FILTERS

Introduction

Filtering is used to eliminate conducted interference. Since the end effect is the same, namely getting rid of noise, we shall not distinguish between filtering and buffering; the difference being only that a buffer uses other media than electric circuits that characterize the electromagnetic filter.

Filtering (and buffering or isolating) for the elimination of electrical noise must be considered under intrinsically broader aspects than conventional frequency-selective filters designed for information handling. Two generic aspects are involved:

a. Technical Aspects:

1. Interference filters are often subjected to much higher power than conventional filters. Since, for instance, power line filters have to carry through the power, they often will be quite a bit larger and the power may bias the (possibility non-linear) filter elements (saturation).

2. Often the power spectrum of the noise overlaps with the power spectrum of the power, control, or signal.

3. The design of communication filters, as all filter books assure, are premised on impedance matching. In power feed lines, particularly, this is not possible since power feed lines are designed to be efficient at the power frequency and designed for nothing else. Thus mismatch often plays a very detrimental role: a drastic reduction of the claimed or expected filtering and, quite often, the occurrence of pronounced ringing. Conventional filter design methods are, therefore, of very limited utility for noise elimination and, in the absence of impedance matching Butterworth, Bessel, and other type of filters become rather inappropriate.

4. High peaked impulse noise combines high energy of the noise with a very broad frequency spectrum.

b. Economical Aspects:

There are many alternative avenues to clear interference. The decision of the most reasonable means must be based on the maximum benefit/cost ratio; with the benefit possibly being not much more than necessary. No specific single rule can be given for the decision involved since it depends on the circumstances of the particular system under consideration and its noise environment. Rather, the reader should be familiar with all aspects of interference elimination, and suppression. Filtering and buffering are quite often the most economical remedy. Filters are the only means to eliminate interference once it is on the line, but also the introduction of a filter or buffer, (close to the source) can save on costly separation or wiring or on shielding. Buffers, in particular, like for instance, electro-optical isolators are quasi-filters that prevent the conduction of certain modes of noise, ground loop-induced or otherwise.

The classification of filters and buffers, in this practical context, will not be made on the basis of operating principles, rather on the basis of those key properties that characterize the relationship of the noise on the one hand and the power, control, or signal to be conducted on the other hand. Typical, therefore, are the differences in power spectrum or the difference in amplitudes. This section, then, treats what is missing in conventional filter design methods.

Frequency Domain Filters

REAL FILTER ELEMENTS

a. Real Capacitors (used by themselves for "high" impedance loads). In many instances, capacitors in conjunction with inserted or already existing inductors are shunted across the line for filtering purposes. This simple measure does not always work too well. Figure 1 shows reasons for, Figure 2 shows the effects of the nonideality of the real capacitors, which are often mistakenly assumed to be rather ideal two-terminal elements. Six differences are often overlooked:

1. If the capacitor is not built as a feed-thru capacitor, capacitative and inductive coupling between input and output leads, particularly at higher frequencies, may make the noise to circumvent, and hence, nullify the effect of the capacitor. This feed-thru requirement applies equally importantly to filters which must also be mounted through the shield to prevent capacitive coupling at higher frequencies. If no shielding is available, the input (and possibly the output) line must be shielded.

2. Another detrimental effect occurs when a not-feed-thru arrangement is applied: though mostly very small (but in terms of the small $1/\omega C$, it is not small enough), the series L in the shunt branch causes series resonance of the capacitor, above which the capacitor behaves like an inductor (curves (a) in Figure 2).

3. Internal shielding of the layers of wound capacitors reduces the ideal capacitance. Curves of Figure 2 (b) deviate from the ideal capacitor behavior characterized by the straight line of 20 dB/decade of frequency. This behavior is typical of paper, Mylar, or ceramic multilayer capacitors.

4. The series resistance, at the small reactances occurring at high frequencies can become dominant: curve (c) of Figure 2, typically representing tantalytic capacitors which deviate drastically from the expected capacitive behavior. As curve (c) indicates, this can happen already at quite low frequencies. Hence, tantalytic capacitors, though excellent at low frequencies, must be complemented by high frequency capacitors to be shunted in parallel.

