FILTERS

Filter Types

Filters for interference-reduction purposes appear in many forms. The simplest type is a shunt capacitor connected from the conductor carrying the spurious noise voltages to ground. The addition of a series resistor isolates the capacitor from the source impedance of the noise circuit allowing additional capacitor effectiveness. However, in some cases, the addition of series resistor introduces excessive series voltage drop and degrades voltage regulation.

Instead of an RC filter circuit, an LC filter circuit can be used for interference reduction and to minimize the series voltage drop. It has been found, however, that the "L" type filter configuration can resonate and oscillate when excited by a transient having the required envelope and frequency. This is not only a result of the equivalent tuned circuit, but also because the series inductor (to reduct I^2R losses) is generally wound on a core having high permeability, resulting in a high "Q" coil configuration. To be effective at radio frequencies, the capacitor also is of high "Q" construction.

It is important to note the possible shortcomings of lumped constant filters. This type of filter is the most versatile and has the widest application of any interference filter in existence today.

The "T" type of filter is the most effective filter in reducing transient-type interference. The reduction of transients has become a very important problem in electromagnetic compatibility. The older military specifications have allowed waivers for transients and the test specified in these military documents were steady-state tests. Modern electronic equipment uses a digital signal format and the equipment is incapable of differentiating between a spurious transient and normal digital signals of similar envelope dimensions.

The "pi" type of network has been in most general use as an interference-suppression device. This type of network has two shunt capacitors and a series inductor separating the capacitors. However, the "pi" type network is susceptible to oscillatory ringing when excited by an intermittent transient. The standard "pi" network has two feed-through capcitors that provide a high degree of internal shielding, which is at maximum in a cylindrical case. This shielding provides the attenuation at the higher radio frequencies where the capacitors are inductively reactive and the series inductor is capacitively reactive. Therefore, the filter assembly will exhibit high attenuation to at least one gigahertz, but due to internal component spacing and internal shielding the attenuation characteristics of the filter assembly can begin to fall off very rapidly above one gigahertz.

Filter Insertion Loss

Insertion loss is the loss in dB introduced by a network in the passband of the same network to the electromagnetic spectrum. Interference-reduction filters of the low-pass configuration introduce a very negligible loss in the passband. A loss normally encountered is due to the use of series inductors. There is an I^2R loss due to the length and diameter of the wire used to form the series inductor, a phase shift is introduced by the inductance at the power-line frequency, and attendant core losses are present at the same power-line frequency.

MIL-STD-220A, titled "Military Standard, Method of Insertion-Loss Measurement is primarily devoted to the attenuation characteristics of the interference-reduction filter. The attenuation characteristics of a filter, as measured in accordance with MIL-STD-220A, are obtained in a 50-ohm resistive system as shown in Figure 1. By substitution, the attenuation characteristics in the frequency spectrum of interest can be obtained for the filter network.

As soon as the design engineer finds that he gets less attenuation in his circuit than the MIL-STD-220 insertion loss advertised he sometimes accuses the manufacturers of false advertising. However, when he gets more attenuation than he expected from MIL-STD-220 tests, the manufacturer never hears from him.

This problem stems from the variety of impedances that an interference filter sees and the combinations of inductance and capacitance that the manufacturer has at his discretion to build the filter.

The design engineer usually tells the filter manufacturers to give him "x' dB minimum at some frequency. If more than one manufacturer is bidding on this requirement, the number of combinations of inductance and capacitance will be equal to the number of persons submitting proposals. The only frame of reference that the filter manufacturers can use under these circumstances is MIL-STD-220A attenuation.

Miniaturization of capacitive elements has enabled us to make very small filters which give excellent attenuation in high impedance circuits. However, miniaturization of inductances is still mostly experimental. And for low impedance circuits some inductance is necessary. The use of ferrite beads and single turn inductors by some can be construed as an inductor. At frequencies above 10 MHz this may be true but at the low end of the frequency range they might just as well not be there.

Before selecting a filter or a design of a filter we must consider the significant requirements.

Given this information, any filter manufacturer can now design a filter which will operate satisfactorily in the circuit. MIL-STD-220A could then be used only as a quality assurance test to prove that one filter is equal to others.

