NEED FOR FILTERS

Interference is inherent in some electrical, mechanical, and electronic systems. Even when a system has been well designed and provides proper grounding and shielding, the wiring can still conduct unwanted energy into or out of other areas. Filters stop this unwanted energy before it can be conducted to susceptible units to appear as interference. Because of this, filters play a necessary role in achieving electromagnetic compatibility.

Switch noise is a good example of interference for which filtering may be required. Consider a circuit with an inductive load. When an inductive circuit is broken by opening a switch, a back electromotive force is produced by the collapsing magnetic field. This potential rises rapidly in amplitude until an arc occurs across the switch contact. Because the arc is of low impedance, the potential falls until the arc is extinguished, at which time the potential begins to rise again until an arc strikes a second time. This action occurs as the switch contacts travel apart and takes place in a microsecond of time. The arc produces a broad band of interference, which is radiated and conducted away from the switch. Shielding will attentuate the radiated interference at the switch, but filtering will be required to reduce conduction of the noise generated by the arc and possible further radiation. Interference-reduction filters are the primary method by which extraneous energy and interference voltages are isolated from areas where they may prove detrimental.

While filters are necessary and should be placed where needed, care should be taken to avoid using redundant filtering to solve problems caused by uncoordinated efforts of separate design groups. Redundancy usually occurs when each "black box" is required to meet an interference control specification regardless of its cable tie location or its final installation location. Economy measures, the use of equipment of older design in a new system, and schedule constraints can also result in redundant filtering. Although trade-offs must be made among these factors, there is no substitute for a well thought-out system EMC control plan. If formulated well ahead of the design of the system, duplication of filtering on interconnecting leads will be avoided. One precaution should be observed, however, when considering the reduction of redundant filters; equipment at both ends of the cable must be able to tolerate the noise levels passed in both directions.

FILTER DESIGN CONSIDERATIONS

FILTER TYPES AND APPLICATION

Filters are electrical circuit configurations designed to attenuate at certain frequencies while permitting currents at the desired frequencies to pass. They do this by using combinations of capacitances and inductances to set up a high impedance in series with, or a low impedance shunt to ground for, the interfering currents. The passband of a filter is the frequency region in which there is little or no attenuation. The transmission characteristics are not necessarily uniform but the variations are usually small. The stopband is the frequency region in which attenuation is desired. The attenuation may vary in the stopband and is usually least near the cutoff frequency, rising to high values of attenuation at frequencies considerably removed from the cutoff frequency. Filters can be classified according to the position of the passband in relation to the stopband on the frequency spectrum. There are four classes: low-pass, high-pass, bandpass, and band-reject. Attenuation as a function of frequency for each of these classes is shown in Figure 1.

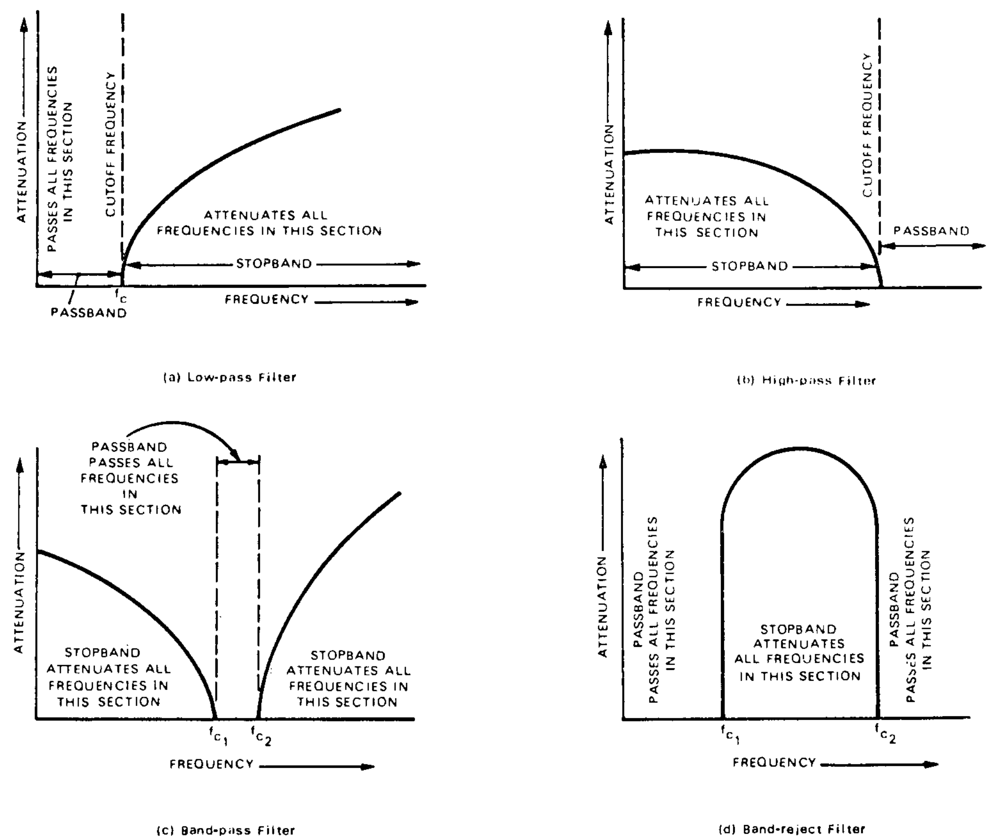


Figure 1 Four Classes of Filters

See LectroMagnetics and Spectrum Control on back cover and the Potter Company inside the front cover.

The control of EMI usually requires filters of the low-pass type. Power line filters are of the low-pass type to pass DC or power frequency currents without significant power loss while attenuating all signals above the cutoff frequency. Filters incorporated in amplifier circuits and output circuits are usually of the low-pass type so that the fundamental signal frequency can be passed while harmonics and other spurious signals are attenuated. The following discussion describes the various types of low-pass filters used in the control of EMI.

These filters are generally made of discreet elements of capacitance and inductance and are often referred to as lumped-constant devices to distinguish them from distributed constant devices such as transmission lines, coaxial cables, or dissipative filters using ferrites.

Shunt Capacitive Filters

There are many forms of filters for interference reduction, with the configuration depending on the frequencies to be filtered out. The simplest interference reduction filter is a shunt capacitor connected from the interference-carrying conductor to ground. A capacitor exhibits capacitive reactance until the self-resonant frequency is reached. Above this frequency the capacitor behaves like an inductive reactance.