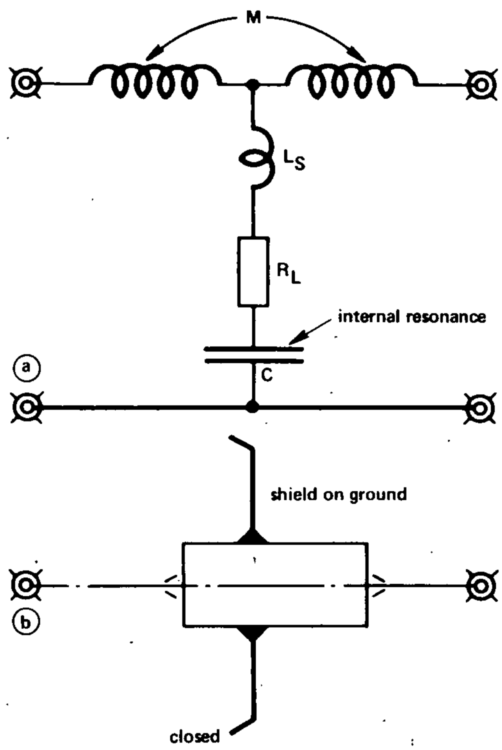


Figure 1

(a) Equivalent circuit of a shunting capacitor, not constructed as feed-thru.

(b) Feed-thru configuration.