By using the information provided in Table 1, a designer may select the proper filter circuit configuration dependent upon the load and source impedance. Then, he may calculate the values of L and C or, if using a fixed value, he may calculate the attenuation that will be obtained. As an example, assume that the filter configuration shown in circuit 4 is to be used. The catalog attenuation is presented as measured in a balanced 50 ohm system, but it is estimated that the source impedance will be 1 ohm. In order to determine the reduced attenuation because of the low source impedance, the formula may be used as a ratio using 50 ohms and 1 ohm as follows:

$$A^1 = 20 \log \left[\left(wl/50 + lcw^2 \right) / \; wl + lcw2 \right]$$

A' represents the delta or reduced amount of attenuation and should be subtracted from the curves provided in the catalog in order to obtain the actual attenuation. It should be noted that the source impedance effect is only significant at the lower frequencies. As WL 50 and LCW 2 WL/50, the source impedance becomes insignificant.

See the LectroMagnetics filter ad on the back cover.

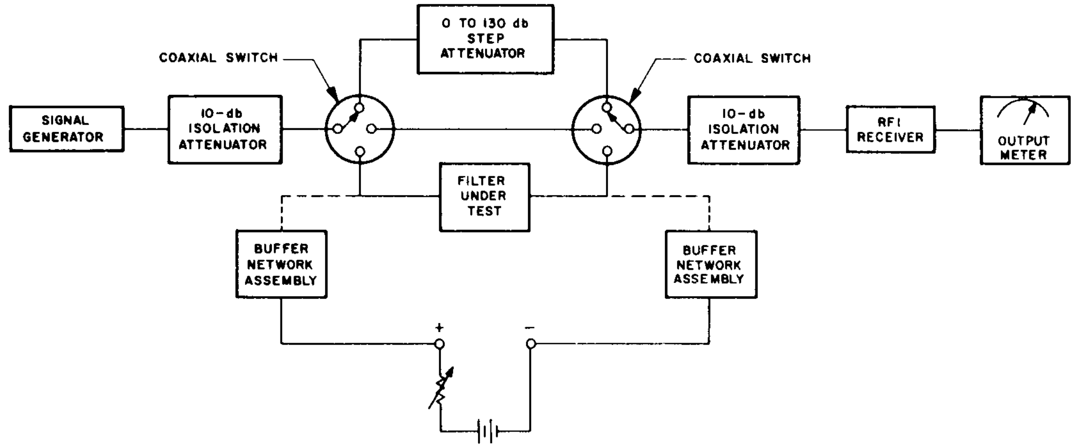

Figure 1. Interference Reduction Filter Attenuation Test Per MIL-STD-220A

Capacitors

The simplest interference-reduction filter is a bypass capacitor connected in shunt across an interference source.

A capacitor has capacitive reactance until the self-resonant frequency of the capacitance is reached. Above this frequency, the capacitor becomes inductively reactive. In addition to the self-resonant frequency of the capacitor, the lead lengths of the capacitor will shift the resonant frequency of the capacitor lower as the lead length is increased. The capacitor construction will directly affect the resonant frequency of the capacitor as well as the capacitance. The choice of a suitable radio-frequency bypass capacitor is therefore dependent on a number of physical characteristics as well as electrical characteristics.

The theoretical attenuation of a shunt or parallel connected capacitor can be shown as:

$$a = 10 \log \left[1 + (\pi f c R)^2\right] \qquad (1)$$

where:

a = attenuation db
f = frequency in megacycles
c = capacitance in microfarads
R = line impedance in ohms

When $\pi f c R \gg 1$ (in practical terms, above cutoff):

$$a \approx 20 \log (\pi f c R)$$

A capacitor is not ideal; because of self inductance, lead inductance, foil resistance, and lead-to-foil contact resistance, the characteristics of a practical capacitor do not coincide with Equation (1). Figure 2 illustrates the actual characteristics of several types of capacitors.

All too often, engineers feel that high attenuation is required from the interference-reduction filters at the low-frequency end of the electromagnetic spectrum. This requirement results in large filter assemblies which take up considerable space and weight, both of which are important considerations, particularly in space vehicles. Screen room or shielded enclosure filters, which most filter manufacturers claim have attenuation in excess of 100 db from 15 kilohertz to 10 gigahertz under zero load conditions and have dimensions in the order of 34 inches by 4-½ inches for a 50-ampere rated unit. Under application conditions and at only half load, these filters display only 5 or 6 dB of attenuation at very low frequencies and start dropping in attenuation at about 800 megacycles and have only 70 dB attenuation at 10 gigahertz. However, this is often adequate for most applications.