Refer to Figure 2. The theoretical insertion loss of a shunt or parallel-connected capacitor in a line, where source and load impedances are equal, is:

$$IL = 10 \log [\ 1 + (\pi fCR)^2\ ]$$

wherein:

IL	=	Insertion loss in dB
f	=	Frequency in MHz
C	=	Capacity in microfarads
$R_S = R_L$	=	Source or load impedance in ohms

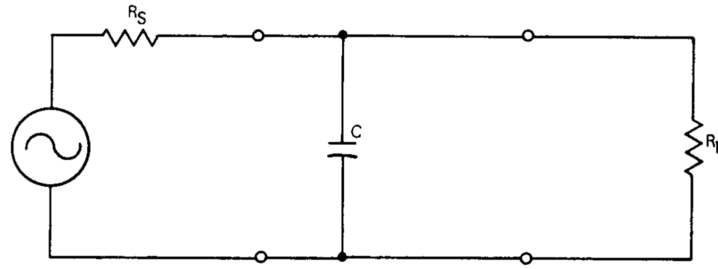
When $fCR >> 1$ (in practical terms, above the cutoff frequency):

$$IL = 20 \log (\pi fCR)$$

However, 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 the theoretical value. Figure 3 illustrates the characteristics of several types of capacitors. The variation from ideal capacitor characteristics depends upon the type of capacitor. Metalized paper capacitors, while small in physical size, offer poor RF bypass capabilities because of high resistance contact between the leads and the capacitor metal film. They are also a source of radio noise as the dielectric punctures and self-heals by burning away the metal film. This effect is indicated by the switch in the equivalent circuit shown in Figure 4. The standard-wound aluminum foil capacitor is useful as a radio frequency bypass in the frequency range up to 20 MHz. Its useful frequency range of operation is a function of capacitance and lead length. The equivalent circuit is shown in Figure 5.

Mica and ceramic capacitors of small values are useful up to 200 MHz. A capacitor of flat construction, particularly if the capacitor plates are round as in a ceramic disc capacitor, will remain effective to higher frequencies than one of square or rectangular construction.

A number of other factors must be considered in the selection of ceramic capacitors as filter elements. A ceramic capacitor element is affected by operating voltage, current, frequency, age, and ambient temperature. The amount the capacity varies from its nominal value is determined by the composition of the ceramic dielectric material. This composition can be adjusted to obtain desirable characteristics such as negative temperature or zero temperature coefficient or minimum size. In obtaining one desirable characteristic, the other characteristics may become undesirable for certain situations. For example, while the dielectric composition is adjusted to produce minimum size capacitors, the voltage characteristic may become negative to the extent that 50 percent capacity exists at full operating voltage and full ambient temperature may cause an additional sizeable reduction in capacity.



$$IL\ (\text{in dB}) = 10\ \text{LOG}\ [1 + (\pi fCR)^2]$$

Figure 2 Determination of Insertion Loss

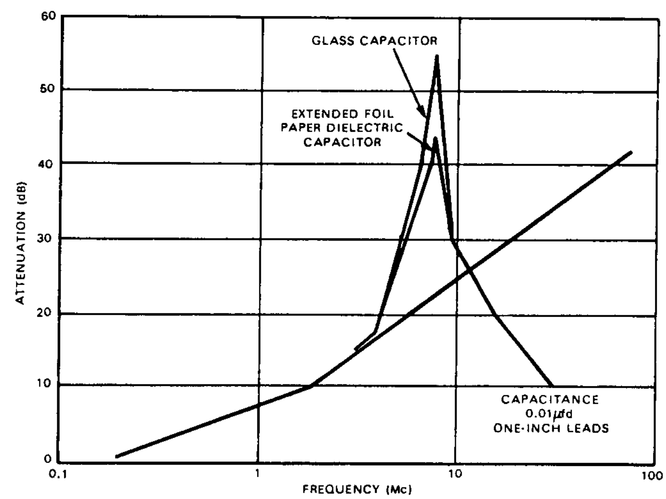
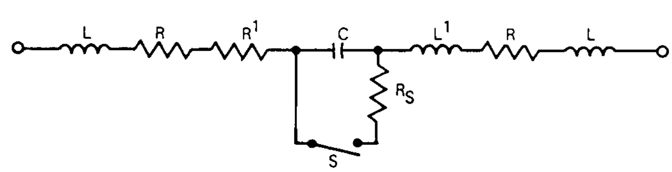


Figure 3 Typical Bypass Capacitor Frequency Characteristics



L = Lead Inductance

R = Lead-to-Foil Contact Resistance

R^1 = Resistance of Metallized Foil

C = Capacitance

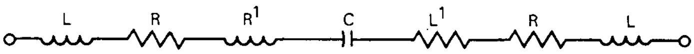
L^1 = Foil Inductance

S = Short Circuit due to Voltage Puncture

R_S = Short Circuit Resistance

Figure 4 Metalized Capacitor Equivalent Circuit

The designer should make his capacitor selection on the basis of true capacity under the most adverse of operating conditions, also taking into account the aging effect. From the time of firing of the ceramic, the dielectric constant of the materials used may decrease. After 1000 hours, the capacitance may be as low as 75 percent of the original value.



L = Lead Inductance

R = Lead-to-Foil Contact Resistance

R^1 = Foil Resistance

C = Capacitance

L^1 = Foil Inductance

Figure 5 Wound Aluminum Foil Capacitor Equivalent Circuit

Three-Terminal Capacitive Filters

Capacitors of short-lead construction and feed-through capacitors are three-terminal capacitors designed to reduce inherent and lead inductances. Figure 6 shows the construction of the three-terminal types. In each case, the inductance of the lead is not included in the shunt circuit. The wound foil capacitor is made with an extended foil type construction so that each plate of the capacitor can be soldered to a washer shaped terminal. One washer is, in turn, soldered to the center lead, while the other is soldered to the case that is the ground terminal.