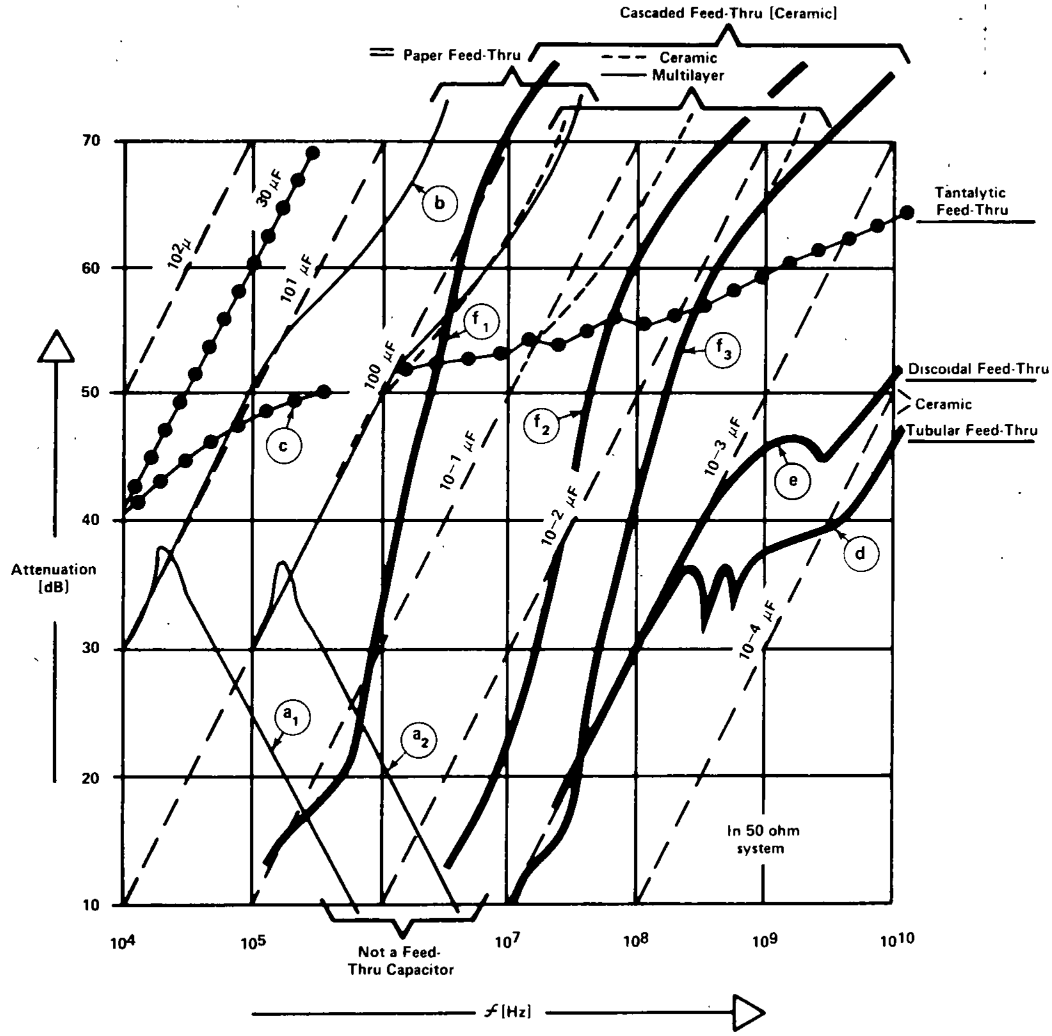


Figure 2 Attenuation of So-Called Capacitors

5. At very high frequencies, ceramic (very high dielectric constant capacitors) are preferred because of size, but internal resonances caused by transmission line effects, may reduce their effectiveness. Discoidal (disc-like) feed-thru capacitors are quite a bit better than tubular ceramic capacitors, (e), (d), respectively. By splitting ceramic capacitors into two portions and providing a ferrite bead on the interconnecting wire, the capacitors can be made better (f_1, 2, 3) (slope in Figure 2 is larger than 20 dB/decade of frequency) than even ideal capacitors. Again, this is premised on feed-thru configurations (6).

6. Ceramic capacitors, when using very high dielectric constants and if improperly designed, may show voltage bias effects (reduction of effective dielectric constant by up to 70-80%), similarly to the current-induced bias effect of inductors having magnetic cores (iron or ferrite).

b. Real Inductors (used by themselves for "low" impedance loads). Ideal inductors do not exist as ideal capacitors do not exist. An inductor, if iron or ferrite cored, may lose quite a bit of its inductance by saturating currents. This is quite pronounced in power feed line filters; it must be compensated by air gaps. (Exception: common mode filters: see later.)

Real wound inductors with increasing frequency alternate between inductive and capacitive effects. Lossy inductors can be made of thick iron laminations at the expense of lowered inductance.

There is a highly useful, cheap inductor useful from about 1 MHz on. That is the ferrite bead or block. One such bead, strung on a wire (one turn) represents an impedance of 20-50 ohms with about 45° phase angle, for all frequencies about 1 MHz, and it does not "exist" (is negligible) at low frequencies. Current bias effects can be minimized by proper ferrite selection or by cracking the ferrite beads and gluing them together again (air gap).

LC FILTERS UNDER MISMATCHED CONDITIONS

(The following is condensed from Bibliography (1). LC filters are presumed to be quite familiar to electrical engineers, and may seem hardly worth reconsideration. Yet the very confidence in well established filter theory is badly shaken if one finds that filters often do not work as predicted.)

There is nothing wrong with established filter theory.* However, one must recall that the filter theory is premised upon impedance matching. Yet, impedance matching does not at all exist in signal and control lines, and much less so, in power feed lines. Power feed lines are the sole purpose of transferring power

*In this context, it is tactily assumed that the biasing (saturating) effect of power voltage and current has been reduced by proper design.

*According to MIL-STD-461, another unrealistic approach to filter testing.

with high efficiency from the power source to the load. For lack of a better method, filter performance is presently being measured according to MIL-STD-220A. That means it is measured in a 50 ohm system. The actual system, however, in which the filter is supposed to work, consists of source and load impedances, interface impedances, which seem to vary "all over the map" as a function of frequency, location, and time.