The metallized construction capacitor displays the poorest bypassing capabilities for radio frequencies in that the capacitor bypassing usefulness does not exceed about one to ten megahertz regardless of capacity value. This is due primarily to the high-resistance contact between the leads and the metallized capacitor foil.

The standard wound aluminum foil capacitor is useful as a radio-frequency bypass in the frequency spectrum of 1 to 20 megahertz. Its useful frequency range of operation is a function of capacitance and lead length.

Mica and ceramic capacitors are useful up to 200 megahertz. A flat construction capacitor, particularly if the capacitor plates are round, such as in a ceramic disc capacitor, will continue to function as an effective capacitor to bypass radio-frequency energy to higher frequencies than those of square or rectangular construction due to the concentration of electrical energy at the edges and the usual connection of the leads to the capacitor plate ends. In the disc ceramic capacitor, lead contact is across the silvered plate, increasing the contact area as shown in Figure 3.

Short-lead construction and feed-through capacitors are both three-terminal capacitors designed to reduce inherent and lead inductances. By reducing the lead inductance, the frequency bypassing capability of the capacitor has been extended by a factor of almost ten times that of the regular two-lead capacitor.

The useful frequency range of a feed-through capacitor is further improved by its case construction in which a bulkhead or shield isolates the input and output terminals from each other.

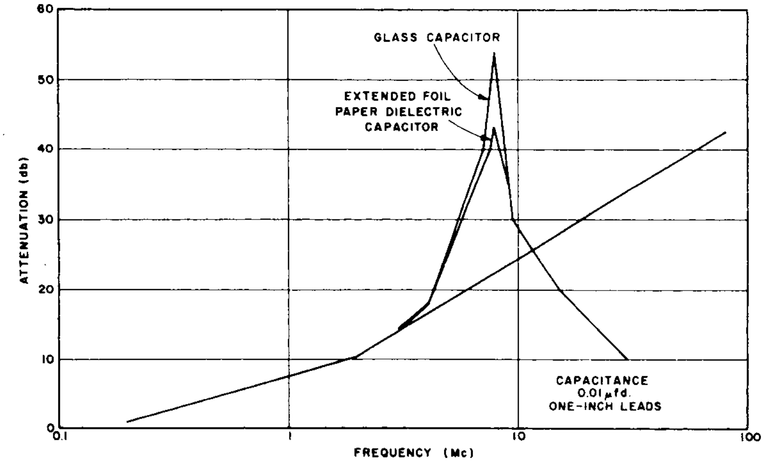

Figure 2 Typical Bypass Capacitor Frequency Characteristics

The lead length of a capacitor as shown in Figure 4 is a critical item for effective radio-frequency bypassing. Advantage can be taken of the lead length to create a series tuned circuit to reduce a specific interfering frequency. In any case the capacitor lead to the ground plane should be as short as possible, whereas the lead from the capacitor to the circuits being bypassed can be of longer length.

The ceramic capacitor is susceptible to mechanical shock, which causes it to generate a voltage potential. Therefore, the use of ceramic capacitors should be limited where the using equipment will be subjected to a mechanical environment.

Filter Selection

Selection of an appropriate filter network requires a detailed examination of the source and terminating impedances into which the filter network will be working. The source impedance will include (1) the reactive impedance of the power distribution transformer or the direct current source, for even a battery has an ac resistance which varies with the age of the battery; (2) the power distribution system, since this system represents a transmission line and is comprised of series inductance and resistance and shunt capacitance. At the higher power-line frequencies, such as 400 hertz and 1600 hertz used by the military services, the reactive load of the transmission line upon the source generator has to be corrected, utilizing a power factor correction network, otherwise a larger generator is required for power generation to overcome distribution line losses. The addition of a interference-reduction filter with large value shunt capacitors will introduce additional losses and will also introduce an additional phase shift through the series inductor, which will be a function of line current through the filter network, in some cases reducing the efficiency of the load circuitry.

The time-varying terminating impedance will also have to be considered prior to the selection of an appropriate interference-reduction network assembly. The voltage drop through the filter is determined by regulation requirements.