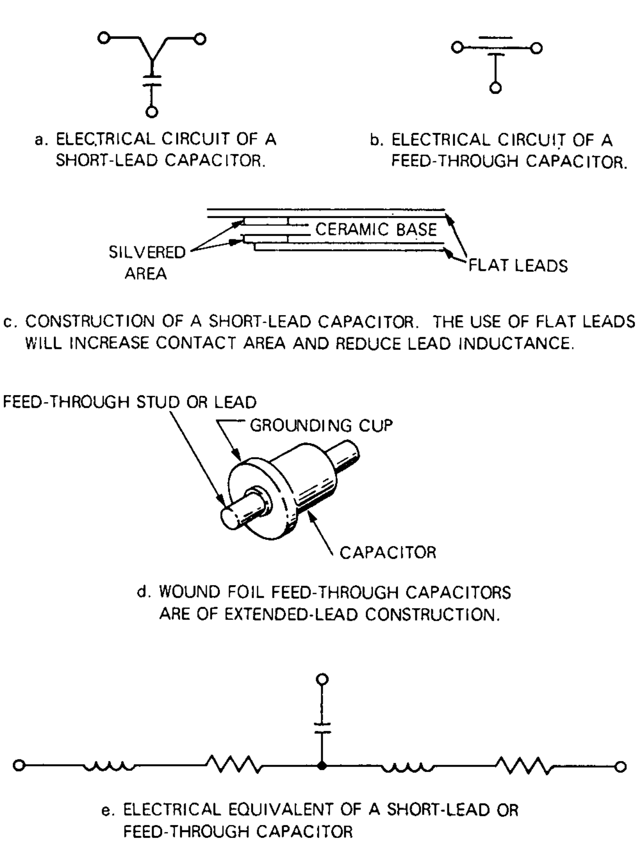


Figure 6 Three-Terminal Capacitor Construction

Theoretical insertion loss of three-terminal capacitors is the same as for an ideal two-terminal capacitor.

When fCR>>1 (in practical terms, above the cutoff frequency):

$$IL = 20 \log (\pi fCR) \tag{3}$$

wherein:

IL = Insertion loss in dB
f = Frequency in MHz
C = Capacity in microfarads
R = Line impedance in ohms

However, the insertion loss of a real three-terminal capacitor follows the theoretical curve much more closely than does a two-terminal capacitor. The useful frequency range of a feed-through capacitor is improved further by its case construction in which a bulkhead or a shield usually isolates the input and output terminals from each other.

While the three-terminal capacitor is ideally suited to EMI suppression in the frequency range of 1 to 1000 MHz, feed-through capacitors are now available with a resonant frequency well above 1 GHz. The feed-through current rating is determined by the stud diameter. Figure 7 shows the attenuation of a typical three-terminal capacitor.

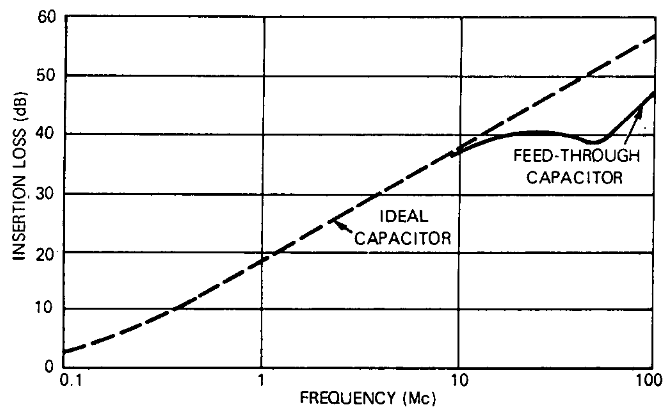


Figure 7 Insertion Loss of Typical Three-Terminal Capacitors

"L" Section Filters

Attenuation in the low frequency range can be increased by the addition of an inductor in series with the circuit carrying the signal. This addition forms a circuit known as an "L" section lumped-constant filter.

The theoretical insertion loss of an "L" section lumped-constant network is:

$$IL = 20 \log \left(1 + \frac{\omega CR}{2} + \frac{\omega L}{2R} + \frac{\omega^2 LC}{2}\right)$$

wherein:

IL = Insertion loss in dB
ω = $2\pi f$
f = Frequency in MHz
C = Capacitance in microfarads
L = Inductance in microhenries
R = Line impedance (resistive) in ohms

Above cutoff, where $\omega L >> R >> 1/\omega C$

$$IL \approx 20 \log \frac{\omega^2 LC}{2} = 20 \log 2\pi^2 f^2 LC$$

Notice that as frequency is increased by a factor of ten above the cutoff frequency, insertion loss increases by 40 dB.

The theoretical insertion loss for the "L" section filter is independent of the direction of inserting the "L" section in the line, if source and load impedances are equal. Figure 8 (a) shows the two configurations for an "L" section filter. On the left, the capacitor shunts the source impedance, while on the right the capacitor shunts the load impedance. When source and load impedance are not equal, the greatest insertion loss will usually be achieved when the capacitor shunts the higher impedance.

The physical size of an "L" section filter depends upon insertion loss requirement, current rating, and voltage rating, with the first two usually predominant. The "L" section type of filter may give poor high frequency attenuation because of stray inter-turn capacitance. In some cases, the "L" type may resonate and oscillate when excited by transients.

"pi" Section Filters

The "pi" section filter is the most common type of radio frequency interference suppression network. Figure 8(b) shows the circuit of the "pi" section filter. Advantages are ease of manufacture, high insertion loss over a wide frequency range, and moderate space requirements. Although voltage rating must be considered, current rating and attenuation are the most important factors in determining the size of the filter.

The insertion loss of an ideal "pi" section network is:

$$IL = 20 \log \left(1+\omega CR + \frac{\omega L}{2R} - \omega^2 LC - \frac{\omega^3 LC^2 R}{2}\right)$$

wherein:

IL	=	Insertion loss in dB
ω	=	$2\pi f$
f	=	Frequency in MHz
C	=	Total capacity in microfarads
L	=	Inductance in microhenries
R	=	Line impedance (resistive) in ohms

Above cutoff or when $\omega L>R$ and $\omega C>R$:

$$IL \approx 20 \log \frac{\omega^3 LC^2 R}{2} = 20 \log 4\pi^3 f^3 LC^2 R$$

A typical attenuation curve of a "pi" section filter has a slope of approximately 18 dB per octave, and the high frequency performance can be improved by internal shielding within the filter case. The "pi" circuit is, however, very susceptible to oscillatory ringing when excited by a transient.

A multiple "L" section filter is composed of individual "L" sections arranged in series combining the best characteristics of individual "L" sections and "pi" section filters-and adding an important one of its own: fast rise of attenuation versus frequency above cutoff.

The theoretical slope of an LC network filter rises at a rate of 40 dB per "L" section for each decade increase in frequency. This means that a triple "L" section will rise 120 dB per decade of frequency compared to 60 dB for a "pi" section and 20 dB for a capacitor under the same conditions. A double "L" section filter is seldom used in practice; a "pi" section network is the most common network.