Much has been written on how badly conventional filters can behave under non-matched conditions, but not much has been said on what to do about it in an economical and reliable way. Some people put so-called line-stabilization networks in the system, but for measurement purposes only. The actual filter operation is without line-stabilization networks, making the whole affair quite illusory. Others use brute force filters, heavily over-designing filters, resulting in rather costly and bulky filters. Again, others propose "in-situ" trial of filters. (2,3) That means one tries for each filtering situation all kinds of filters until one finds, hopefully, one that works best; a tedious and non-optimized affair without any chance of predictive planning. Others propose worst case filters (4, 6) having a guaranteed minimum insertion loss operating for all possible interface impedances–a costly affair resulting in large filters.

MIL-STD-461 stipulates to insert a 10 μF capacitor for measurement purposes (short circuit), but not leaving it in for actual operation; again resulting in a difference of assumed and actual performance of the filter.

In military equipment, by necessity, cost is secondary to a high assurance of electromagnetic compatibility. In contrast, in industrial and consumer equipment, cost considerations dominate over the degree of electromagnetic compatibility as far as incidental interference is concerned. Hence, for low cost applications, it was decided trying to establish a data base on interfacial impedances such that filters do not have to be designed for any imaginable interface impedances, but for statistically significant data only. After developing new, more reliable impedance measurement equipment (measurement under bias), and measuring quite a number and variety of AC and DC sources, it was found that their respective values cluster surprisingly, particularly in the critical frequency ranges from 1 to 150 KHz, in fact, so much so, that a simple equivalent circuit of a series L of 30 μ Hy could be described, representing 90 to 95% of all cases. Above 150 KHz, a rather broad dispersion of impedance values was found. But this does not much affect filter performance, which is usually characterized by high attenuation normally expected at these frequencies.

The statistics of load impedance data were found rather unsatisfactory due to the great variety of loads. Although loads could be categorized into broad classes, each defining a specific equivalent circuit, comprising significant statistical single peaking, it was decided at least for the time being, not to establish equivalent circuits for load classes until more data, sufficient for each generic class, can be gathered.

Nevertheless, statistical values for the generator impedances also permit a better understanding of what can be expected of actual filter performance. Whereas the selection of interference filters, thus far, was either a trial and error affair or resulted in clumsy filters of not always certain effectiveness, it should now, premised upon the statistical data base tentatively established, be possible to proceed systematically and predictively for the most economic results. It was hoped that some simple rules on the application of filters could be set forth in a cookbook fashion so to speak. It turns out, however, things are not quite so simple. Nevertheless, some conditional rules can be established for the selection of the type of filter best suited for particular circumstances. The question, "What is the best filter, (the Pi, T, or L, or multiples thereof)" cannot be answered categorically. First we have to stipulate: Best for what? There are several "for what" criteria:

1. For fulfilling the MIL-STD-220A condition with the most economic filter (smallest LC), it seems that the "L" has an edge over the "T and Pi" filters. This, however, is a specious superiority, of paper value only.

For statistical AC (including AC + 10 microfarad*) and DC sources, the "Pi" will nearly always behave worse than assumable according to MIL-STD measurements, whereas, the "T and L" tend to give actually better or equal performance to that predicted by MIL-STD-220A.

2. For AC circuits, in general, the most price-worthy filter (filtering LC) will be the Pi, closely followed by the T. However, T filters are not recommended for capacitive loads. For LC circuits, in general, the T has the edge over the Pi and L. This is based on comparing filters of the same LC product (as a first approximation for price).

3. For high interface impedances, Pi filters are best; for low interface impedance levels, T's are best.

4. In many applications, minimal ringing is equally as important as filtering. In general, the L filter has the worst ringing characteristic. The T filter, particularly with small L/C ratio, is best for minimal ringing. If necessary, lossy inductors must be provided.

RC FILTERS, PASSIVE, ACTIVE & QUASI

a. Passive RC Filters: In control systems, 60 Hz energy permeates the whole environment. If it has to be removed from sensitive signal lines, a stable twin-TRC band-reject network may often be sufficient to notch out the disturbing 60 Hz.

b. Active Filters: For signal lines active filters combining R's, C's, and integrated operational amplifiers, replace effectively LC filters which would be too large at low and very low frequencies even at signal line levels, without appreciable bias. A well established literature exists on active filters, the most comprehensive presentation being Huelsman's book (5).