The required filter attenuation characteristics can be determined by two methods:

a. An engineering review examines the electromagnetic environment expected at the site or location, the coupling of spurious energy into susceptible equipment through connecting wiring, and the generation of spurious energy and the coupling and conduction of this energy from the generating equipment. For example, solid-state rectifiers, due to their short transfer time from a nonconducting state to a conducting state, will generate a transient pulse of energy which will occupy a broad frequency spectrum. This spurious energy will be coupled by the solid-state rectifier and associated wiring to adjacent wiring and susceptible components.

A spectrum analysis and a review of the coupling paths will determine the number of filters required and their filter frequency attentuation characteristics. The actual attenuation required will then be a function of the amplitude of the generated levels and either the susceptibility limits of adjacent equipment or the limit requirements of the applicable electromagnetic interference specifications.

b. On the design level, the prediction of spurious interference frequencies and their respective amplitudes is a very tedious exercise. Therefore, the use of a radio frequency receiving device with an output indicator to detect and measure spurious energy frequencies and amplitudes is warranted. The selection of this device will be a function of the expected characteristics of the spurious energy. The standard electromagnetic interference instrument has a very high signal-to-noise ratio, generally in excess of 30 dB, and has a narrow bandwidth. Since most interference or noise has an impulse characteristic with individual pulses being of short duration and of an intermittent repetition rate, the use of a communications receiver with a 30 to 4dB signal-to-noise ratio and of at least one megacycle bandwidth would provide more useful spurious energy characteristics information.

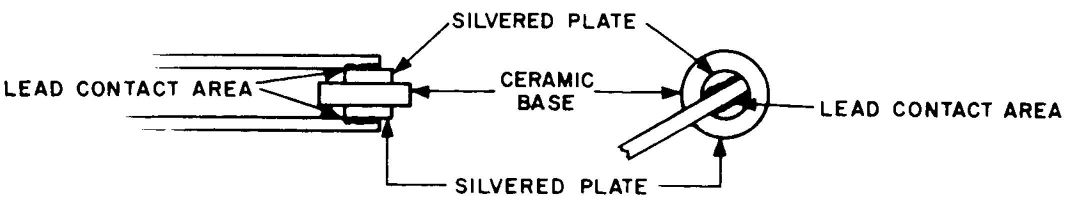

Figure 3 Ceramic Capacitor Construction Details

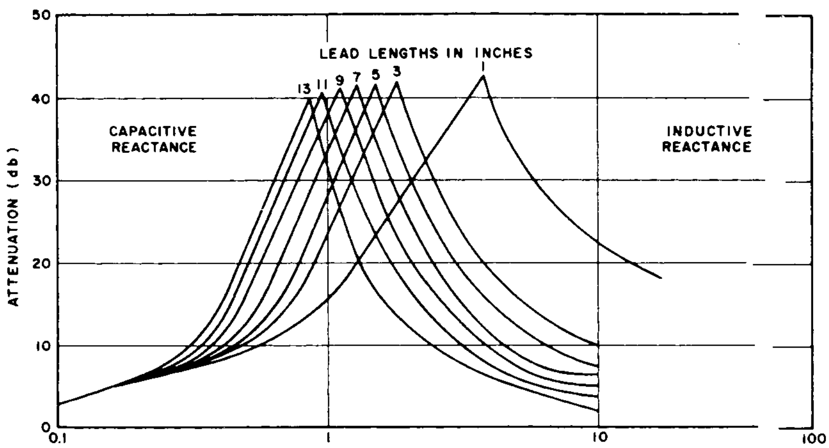

Figure 4 Capacitor Lead Lengths

Since impulse noise is characterized by a rise time in microseconds and sometimes down to nanoseconds, the increase of the rise time of the impulse envelope to milliseconds by the insertion of a low-pass filter network will reduce the high-frequency energy of the spurious noise. The transient pulse amplitude is reduced to a sufficiently low level as not to constitute an interference problem. Therefore, the need for low-frequency attenuation has been reduced. The filter network should provide as much attenuation above one megahertz as possible.

Low surge impedance $\left(\sqrt{L/C}\right)$ grounding practices and effective shielding of the spurious noise generating unit will further reduce the requirement for low-frequency attenuation by an interference-reduction filter.

Simplified Solution

The following procedure should be performed at the frequency of concern or the lowest critical frequency.

Step 1. Consider the noise generator as either a voltage generator or a current generator. Note that a current generator would be characterized as a high impedance source, where a voltage generator is a low impedance source. These high impedances will be either low or high with respect to the input impedance of the filter.

