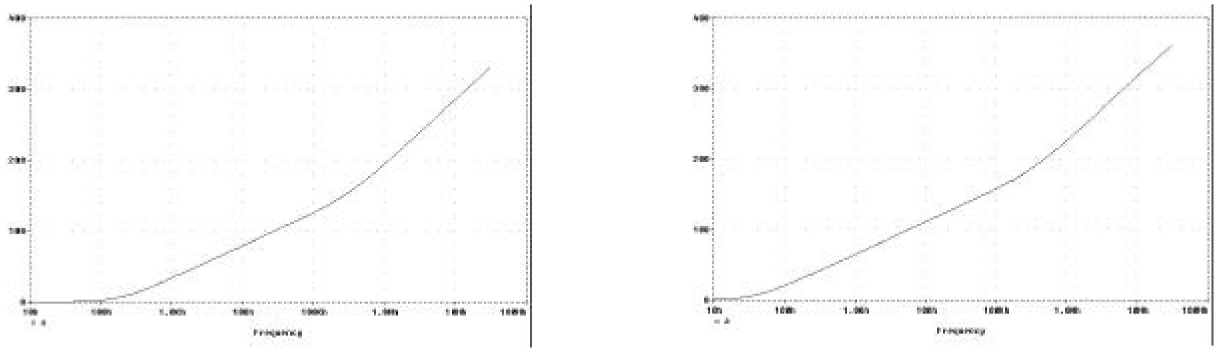

FIGURE 6. The diagram of the differential-mode and common-mode attenuation obtained with the filter in Figure 5

$$f_{RCM} = \frac{1}{2\pi\sqrt{L_{CM}C_{CM}}} = \frac{1}{2\pi\sqrt{\left(L_c + \frac{1}{2}L_d\right)2C_y}} \cong \frac{1}{2\pi}\cdot\sqrt{\frac{1}{L_c.2C_y}} \qquad (1)$$

$$f_{RDM} = \frac{1}{2\pi}\cdot\frac{1}{\sqrt{L_{DM}.C_M}} = \frac{1}{2\pi}\cdot\sqrt{\frac{1}{(2L_d + L_{loss}).C_{DM}}} \qquad (2)$$

Imposing the two frequencies we can calculate the elements of the filter in Figure 5.

Conclusions

The performance of a filter in a particular application may be better understood from its common mode and differential mode equivalent circuits. The inductors and capacitors used in a filter are complex components with their effectiveness being dependent on material properties, placement and means of construction.

Similar filters may not perform identically in a given application because of subtle component differences and parasitic parameters. Many parasitic parameters exist in any filter, which are not determined by measurements. All of these, plus the properties of the materials in the components will likely make two apparently identical filters behave differently in any given application. Power line filters used in switching power supplies are exposed to over-voltages witch can cause damages especially to the filter capacitors.

References

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