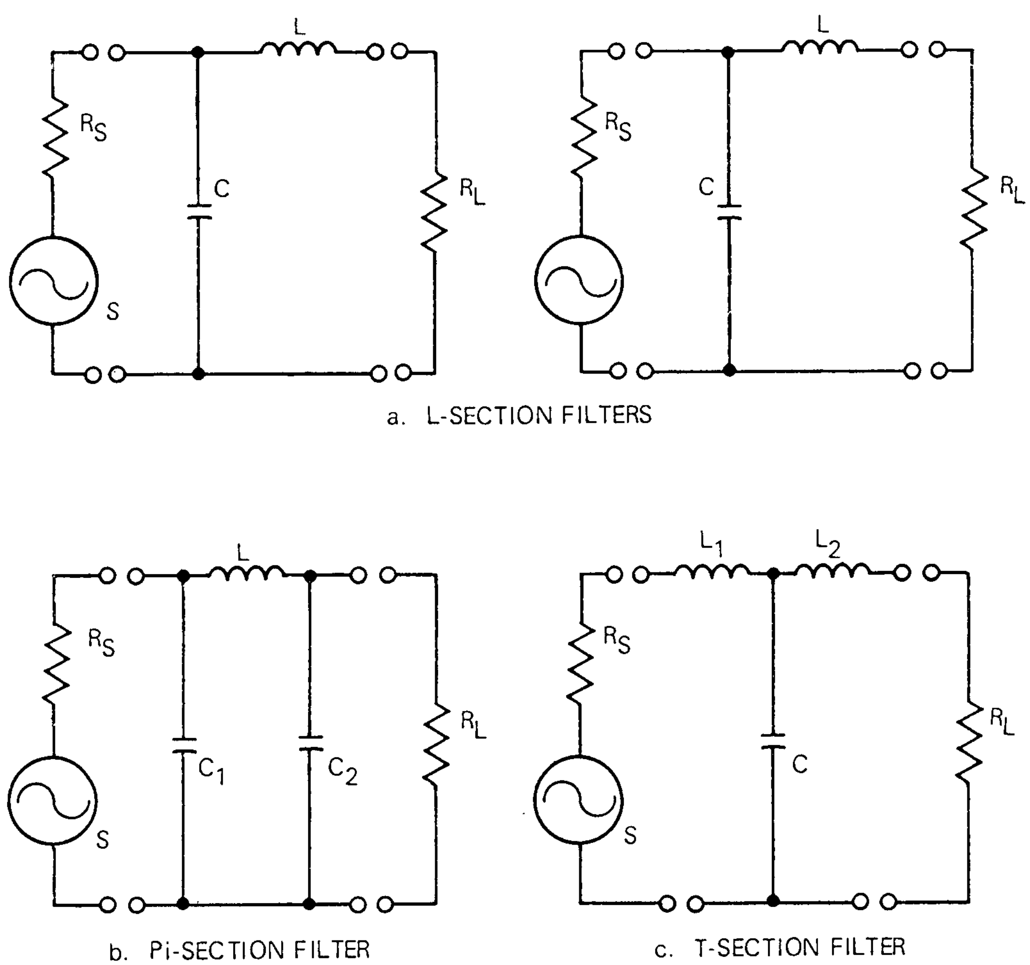


Figure 8 Lumped-Constant Low-Pass Filters

The multiple "pi" section filter has characteristics identical to those of the multiple "L" section filter. The attenuation curve of the theoretical multiple "pi" section filter rises at a rate of 20 dB more per decade of frequency than does a multiple "L" filter of the same number of sections. Although this is not a large increase in attenuation when three or more sections are used, it does provide a capacitive input at both ends of the filter that is sometimes advantageous.

The greatest use for this type of network is in large installations, and for shielded rooms where high attenuation is needed at very low frequencies. The rapid attenuation rise of a multiple "pi" section can be used to achieve a cutoff higher than the power frequency, yet still permit high attenuation in the low frequency spectrum. This technique is rarely applied to airborne equipment and vehicles because of the size of this type of filter. A specially designed M-derived section to achieve the low frequency attenuation in series with a standard "pi" section or "L" section filter has been the standard practice when low frequency attenuation is required. Though the M-derived filter is much higher in cost, it is much smaller and lighter than a multiple-section "pi" filter.

"T" Section Filters

The lumped-constant type of filter can be further sophisticated by the introduction of another inductor to an "L" section filter. This addition forms a "T" section lumped-constant filter, which consists of two inductors in series with the signal-carrying wire with a shunt capacitor connected from the junction of the two inductors to ground.

The "T" type of filter is a very effective form of the lumped-constant type of filter for reducing switching transient interference, although the requirement for two inductors places quite a penalty on it. Reduction of transients has become a very important part of EMI control. Military standards and specifications now include requirements for transient as well as steady state tests. Present-day electronic equipments use a digital format extensively, and such equipment is incapable of distinguishing an EMI transient from a normal digital signal of similar envelope or rise time. Typical "L," "pi," and "T" section filters are shown in Figure 8. Lumped-constant low-pass filters, except the single element R-C filter, use series inductors, and the standard method of insertion loss measurement in accordance with MIL-STD-220A. Operation of lumped-constant filters at or near saturation will differ from operation at rated current. The series inductors are generally wound on toroidal cores of ferromagnetic material (to limit external fields) with a relative permeability of about 125. The size of the core and the ampere-turns will determine the saturation characteristics of the core and the resultant loss in permeability. The use of ferrous cores is dictated by the need to achieve maximum inductance at minimum I^2R wire losses. The degradation of attenuation is a function of current, mismatch between the line and load impedance, the steady-state reactance of the source and load, and the variation of the load in terms of time.

The usual "pi" or "T" filters intended for boardband interference filtering are generally composed of relatively low loss inductive capacitive lumped-constant elements. Such filters cannot dissipate much energy within their rejection range; they merely reflect it so that under certain conditions it may reappear elsewhere as an undesirable signal or interference. Where source and load impedance are mismatched, the insertion of a filter may improve the source to load impedance match. Since the filter can serve to match source and load impedances, insertion of a filter may actually increase the EMI voltage (or current) appearing in the load. In other words, the filter in that circuit at certain frequencies could behave as though it had a negative insertion loss.