Step 2. Consider the load of the circuit as either a current sensitive device or a voltage sensitive device. Note: The current sensitive device would be low in impedance with respect to the output impedance of the filter and a voltage sensitive device would have a high impedance with respect to the output impedance of the filter network.

Step 3. Select a filter circuit which would be the inverse match of the system in which it is operating. The filter then becomes an inverse matching network.

What can be considered current or voltage sources?

Current Sources:	Voltage Sources:
1. Series Field DC Motor	1. Rectifier
2. Power Supply with transformer input.	2. SCR Power supply without input transformer
3. A.C. Induction Motor	3. Relay contact
4. Relay Coil	4. Switch

What are current or voltage sensitive loads?

Current Sensitive:	Voltage Sensitive:
1. 10 mfd feedthru (MIL-STD-826/461)	1. Line Stab. Networks
2. Some low impedance lines	2. High Impedance Signal Lines

Based on the preceding discussions it is obvious that the source and load impedance seen by any interference filter is as significant as the inductance and capacitance of the filter. These are obviously more important than the attenuation in an obviously ambiguous 50 ohm system.

What is primarily needed at this point may not only be another method of testing a filter, such as a modification of MIL-STD-220A or any other standard test method. But most important is a method for the user of a filter to tell the filter manufacturer what he actually needs.

This can be done in either one of two possible methods.

1. User to specify source impedance, load impedance and attenuation over entire frequency range.

2. User to specify (a) minimum values of inductance and capacitance of the filter circuit (b) filter circuit and (c) realistic attenuation measured in some system.

An important factor, which we all lose sight of while getting involved in the day to day operations of meeting a filter specification or noise specification, is the ultimate goal of achieving a compatible system.

In order to accomplish this it will be necessary to start from the system level down through the black box to the filter manufacturer by being more precise in spelling out requirements.

1. The system manufacturer must tell the "Black Box" manufacturer what the impedance interface characteristics are for the black box manufacturer.

2. The "Black Box" manufacturer must know the impedance that the "Black Box" exhibit.

3. The user of the filter must tell the filter manufacturer what the impedances are that the filter will see.

Mechanics of Filter Installation

Quite often the filter attenuation characteristics are compromised by improper application. It should be recognized that since wiring can act as an antenna, radiation coupling or capacitive/magnetic coupling can circumvent the attenuation capabilities of an interference-reduction filter. Therefore, isolation must be provided between the input and output terminals of a filter network. Isolation can be accomplished by the use of a bulkhead whose dimensions are greater than a half wavelength in length, or width of the lowest stop-band frequency of the filter network. Another approach to achieve input-output filter network isolation where a bulkhead is impracticable is to shield the connecting leads to both the input and output filter terminals. The filter terminals will have to be enclosed with bell caps as shown in Figure 5. Where the filter is capable of introducing attenuation of greater than 60 dB in the stop-band, the conductors may be double shielded. The mounting surfaces of the filter network assembly and the associated mating surface should be free of all nonconducting films to maintain a low-impedance current path through the metal-to-metal contact. Surface contaminants (such as grease, oil, corrosion products, rust, oxide films, zinc chromate, paint, and lacquer), inorganic finishes (such as anodize, alodize, and parkerize), corrosion preventative compounds, and all moisture must be removed from mating surfaces prior to mounting the filter assembly.

Peripheral grounding of an interference-reduction filter is to be preferred, allowing maximum utilization of the filter network attenuation capabilities. The use of a bulkhead and a tubular filter assembly provides the minimum surge impedance connection of the filter assembly to a ground plane. Though the tubular construction does not allow maximum component density and space utilization, filter effectiveness can be more readily maintained. Attention should also be directed to electrolysis and erosion effects of mounting surfaces. Filter network performance will degrade as a result of potential buildup between the filter assembly and the ground plane.

A filter assembly, be it only a bypass capacitor or a filter network, should be located immediately adjacent to the spurious energy generating circuit or unit to reduce the radiation effects of wiring.

