
Power-line Noise: How Series Filters Work—

(AND WHY THEY DON'T ALWAYS)

Most power-line treatment products depend upon series filters to correct AC line noise problems in the audio/video system. However, these series filters, unlike MIT's parallel filter system, have inherent flaws that make them ineffective at many vital frequencies in A/V use, and cause them to add more noise and distortions than they remove. In this paper, we will explain how:

- series-filter noise rejection is ineffective in real-world systems
- series inductors create distortion products at audible frequencies
- noise that is supposed to go to "ground" is fed back into the circuit
- safety issues require the use of inadequate capacitance to reduce noise
- series-filter resonances actually create noise at audible frequencies

Utility power-line related noise, as most of us know, affects the audible performance of our audio & video systems. The primary means of reducing noise in the audio equipment's circuits is passive AC line filtering placed in series with the AC utility line. Over the years, increased use of electronic filtering and regulation of DC power supplies have also helped isolate the power-line noise from amplifying circuits. Improved grounding techniques within the chassis (e.g., "star grounding" - please see Glossary, page 6) and from chassis to chassis have improved audio system noise performance.

These "line" filters are composed of inductor (L) and capacitor (C) net-

works placed in series between the AC line and the audio equipment. However, depending on how the noise is coupled to the power line, a great deal remains to be done to remove its effects from our systems.

Hey! Where Does This Utility Line Noise Come From, Anyway?

Power-line noise can come from a number of sources. These sources determine the type of noise and ultimately how it is removed. Noise that is coupled directly through the power-line conductors or wires by other equipment on the line is known as conduction-mode noise coupling. This mode is caused by equipment such as electric motors, arc welders, power supply switching circuits (found in computers,



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etc.), as well as household appliances - equipment that is online both from within and from outside your home and in common with your AC utility source, even from your neighbors' use of the AC line.

Noise that is induced into the line from non-direct contact with the line we call the field-coupled mode of noise coupling. This mode occurs when the line acts like a receptor antenna to external fields. These fields are generated by broadcast stations, radar, and other sources of field radiation.

Some equipment causes both direct and field-coupled modes of noise generation. Equipment such as computers, video components, and digital audio equipment can cause noise to be fed back into the AC power line, and will also radiate a broad spectrum of radio frequencies (RF). Power cords, signal cables, and antenna leads in the vicinity of this equipment will couple noise into nearby equipment.

No matter how the noise is coupled into the home audio/video system, its removal is not always easy. Noise may be classified as either in phase or out of phase with respect to ground. When the two power line wires have noise that is out of phase, this is called differential-mode noise. When the noise voltages are in-phase with one another, they are called common-mode noise. How each one may be dealt with is the story we present here.

Get Rid of that Noise!
Traditional Cure: Series Filters

Noise removal is commonly handled by a selective frequency filter placed in series with the AC line. These filters are composed of inductors (L), capacitors (C), and sometimes resistors (R) and trans-

formers (T). Figure 1a shows an example of how differential-mode noise is typically handled by filtering on the power line. Since the phases are opposite, when they are combined, the noise cancels out. A simple and almost universal method is to place a small value capacitor (.01-.05 μ fd) across the lines to effect this cancellation of unwanted frequencies (noise). As frequencies get higher, the capacitor begins to look like a good conductor, and the two out-of-phase noise signals will cancel each other out.

When the unwanted noise is in-phase on each line (a common-mode signal), then a small value capacitor may be placed from each line to a common ground wire, as shown in Figure 1b, thus shunting or bypassing the undesired noise to ground before it reaches the circuit.

Another method, often used in conjunction with bypassed line capacitors, is to add inductors in series with each line to form an LC network that rolls off the unwanted noise at a faster rate. Figure 2 shows such a circuit with a 12 dB/octave attenuation rate. Sometimes these two inductors are wound together on a common core. When this is done, both differential and common-mode noise may be rejected. The two common inductors produce a transformer action that inverts the phase of each in-phase noise signal, turning the common-mode noise into differential-mode, which is then canceled. Any remaining differential noise is then further canceled by the line-to-line capacitor. This transformer is known in the industry as a common-mode (rejection) transformer.

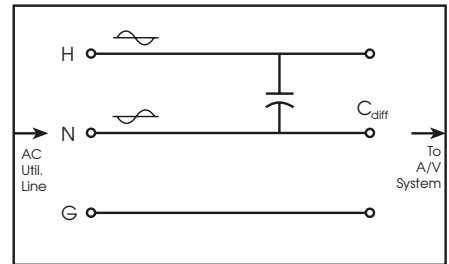


Figure 1A: A series type filter.
NB: The top line = Hot; middle = Neutral; bottom = Ground.