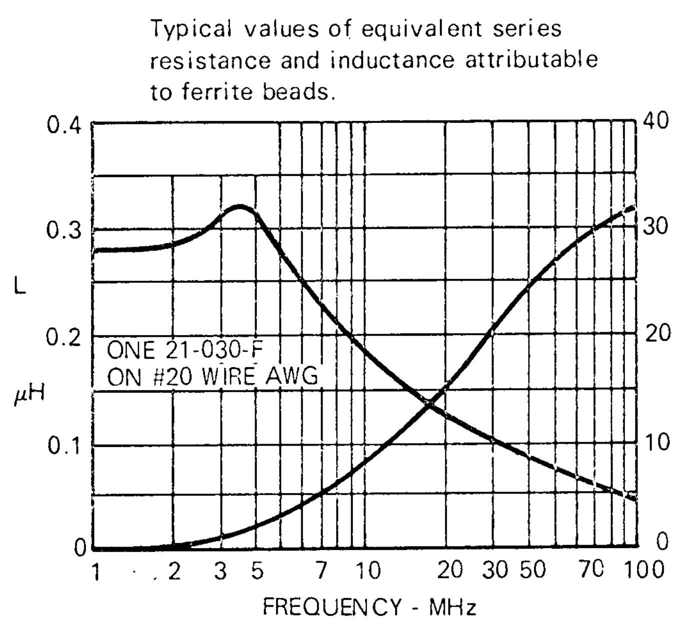
Dissipative Filters

Unlike carefully designed laboratory circuits used for insertion loss measurements, where source and load impedances are fixed at exactly 50 ohms resistance, the impedance that a filter sees in most practical powerline applications is extremely variable with frequency, ranging from very high to very low impedance, with wide variations of phase angle. Examples of this effect have been observed in which the insertion of a reactive filter into a line carrying interference has actually resulted in more, rather than less, interference voltage appearing on the line beyond the point of application. This deficiency, inherent in all filters composed of low loss elements, has led to the investigation of dissipative types of filters that take advantage of the loss-versus-frequency characteristics of magnetic materials such as ferrites.

One form of dissipative filter uses a short length of ferrite tube with conducting silver coatings deposited in intimate contact on the inner and outer surfaces to form the conductors of a coaxial transmission line. The line becomes extremely lossy; that is, it has high attenuation per unit length in the frequency range where either electric or magnetic losses, or both, become large and increase rapidly with frequency. Dissipative filters of this type are necessarily low-pass. One of the large uses of such filters is in general-purpose powerline filtering, in which the dissipative filter is combined with conventional low loss elements to obtain the necessary low cutoff frequency.

Ferrite Bead Filters

Ferrite beads provide a simple, economical method for attenuating unwanted high frequency noise or oscillations. One bead slipped over a wire produces a single turn RF choke that possesses low impedance at low frequencies and moderately high impedance over a wide high frequency band. The efficacy of this impedance in reducing noise will depend upon the relative magnitude of the source, suppression, and load impedances.



TYPICAL PROPERTIES	
Flux Density (B) at 5 O_e	2400 G
Coercive Force (Hc)	0.56 O_e
Hysteresis Factor (h/μ^2)	22×10^{-6}
Initial Permeability (μo)	450
Permeability (μ) at 250G	900
Resistivity - Ohm - cm	$\geq 10^7$
Curie Temperature	$\geq 155\,^{\circ}C$

Figure 9 Filter Characteristics of Ferrite Beads

The presence of a ferrite bead on the wire causes a local increase of series inductance and resistance presented to currents in the wire. Figure 9 illustrates the effects of one ferrite bead on a length of wire. Adding more or longer beads provides additional units of series inductance and resistance in direct proportion. This technique is effective at all frequencies. Extra turns of wire can be passed through the bead, increasing both resistance and inductance in proportion to the square of the number of turns. Because of distributed winding capacitance, this technique is most effective at the lower frequencies. There will also be an increase in DC resistance.

High amplitude DC or low frequency signals will cause some reduction in the suppression effect. However, as long as only one turn links the core, fairly high currents can be tolerated before saturation is approached. At saturation, inductance and resistance will be low, but will return to normal values upon removal of the high field. High RF levels can cause excitation greater than that used for the measurements shown in Figure 9. Generally, these will cause the effective resistance to increase because of the contribution of hysteresis losses.

Ferrites are inert ceramics free of any organic substances. They will not be degraded by most environments. Properties will vary somewhat with temperature. Generally, inductance increases with increasing temperature, while the effect on resistance is small. Above the Curie temperature, the bead is nonmagnetic and no suppression can be expected. The effect is, however, completely reversible, and once the temperature is reduced below that point, normal performance is regained.

Because of the high resistivity of ferrite beads, they may be considered insulators for most applications.

FILTER SELECTION AND USE

In designing or selecting a filter for a particular application, many parameters must be taken into account if the filter is to be most effective.

Attenuation, insertion loss, and frequency range of attenuation are the primary electrical characteristics that determine the suitability of a filter for a particular EMI application. Size, weight, cost, and reliability are also important design considerations, particularly in aerospace systems.

If a filter does not provide the minimum attenuation required for the stopband, then the filter is not satisfactory no matter how suitable the other characteristics may be. The attenuation is defined as the ratio of the filter input voltage to the filter output voltage under normal circuit conditions:

$$\text{Attenuation (dB)} = 20 \log \frac{E_i}{E_o}$$

Wherein:

E_i = Voltage across filter input terminals

E_o = Voltage across filter output terminals

The attenuation in dB from this formula does not consider the source and load impedances, and therefore does not give a true indication of the suppression effectiveness of the filter. Insertion loss measurement presents a far more reliable picture, since it is a function of the source impedance, load impedance, and the filter itself. Insertion loss is defined as the ratio of the voltages, at a given frequency, across the load terminals before and after the filter is inserted into the circuit:

$$\text{Insertion loss (dB)} = 20 \log \frac{E_1}{E_2}$$

wherein:

E_1 = load voltage without the filter in the circuit

E_2 = load voltage with the filter in the circuit

Design Tolerances

Insertion loss figures quoted by a filter manufacturer are usually normalized for a 50-ohm system. If the circuit to be filtered does not have both 50-ohm input and output impedances, the insertion loss will differ from the quoted value. The difference may amount to 20 dB or more.

A determination of filter insertion loss requirements must take into account that different samples of the same device to be filtered will differ somewhat in interference emission or susceptibility characteristics. Tolerances on filter element values will also cause filters to vary slightly in performance. For these reasons, it is important to allow a safety margin in calculating insertion loss requirements. It is a common practice to allow at least a 6-dB margin in the stop band.