Although bibliography (6) describes an active 60 Hz power feed line filter, and although such filters have been built, it seems more economical and more adequate to apply filter-regulators to be described in the following section. Active DC line filters are essentially power regulators. Typical examples and conditions to be observed are given in bibliography (6).

Other Filtering Approaches

FILTER REGULATORS

Switching loads may cause severely disturbing transients. The power spectrum of transients contains such low frequencies of high amplitude that conventional LC filters would have to be of unmanageable size to be working efficiently. In DC lines, active filters, as previously outlined, can reduce this interference to quite acceptable levels. Quite often simple energy storing elements are adequate, as for instance, tantalytic capacitors or secondary batteries. But even in logic curcuits (since switching times are in the order of nanoseconds and can, even for a small L, cause large L(di/dt), energy storage in form of simple ceramic capacitors, like chip capacitors, across the DC line, close to the gates, can eliminate undesirable transients in shared power supplies. In AC lines, storage elements are tuned circuits, which are rather unwieldly arrangements at 60 Hz. Since storage elements are much easier to provide for DC, rectification, storage, and conversion back to AC (for instance, by oscillator amplifiers, switching or inverter types), can stiffen power supplies quite drastically. Such devices also render good filtering but are usually quite expensive. Hence, for low cost, often ferroresonant transformers are inserted in the line. They are not only modest in price, but also modest in performance unless properly modified.

LIMITERS

If transient spikes are additive to and exceeding the extremes of the useful voltage (and not substractive like notches being most economically handled by means outlined in 2) limiting elements, so-called non-linear filters, are indicated.

For signal lines, backto-back diodes (avalanche or selenium), shunted across the lines are good protectors, for instance, for differential amplifier inputs. Current impulses are drastically reduced by positive temperature coefficient (PTC) resistors put in series with the line.

For lines carrying power, highly energetic spikes are squelched by air gap suppressors, sharp kneed selenium rectifiers (back-to-back for AC, very rugged) or zinc-oxide non-linear resistors, so called varistors. Their selection depends on the expected rating of the spikes. In digital systems, clipping (by emitters) can render the spikes harmless, if and only if the spike width is much smaller than the width of the digit.

INFORMATION MATCHED FILTERS

This section is briefly concerned with noise in signal lines, specifically with signals buried seemingly irretrievably in noise, at least not retrievable with conventional S-domain filters, irrespective of how much effort is being made.

It is beyond the scope of this Noise Guide to elaborate, in any detail, the methods to extract such signals from noise, yet the reader should be at least made aware that such sophisticated filters exist.

BIBLIOGRAPHY

1. H. M. Schlicke (F), A. J. Bingenheimer (M), H. S. Dudley, Allen-Bradley Company, *"Elimination of Conducted Interference, A Survey of Economic, Practical Methods,"* Invited Paper for the 1971 Annual Meeting of the IEEE Industry and General Application Group.
2. D. B. Clark et al, *"Power Filter Insertion Loss Evaluated in Operational-Type Circuits,"* IEEE Transact. EMC, June, 1968.
3. D. F. Fischer, and R. B. Cowdell, *"New Dimensions in Measuring Filter Insertion Loss,"* EDN, May, 1968.
4. H. M. Schlicke, H. Weidmann, *"Effectiveness of Interference Filters in Machine Tool Control,"* Paper given at 19th Annual IEEE Machine Tool Conference, October, 1969.
5. L. P. Huelsman, *"Theory & Design of Active RC Networks,"* McGraw Hill, 1968.
6. H. M. Schlicke, H. Weidmann, *"Compatible EMI Filters,"* IEEE Spectrum, October, 1967.
7. H. M. Schlicke, R. Fredrickson, W. Vebber, *"Filter-Regulators for 60 Hz Power Lines,"* 1971 IEEE International EMC Symposium, Record.