C_{diff} cancels out-of-phase (differential-mode) RF noise frequencies. The two sine waves represent a noise signal and its polarity.

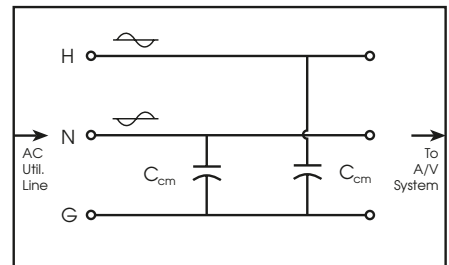


Figure 1b: A series type filter with an idealized or perfect ground.
NB: The top line = Hot; middle = Neutral; bottom = Ground.

The bypass capacitors, C_{cm} , shunt RF noise frequencies that are in phase (common-mode) to ground and away from A/V equipment. For safety, the values of the bypass caps must be too small to be effective in removing audio-frequency noise.

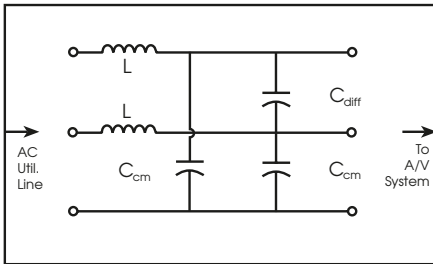


Figure 2: Inductors (L) in series with the line cause a faster rate of noise attenuation for greater noise rejection. The impedance offered by the series L increases as noise frequencies (RF) increase. These inductors usually include ferrous core materials, which can introduce distortions of their own.

NB: The top line = Hot; middle = Neutral; bottom = Ground.

PROBLEM #1

What's Wrong With It? It Tests Well!

In practice, many things can go wrong with this most common type of AC line filtering. First, filters are designed and measured in a standard 50 ohm test system. The test signal source has a 50 ohm output impedance going into the filter, and the filter is loaded with a 50 ohm resistive termination. However, the frequency response of such filters does not represent the real world by a long shot. The AC utility line source is anything but 50 ohms; its value varies from home to home and is certainly not a constant at frequencies much above the intended line frequency (50-60 Hz). The AC line filter's actual load is, in practice, the combined inductance from the audio/video equipment's power transformer primary windings, and from the other devices on the AC line. So the published (measured) noise rejection characteristics of such filter circuits are suspect.

PROBLEM #2

What Causes Low-Frequency Noise Modulation?

Because of the very nature of its topology, the series type filter has elements placed in the path between the power line and the user's equipment. If there is any appreciable current frequency or current transient flowing through the "filter" that causes a voltage drop across the filter, a line modulation (noise) will occur at those audio current frequencies. This reduces clarity and injects audio-frequency noise into other equipment on the line.

High current audio pulses from power amplifiers can be fast enough and of sufficient current magnitude to interact with the filter's series impedance. This generates audio-frequency noise on the

AC line that would not be present without the filter. This is not good. The series filter is best designed for a constant load (current) and a particular, known load impedance. Computers are a constant load. Motors are a constant load (except when first started or turned on). Most power amplifiers, however, are not. The current drawn from the AC line and through the series filter from a power amplifier is impulsive or transient by nature owing to the music signal that is driving it. As long as the filtering impedance is in series, the response time to acquire high instantaneous current from the AC line will be slowed and limited. The audible results: a compressed or limited dynamic range. Transient energy will be obscured, and the overall sound will seem "smoothed over" and dull.

In addition, inductor cores generally saturate with differential-mode signals and become ineffective at much lower current levels than many engineers recognize, especially at higher frequencies, according to our tests on a variety of series filters. A core material that is suitable for 50-60 Hz operation usually saturates at a lower current level when higher frequencies are encountered. When core saturation occurs, the inductance falls to zero (no filtering), which usually creates distortion products or harmonics on the AC line. Therefore, series filters, utilizing series inductors as part of the filtering process, are suspect in audio usage, again reducing clarity and detail resolution.

PROBLEM #3

A No-Ground "Ground" for Bypassing Noise

The grounding system used for the removal of the bypassed, unwanted noise on the line can also create problems. In a test-bench set-up,

the ground path length to and from the filter is controlled to be very short (inches) and usually shielded. Again, this is not the case in the real world environment. A utility ground or safety wire is very long in a home situation; the distance from the wall receptacle to the actual common and earthed connection at the utility box and nearby earth connection (ground) is tens of feet. This represents a considerable wire path length, and thus the wire's impedance is not low at frequencies above the 50-60 Hz for which the utility company designed it. The inductance in the wire causes the impedance to increase with increasing frequency. And inductance increases with wire length. Consequently, noise that is supposed to be bypassed on the utility line often does not get bypassed to ground, and radio frequencies are effectively blocked from the "ground" path route by the ground wire's high impedance. Thus, the effectiveness of the topology is suspect here, also. (See Figure 3).