Other characteristics that must be considered in filter selection are:

1. Voltage rating of the circuit in which the filter is to be used
2. Maximum current that will pass through the filter
3. Operating frequencies of the filter and the frequencies to be filtered
4. Maximum voltage drop across the filter at its operating power frequencies
5. Maximum and minimum temperatures at which the filter will be operating
6. Minimum filter life (number of hours that a filter will be required to operate under rated conditions at the minimum ambient temperature)
7. Size, weight, and cost restrictions on the filter

Inductor Design

Filter inductors are usually toroidal, wound on cores of powdered iron, molybdenum permalloy, or ferrite material. The size of the core is determined by required inductance and current rating. The magnetic flux (number of turns multiplied by the peak current) must not drive the core to more than 50 percent of magnetic saturation. The choice of core materials is determined by operating frequency and current rating. Powdered iron cores can be used for all DC applications and for most 60 Hz applications. For high current 60 Hz devices, and for all 400 Hz applications, molybdenum permalloy cores must be used. For extremely low current applications of less than 0.1 ampere, ferrite materials can be considered.

Windings should be placed on the coil so that input and output turns are separated as much as possible. Each turn of the coil will be at a slightly different instantaneous potential, therefore there is capacitance from each turn to adjacent turns, depending on the spacing and area of each successive turn. There is also capacitance between the coil terminals. Stray or distributed capacitance in a filter inductor can have two detrimental effects from the EMI suppression viewpoint: EMI may be coupled from input to output of the filter via the capacitance, when input and output turns (or terminals) are close together, and the capacitance may cause the filter to become self resonant at one or more critical frequencies. Distributed capacitance effects are reduced by a careful arrangement of turns to minimize the potential difference between them. In some cases, two or more coils wound on separate cores are connected in series to raise the self resonant frequency. Thus, a given inductance split into two equal parts, and without mutual coupling, will have a resonant frequency twice as high as a single coil of the same total inductance.

Loss resitance R_L is a measure of all power losses, hysteresis losses, and frequency dependent absorption losses in the core. Loss resistance R_L increases with frequency because of skin effect in the conductor and because of changes in core losses with frequency. The losses represented by R_L enter directly into the impedance equations for filter design as do the capacitive reactances and flux linkages. Each has an influence on the magnitude and phase angle of the impedances. An increase in R_L represents an increase in the attenuation of the filter passband. Its effect on reflection losses will depend upon its relation to the source and load impedances. Losses in the core are not particularly detrimental except when the insertion loss in the passband must be kept low.

The losses in the windings, plus losses in the core, cause heating of the filter. This heating must be taken into consideration when rating the filter for ambient temperature conditions. An empirical relationship has been developed that indicates approximate temperature rise of the filter case:

$$\text{Temperature rise (°C)} \quad \frac{\text{Watts}}{0.006A}$$

Wherein:

A = total surface area in square inches.

This expression is based on the heat dissipation of tinned steel cans.

Capacitor Design

Capacitor selection is determined in part by the voltage, temperature, and frequency range in which the filter must operate. Most EMI powerline filters are rated for certain standard voltages.

For 28 VDC applications, capacitors rated at 100 WVDC are quite adequate. Metallized mylar capacitors offer the most compact design and good reliability. The dissipation factor is very low and lead length can be kept short to improve high frequency performance.

If a large value of capacitance is required in a small space, tantalum capacitors may be considered. Because tantalum capacitors are electrolytics, they are more sensitive to overvoltages, and are damaged by reverse polarity. The dissipation factor is considerably higher than for mylar or paper capacitors, and high frequency characteristics are poor. A fairly large tantalum capacitor reaches its minimum impedance at 2 to 5 MHz or less, depending upon construction and capacitance value.

Capacitors for 120 VAC applications should be rated at 400 WVDC and be suitable for AC use. A unit of mylar and foil or of paper-mylar and foil is recommended. Dissipation factor is low and high frequency performance is good. For 240 VAC applications, an oil impregnated paper and foil unit is recommended.

If good capacitor performance is to be expected above about 50 MHz, it is necessary to use design incorporating feedthrough capacitors. Lead inductance in a feedthrough capacitor is not part of the shunt circuit, so that, compared to capacitors with leads, its insertion loss is not degraded as rapidly with increase in frequency (see Figure 7).

FILTER INSTALLATION

Once a filter has been selected, its contribution to EMI control must not be degraded through faulty installation. For control of high frequency EMI, filter installation requirements become very critical.

A filter should be located as close as possible to the source of EMI for suppression, and as close as possible to the susceptible circuit for protection against external interference sources. Ideally, a filter should be mounted at a point where the conductors being filtered pass through a natural boundary such as a chassis or shielded enclosure. This style of mounting tends to prevent interference from coupling across the filter input to output.

For good high frequency performance, input and output wiring should be effectively separated. Otherwise, EMI emitted from the input leads can couple directly into the ouput wiring and thus nullify the effects of the filter. Separation of wiring is most easily achieved by mounting the filter through the chassis so that the output leads protrude through the chassis or bulkhead and are shielded by it. When this is not possible, the wiring should be isolated by shielding. The leads on the "clean" side of the filter should not be routed through a region containing interference fields. If this is unavoidable, then the leads should be shielded carefully to prevent recontaminating them. In no case should the filter input and output leads be bundled together. Only when the output of a filter is completely isolated from the input can the filter insertion loss achieve the design figure.

An important factor in filter performance is the bonding of the filter case to the ground plane structure of the suppressed or protected device. This requirement is of the utmost importance if the filter is to achieve its design capability. The mounting surface for the filter must be a clean conductive area.

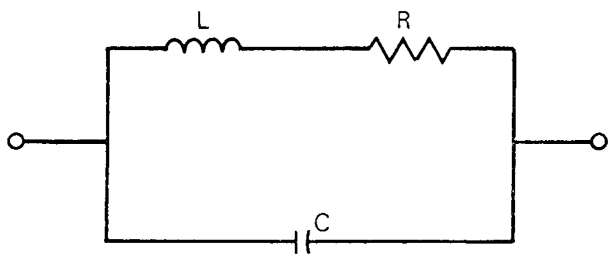


Figure 10 Simple Wavetrap Circuit

SPECIAL EMI SUPPRESSION NETWORKS

A number of special networks and circuits have been developed to reduce radio interference. Four of the more important ones are treated in this subsection.

WAVETRAPS AND NOTCH FILTERS

Wavetraps and notch filters are circuit networks designed to attenuate a specific narrow band of frequencies that may be causing interference problems. This type of device is normally used as a band-reject filter between the interference source and the load. An alternative is to use a bandpass configuration that shunts the interference to ground.

A wavetrap may take the form of a lumped-constant inductor-capacitor circuit, or it may be a shorted quarter-wave coaxial or waveguide stub, or a crystal or ceramic filter lattice. The inductive characteristics of capacitor leads and foil can be planned so that the capacitor acts as a self-contained wavetrap. For frequencies below about 1 MHz, a twin-T resistor-capacitor filter can serve.