Filter Design

A filter is made up of two basic elements; a capacitor, and an inductor. To understand how these items function in a filter, it is first necessary to review the reactance characteristics of both. When a voltage at a given frequency is applied to either a capacitor or inductor, a current will flow. The magnitude of the current is dependent on the voltage applied and inversely to the reactance X.

$$I = \frac{V}{X}$$

It can be said that the reactance of a capacitor or inductor is the property of the device that impeds the flow of current. In other words, the higher the value of reactance the less current will flow when a given voltage at a given frequency is applied.

$$X_C = \frac{1}{2\pi f_C} \qquad X_L = 2\pi f L$$

Examination of the above two equations lead one to conclude that as frequency increases, X_C decreases and X_L increases. This is demonstrated in Figure No. 3.
This may be visualized as shown in Figures 4 & 5 below.

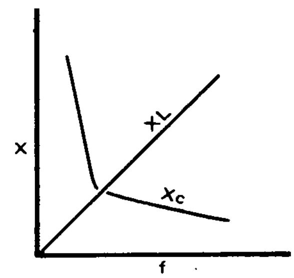
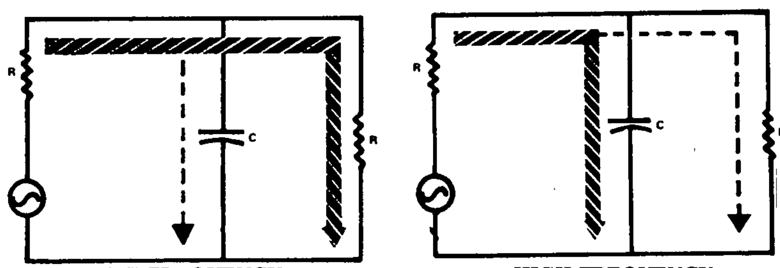


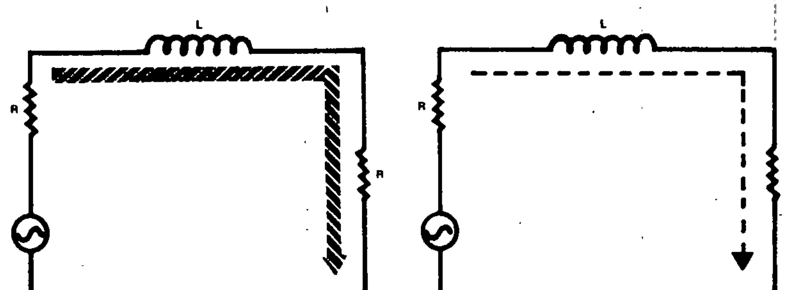
Figure 3



LOW FREQUENCY
(a)

HIGH FREQUENCY
(b)

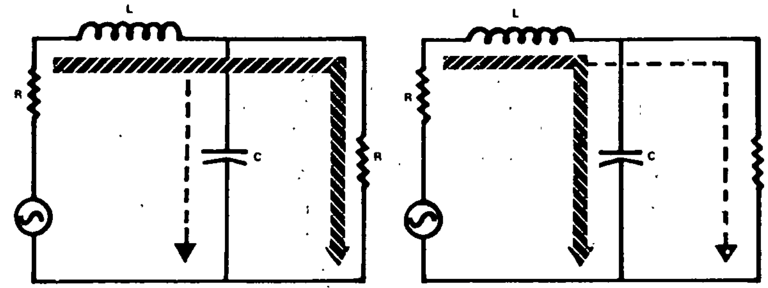
Figure 4



LOW FREQUENCY
(a)

HIGH FREQUENCY
(b)

Figure 5



LOW FREQUENCY
(a)

HIGH FREQUENCY
(b)

Figure 6

By combining these two elements into one circuit, an "L" circuit filter is achieved. The effectiveness of the L filter in suppressing high frequencies is much better than when using a single element. This is demonstarated in Figure 6.