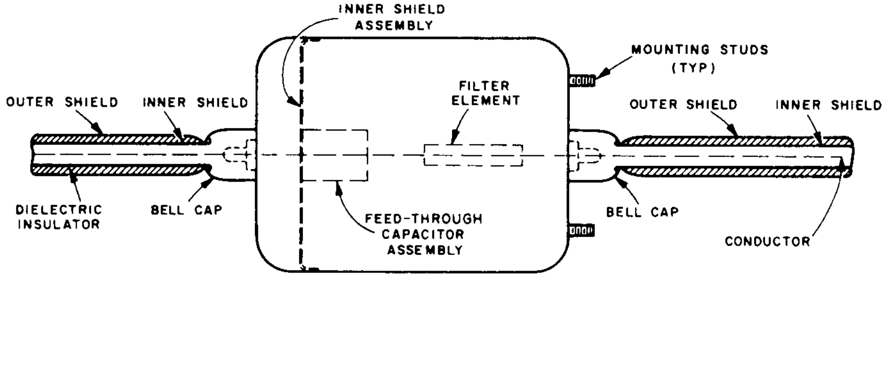

Figure 5 Interference-Reduction Filter Assembly

BUYING HINTS

Define Important Parameters and Characteristics

The importance of fully defining the parameters required when specifying an interference filter cannot be over emphasized. The following parameters and characteristics should always be specified:

1. Mechanical and physical configuration.
2. Pass band or fundamental frequency response. (In a power line filter, this would be a voltage drop requirement at power freqeuncy.)
3. Attenuation.
4. Filter Circuit Schematic.
5. Current and voltage ratings.
6. Maximum and/or minimum capacity and inductance.
7. Environmental characteristics. (MIL-F-15733 is generally assumed, if a reference is not made on the drawing.)

REMEMBER

Source and Load Impedance

An electronic device can either be a source of interference or it can be susceptible to an interfering signal. A filter, obviously, can only reduce interference on a lead or conductor to this device. The direction of suppression should be determined prior to suppression to optimize the design of the suppression network or filter.

Mechanical and Physical Characteristics

Mechanical and physical characteristics are important because the method of installation, mounting and orientation of the filter will affect its performance. For example, a bulkhead mounted filter will give maximum isolation between input and output terminals. The same filter mounted with a bracket would not afford the isolation which is required for frequencies above 10 MHz. On the other hand, if maximum attenuation above 10 MHz is not required, a bathtub-type filter could be less expensive and would do an adequate job.

Pass Band on Fundamental Frequency Response

The pass band insertion loss or voltage drop requirement assures that the proper power or signal can pass through the filter to enable the equipment to function properly. This voltage drop - between 1% and 5% of the rated voltage - should be allowed for when planning the basic equipment design, to enable the equipment to function properly. If the voltage drop of the filter is specified too low, the filter's size, weight and cost will increase proportionately.

Attenuation

An attenuation curve showing the insertion loss over the desired frequency range is necessary to adequately specify "hidden" characteristics which become significant in an interference filter which must function over a broad range of frequencies.

See the Spectrum Control filter ad on the inside back cover.

FILTER CIRCUIT SCHEMATIC

A schematic diagram or the filter configuration should accompany the insertion loss curve because of the variance of source and load impedances. If a classical filter is terminated and tested in its characteristic impedance, the response of a "T" configured filter is identical to that of a "Pi" configured filter. When used in the actual circuitry, the loss or gain of attenuation can be as much as 60 dB. Many times a "L" type filter can achieve more effective attenuation in a smaller size than either a "T" or a "Pi" filter.

Current and Voltage Ratings

Current and voltage requirements are necessary for the obvious reasons, and often these requirements will dictate the values of inductance and capacitance which are most economical from a size and cost standpoint. Many times, values of inductance and capacity for a filter can be adjusted to compensate each other and still maintain a constant attenuation. Because of this flexibility, it is necessary to incorporate the maximum and/or minimum inductance parameter.

Maximum-Minimum Inductance.

Maximum and/or minimum inductance and capacitance should be a part of any filter specification since there may be a wide variation in capacitance and inductance. It can be shown mathematically that a filter attenuation will be a function of the "LC" product (total capacitance multiplied by the total inductance at a given frequency). Therefore, similar attenuation can be achieved with 1 microhenry and 100 MFD, as with 100 microhenries and 1 MFD. These filters might meet all other requirements as to schematic and attenuation, but one might work on the equipment and one might not.

Other considerations on this point are: Some circuits, such as solid state regulators, cannot function properly if too much inductance appears in the line; Underwriters' Laboratories sets requirements for maximum capacity between power lines and ground; and the power factor of the total electrical or electronic equipment may be upset by the addition of too much capacity or inductance.