The simplest type of wavetrap is a parallel resonant circuit such as that shown in Figure 10. This configuration will give a very high impedance at the anti-resonant frequency, and therefore this frequency is attenuated greatly. The impedance of this circuit is given by:

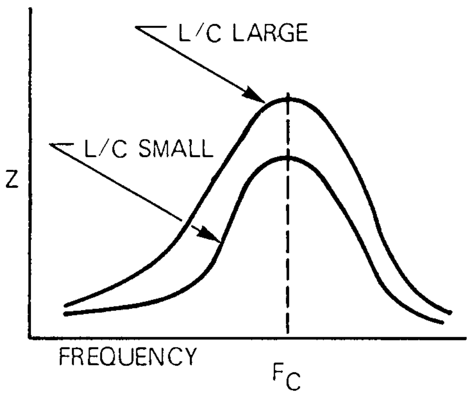
$$|Z| = \left| \frac{R + j\omega L}{j\omega C\left[R - j(\omega L - 1/\omega C)\right]} \right|$$

$$= \frac{f_r}{f}\, 2\pi L\, \frac{Q^2 + 1}{Q^2\left[\left(\frac{f_r}{f}\right)^2 - 1\right]^2 + 1}$$

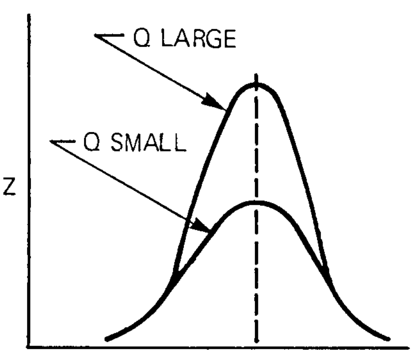
Where:

$\lvert Z \rvert$	= Impedance (absolute magnitude) of wavetrap circuit
R	= Resistance of inductive leg of circuit
L	= Inductance in wavetrap circuit
C	= Capacitance in wavetrap circuit
f_c	= Tuned frequency of wavetrap
f	= Signal frequency
q	= Figure of merit of wavetrap circuit

If Q is increased with a constant L and f_c, there will be little difference except in the region where f_c/f is close to unity. This means $\lvert Z \rvert$ rises to a higher value at f_c but is comparatively unaffected farther from f_c. To get the highest attenuation in a narrow band, the circuit should be designed with a high Q and a low L/C ratio. The dependence of Z on L/C and Q is shown in Figure 11. High values of Q can be achieved by using quarter-wave stubs, crystals and ceramic filters.



(a) Effect of L/C ratio on impedance



(b) Effect of Q on impedance

Figure 11 Circuit Effects On Wavetrap Impedance

The twin-T notch filter, shown in Figure 14-12, is useful as a band-reject filter in the lower frequency ranges such as the IF and AF circuits. At low frequencies, the twin-T filter can achieve a circuit Q on the order of 100, which would not be economically feasible for a wavetrap or inductance capacitance type filter at the same frequency. Because the twin-T is a three-terminal filter, shunting effects reduce its usefulness at high frequencies. The notch frequency is determined by:

$$f_o = \frac{1}{4\pi C_1 R_1}$$

Where:

f_o	= Tuned frequency
C_1	= Capacitance identified in Figure 12
R_1	= Resistance identified in Figure 12

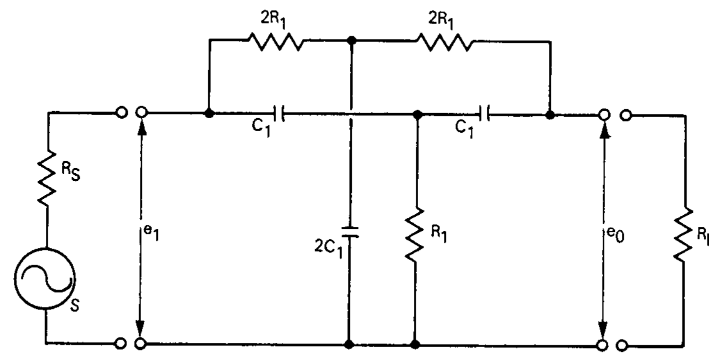


Figure 12 Twin-T Notch Filter

Typical applications and locations of wavetrap, crystal, ceramic, and twin-T notch filters include the following:

1. At receiver input terminals to reject strong nearby out-of-band interference that otherwise would overload the receiver
2. At receiver input terminals to reject troublesome image frequencies
3. At receiver input terminals to reject IF-feedthrough signals
4. At transmitter output or interstage terminals to reject harmonics or unwanted mixer products
5. In AC or DC power distribution leads to reject EMI such as radar PRF, computer-clocked surges, or rectifier ripples
6. At audio amplifier input or interstage terminals to reject IF or BFOfeedthrough, unwanted heterodynes, signal tones, radar PRF

NOISE LIMITERS

For interfering signals consisting of short impulses of large amplitude, noise limiters can prevent the peak amplitude of the interference from rising above the wanted signal. Noise limiters are not effective against thermal noise or any other type of steady-state EMI except in FM receivers or Dicke-fix receiver applications. There are two types of noise limiters in current use: the peak amplitude limiter and the gated noise limiter.

The peak amplitude limiter reduces the effect of interference by clipping all impulses above a certain threshold region. To be most effective, the clipping level should be as close as possible to the peak level of the desired signal, but not set to clip so heavily as to produce significant degradation of the desired amplitude modulation. FM receivers can clip heavily because the desired information is contained in the frequency components rather than the amplitude components of the signal.

Dicke-fix receivers also clip heavily in the early stages of receivers that use sufficient bandwidth so as not to distort the noise power spectrum appreciably. Noise power occupies much more spectrum than the desired signal, and heavy amplitude clipping in wideband stages can prevent noise power amplitude from exceeding signal power amplitude. The amplitude of the wanted signal power can then be enhanced above noise by processing the signal-plus-noise through narrowband stages that use bandwidth limiting but not amplitude limiting. The degree of enhancement is a function of the ratio of the two bandwidths. Several successive stages of a receiver may employ amplitude limiting to provide progressive degrees of limiter action. Diode devices are commonly used, although tube or transistor amplifiers biased to swing into a nonlinear region on strong signals may also be used. The 6BN6 and similar tubes are especially designed for this purpose. The disadvantage of peak amplitude limiters is that they introduce nonlinearity and the resultant possibility of cross-modulation on strong signals.