PROBLEM #4
Noisy Ground

Of course, in the home or elsewhere, the safety or ground wire used as an RF or unwanted signal ground is in actuality a very noisy place to tie into. Often, AC utility grounds are a source of noise themselves. Noise that is supposed to go from filter to ground may actually go from ground to line via the line filter caps tied to the ground and lines. Noise does not go in only one direction because we wish it to. It is free to take any available path to complete a circuit loop.

Even when we do not have a direct-wired connection to ground, there are paths for noise to get into and out of our systems. For example, the stray capacitance from

circuit elements and wiring to the grounded chassis is a path for noise to cause trouble. Another common noise entry point is the power transformer. The stray capacitance from the transformer case or core to the transformer windings is enough to pass RF or noise in either direction (see Figure 4), especially if the transformer case/core is bolted directly to the chassis, which is also the signal and power ground or common. This is one reason we suggest floating or isolating power transformers, physically as well as electrically, from the chassis. When this is done, this capacitive coupled path is reduced and noise rejection increased. This is rare in practice, however.

We can reduce the primary to secondary winding capacitance of the typical "isolation" transformer by inserting a shield between the windings, thus reducing the amount of noise coupling from primary to secondary winding. But if the transformer's shield is grounded, as is frequently the case, the effectiveness of such an AC line noise-isolation scheme is reduced. So, even if a series type filter were perfect in effectiveness, AC utility power line noise can still find ground paths, used in series filters, to enter the components' circuitry.

Do Balanced Circuits Help This Problem?

Unbalanced audio-video circuits have their signal common tied to the chassis or power supply common, which in turn gets tied to AC utility either directly or indirectly. Some equipment with series type filters built inside the equipment bypass the AC utility lines to the chassis and circuit signal common, which puts the AC line noise directly onto the desired signal common. This, too, is not good.

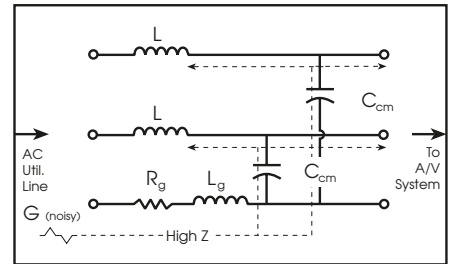


Figure 3: In reality, the ground wire has too high an impedance to allow effective bypassing of common-mode RF noise. Also, utility grounds are themselves noisy and may pass the noise onto the AC after the "blocking" inductors, L (see dotted lines). Increasing inductance L_g may help reduce ground noise as a source, but this renders C_{cm} useless.

NB: The top line = Hot; middle = Neutral; bottom = Ground.

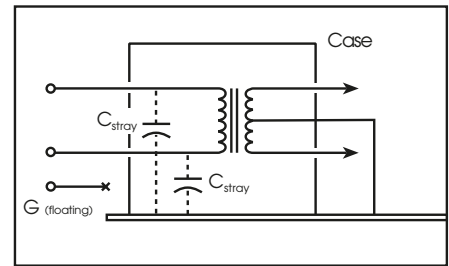


Figure 4: Even when the ground wire isn't used, noise from the AC line finds its way into audio or video equipment through C_{stray} . This can be reduced by floating (isolating) the transformer from the chassis.

NB: The top line = Hot; second = Neutral; X = Ground - floating.

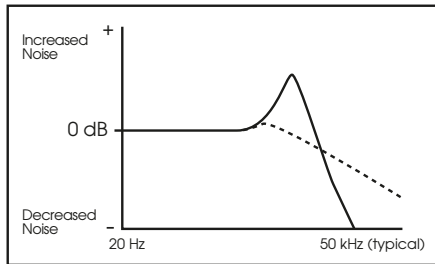


Figure 5: Series filters cause a resonance peak that accentuates noise in the region. When we attempt to reduce the peak and its concomitant noise increase, the rate of noise attenuation is reduced. Thus the filtering effects on unwanted noise are reduced.

Balanced circuits, on the other hand, if designed with complete attention to details, can offer better noise immunity from unwanted line noise because one side of the signal is not in common with the ground path. The shield can be used as a true shield, enclosing the chassis and blocking RF and other forms of noise coupling, while keeping the signal away from utility ground. Multiple shields can be used to reduce ground-coupled noise via capacitance with techniques found frequently in industrial equipment - a subject for another article.

PROBLEM #5 What About Low-Frequency Noise?