The gated noise limiter is an audio frequency device usually located between the detector and the first audio amplifier. Basically the circuit consists of a diode or combination of diodes having a fast time constant network at the input, and a slower time constant network at the output. As long as the charge-discharge period at the output can follow the desired audio input signal from the detector, the diode gate continues to conduct and the input signal is delivered to the audio amplifier. However, an impulse from the detector will possess a rise-decay rate greater than that provided for at the noise gate output. This will cause the gate to be back-biased and cut off momentarily until the slower time constant at the output can catch up with the input. Noise impulse steep wavefronts are thus kept from coming through, except for that portion attributed to capacitive coupling. The gated noise limiter is beneficial only when used with near-sinusoid waveforms such as speech.

The usefulness of both types of noise limiters depends on the width of the receiver bandpass. It must be broad enough to avoid receiver "ringing" on noise impluses. Bandwidth-limiting can alter the noise impulse envelope so that subsequent limiter action is ineffective.

BLANKING CIRCUITS

If the interfering signal is a pulse and there is no other way of protecting the receiver, a blanking circuit can be used. A blanking circuit protects the receiver by rendering it inoperative for the duration of the pulse.

The blanking circuit can be triggered by the interfering pulse or by an independent signal arriving before the interference pulse. When the interference pulse triggers the blanking circuit, delay lines must be provided to delay the signal long enough to allow the blanking circuit to turn off the receiver before the interference pulse reaches it. An independent pulse can be used if the arrival of the interference pulse is known beforehand, as when it comes from other equipment in the same aircraft. In this case, the triggering pulse can be provided by the interfering piece of equipment. Blanking action is usually provided by a simple circuit that can be gated off by the trigger pulse.

Blanking circuits lack the simplicity of wavetraps and limiters. They are complete units in themselves and include amplifiers, trigger pulse amplifiers, and delay circuits. They can also cause interference in themselves. The periodic cutting off of the signal is a form of modulation, which will appear in the audio output as noise.

INTERFERENCE CANCELLING CIRCUITS

An interference cancelling circuit suppresses interference by allowing the interference signal to travel along two paths. One of the two paths carries the interference signal and the desired signal; the other carries only the interference signal. The interference signal is then shifted 180 degrees in phase, adjusted in amplitude, and added to the other signal, thus cancelling the interference and leaving the desired signal. This method can be used only when the path of entry and the nature of the interfering signal are known. Interference cancelling circuits are useful in suppressing interference from equipment in the same aircraft that give out definite interference signals, such as radar transmitters.

Figure 13 illustrates one arrangement for eliminating interference by cancellation. Two directional couplers are used. One, indicated as DC-1, samples the interfering signal at the offending transmitter. The signal is routed through delay lines to introduce the required phase shift, through attenuators to set the power level, and then coupled to the receiver via another directional coupler, indicated as DC-2.

The arrangement shown in Figure 13 can be used only when the interfering transmitter is in the same vehicle as the affected receiver. The directional couplers are of the type commonly used for SWR measuring devices and other test purposes. They introduce negligible insertion loss in the main through-line path.

For cancelling interference sources not in the same vehicle, a different pickup arrangement will be needed, and the phase and attenuation control methods will be more complex.

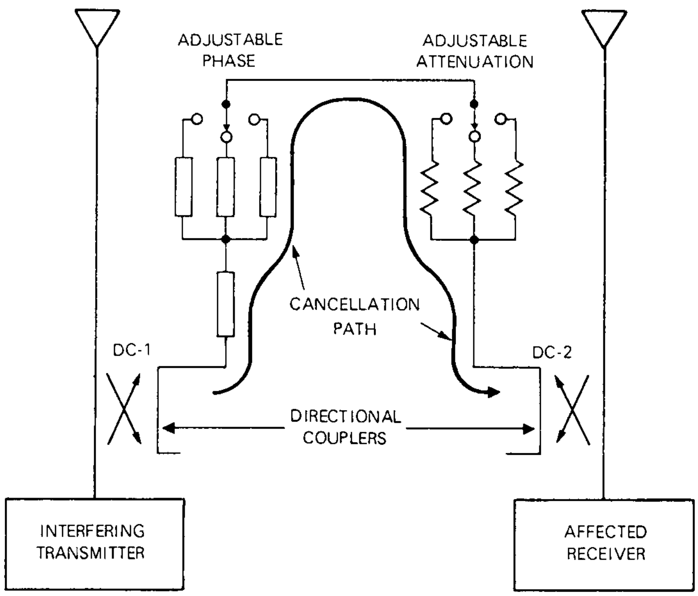


Figure 13 Block Diagram of An Interference-Cancelling Network

ACTIVE FILTERS

EMI power line filters made of passive elements are bulky and heavy. Active filters, using transistors, can provide large values of L and C without excessive size and weight. Moreover, the low impedance levels existing at low frequencies in power lines can be more easily accommodated. Two major criteria exist in analyzing the filtering conditions:

1. Power flow (DC, 60 Hz, 400 Hz) with respect to the interference flow
2. Either voltage or current attenuation as the dominant and desired feature

For the power flow criterion, three basic conditions must be distinguished. The first is the interference originating in the power supply and flowing toward the load, as in filtering a power line supplying a shielded room. The second involves interference originating in the load and flowing toward the power supply. An example is the spreading of interference arising from SCR switching, computers, and other digital equipment or solid state choppers, through the power distribution system. Another example is current pulses that drive a teletypewriter and carry classified information must be confined within a secure area. The third condition covers those cases in which interference is generated both at the power source and load, or where there is uncertainty about its origin. In these cases, bidirectional filters are required.

Underlying Principles of Operation

There are four well-known methods that can be used alone or judiciously combined to prevent interference from passing through a network. They are:

1. Storing and averaging out the interference (such as through the use of a capacitor in a DC line)
2. Using a large series impedance (series regulator) to obstruct the flow of interference
3. Using a low shunt impedance (shunt regulator) to bypass interference to ground.
4. Using an equal but opposite signal to cancel the original signal

Electrical devices such as capacitors and inductors do not store the sizable amounts of energy required for high power low frequency filters. There is also the difficulty of storing energy in the form of alternating current in resonant circuits. For example, whatever portion of the interference that cannot be stored and averaged out in a passive element must be prevented from passing through the active section of the filter. This is done either by providing a high impedance path to the interference signal (series regulator), shunting it to ground (shunt regulator), or canceling it by an opposing signal of the same magnitude. Active filters for a DC line may therefore contain capacitors as storage elements and modified series regulators to create a high impedance path, and modified shunt regulators in combination with high gain feedback systems for cancellation. In the case of AC line filters, cancellation is a most effective way to minimize interference. In contrast to conventional regulators used in regulated power supplies, these filters must not regulate the amplitude of the power to be passed.

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