Safety issues with typical series type AC line filters prevent us from using AC line bypass capacitors large enough to filter out line noise below RF. The line current that flows constantly through the bypass capacitors at the AC line frequency (50-60 Hz) dictates that the capacitors must be under a value of .05 μ fd. Otherwise, should the safety ground wire become open, excessive and lethal currents can flow. We limit this current to a safe level by using a small value of capacitance.

However, as we have seen, a small value of capacitance does not act as a significant bypass to unwanted noise frequencies in the audio-frequency range. And in most cases, it is the frequencies lower than RF that cause the greatest audible trouble. Frequencies on the AC line within the bandpass of the audio or video equipment create greater negative effects than do out-of-band frequencies. And series filters only affect the out-of-band frequencies, or those frequencies above the audio equipment's frequency response.

PROBLEM #6 Resonance Leads to Increased Noise

The use of L (inductance) and C (capacitance) together leads to a resonance somewhere, which usually leads to a peak in the filter's response at the frequency where the attenuation is to begin. The response peak causes those frequencies to be accentuated (!) rather than attenuated (see Figure 5). That is, in the affected region, the noise is actually increased. Once again - not good!

We can use resistance to dampen the resonance, reducing the size of the response peak, but this method, unfortunately, also reduces the slope of the attenuation response. This means a less effective removal of unwanted frequencies.

So - What Does Work? A Parallel Filter

It should be clear by now that the series filter approach often leaves users with a mixed set of conditions. Some areas of audible perception may have been improved slightly, while new problems have been introduced. In the long run, can we say that things have been improved overall?

This question, and the problems of the traditional series line filtering method, led us to research the subject, and in time, to develop a new, *parallel* concept for audio/video line filtering - an AC line filter topology (now patented) that does not rely on bypassing to a potentially noisy and high impedance ground. Nor is the new filter placed in series with the AC line and the equipment. This new topology is effective in removing noise from just above the line frequency

(50-60 Hz) throughout the audio frequency range and out to HF and RF. It does not have the drawbacks of series filters because it is placed in parallel with the line and "traps" unwanted frequencies flowing past its location (see Figure 6a & b).

Basically, the parallel filter looks like about a 0.5 ohm short across the line for all frequencies above the line frequency; this handles the dominant direct coupled or conduction mode of differential type noise. This particular parallel filter technology relies on a number of overlapping LCR filter traps to cover a broad frequency range of attenuation. This parallel circuitry, consisting of L, R, and C, results in a wide bandwidth resistive termination.

The parallel filter removes the predominant type of noise from the A/V system - the differential mode. Other topologies are required to removed the common mode of noise from the line and to provide proper ground isolation.

Resonances, too, can exist with the parallel circuit method. However, they are controlled in such a way as to form a very low value (0.5 ohm) resistive termination to the AC line. And being in parallel with the AC line, this filter does not cause the negative effects of the series filter: increased impedance to the flow of current, distortion from inductor cores should they saturate, noise from components tied to ground (the green safety wire), and reduced filter effectiveness. A parallel filter that is resistive (a zero degree phase shift) will absorb and dissipate as heat any frequencies passing through it. And because there are no safety issues concerning ground current paths, the component parts

can be scaled to provide filtering down into the audio frequencies, which is a great benefit.

In Sum

Utility line noise is prevalent everywhere and getting worse with the proliferation of audio/video equipment, RF controls, cellular phones, and home office electronics. Parallel filtering of the AC line offers greater noise rejection for audio & video systems than do the commonly used series filters.

- From the MIT Engineering Dept.

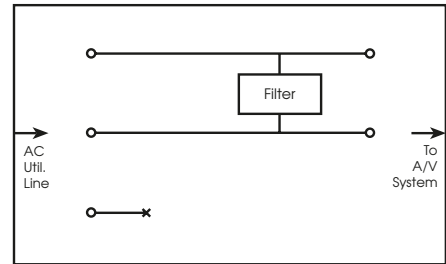


Figure 6a: A parallel filter used to remove differential-mode noise. A parallel filter does not depend on bypassing to ground. It does not use ground in its topology, nor does it have a series impedance between the AC line and the A/V equipment. Therefore, it allows all the available current to flow unimpeded and as fast as possible to the A/V equipment.

NB: The top line = Hot; second = Neutral; X = Ground - floating.

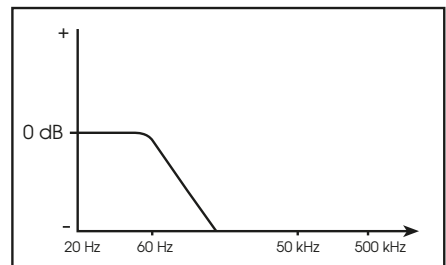


Figure 6b: Frequency response of parallel filter. **Note: Only the parallel filter also removes the audio-frequency noise.**

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