The values of the components is determined by the impedance in which the filter is to operate (the value of source and load resistance) and the highest frequency to be passed (the cutoff frequency).

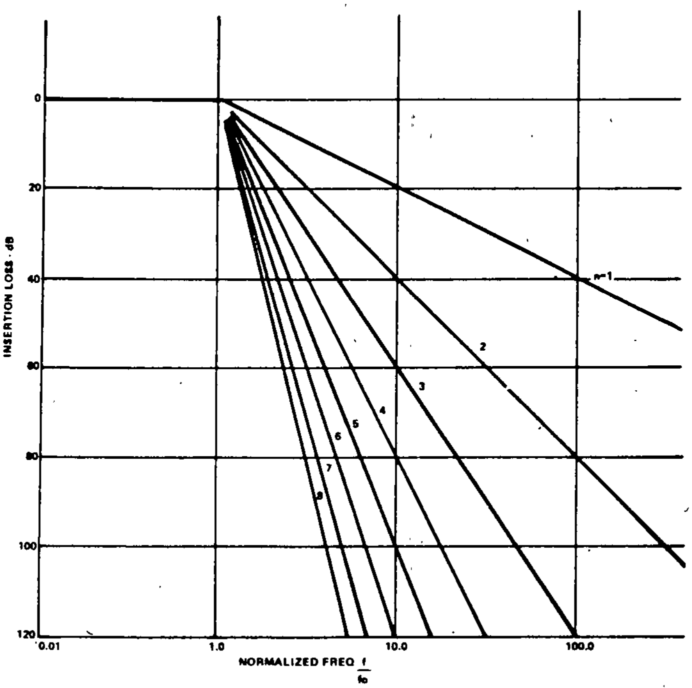


Figure 7

Note in Figure 7 that in properly designed and terminated filters, there is minimum attenuation in the pass band up to the cutoff frequency while the area above the cutoff frequency is the reject band. A single element filter, such as a feed-thru capacitor, cuts off at the rate of 6 dB/octive (20 dB/decade). A two element filter, such as a "L" type, cuts off at the rate of 12 dB/octive (40 dB/decade). Three element filters, such as "π" and "T" types, cuts off at the rate of 18 dB/octive (60 dB/decade). In short, for each element added to a filter, the rate of attenuation is increased by 6 dB/octive (20 dB/decade).

The values of the individual components in a proper designed filter in a matched impedance system is determined by the resistance and the desired cutoff frequency as shown in Figure 9. Note that a three element filter can be either a "π" or "T" type and that the cutoff frequency and rate of attenuation is the same for both. Also note that in the units with even number of elements, the choice of inductive or capacitive input has no bearing on the performance or arate of insertion loss.

As an example of a filter design, let us assume it is desired to obtain a filter rated at 120 V, 60 Hz and 20 amps that will provide 60 db insertion loss at 150 KHz in a balanced 50 ohm system. Refer to Figure 9. This results in either a "π" filter with an inductor of 1.06 millihenry and two capacitors of .217 MF, or in a "T" filter with two inductors of 530 micro henry each and a capacitor of .434 mf. The choice of which type of filter is usually determined by system needs as well as economics.

One of the interesting aspects of filter design, and one often employed in EMI filters due to necessity, is that of impedance mismatching. To illustrate, let us take the same "π" filter as above, design it on a 5 ohm impedance level and shift the cutoff frequency to 30 KHz. This results in a filter with an inductance of 53 uh and two capacitors of 1.08 uf each.

Note in Figure 10 that when tested in a 5 ohm system, the IL behaves in the expected manner with the cutoff frequency at 30 KHz and 42 db at 150 KHz, and 60 db at 300 KHz. You will also note that this same filter, when tested in a 50 ohm system, has a very definite resonant point at the cutoff frequency while providing the required 60 db at 150 KHz. The advantage of this design over the normal 50 ohm is obvious. It is much easier, and more economical to provide 53 micro henry than it is 1060 micro henry, particularly at the relatively high current of 20 amps.

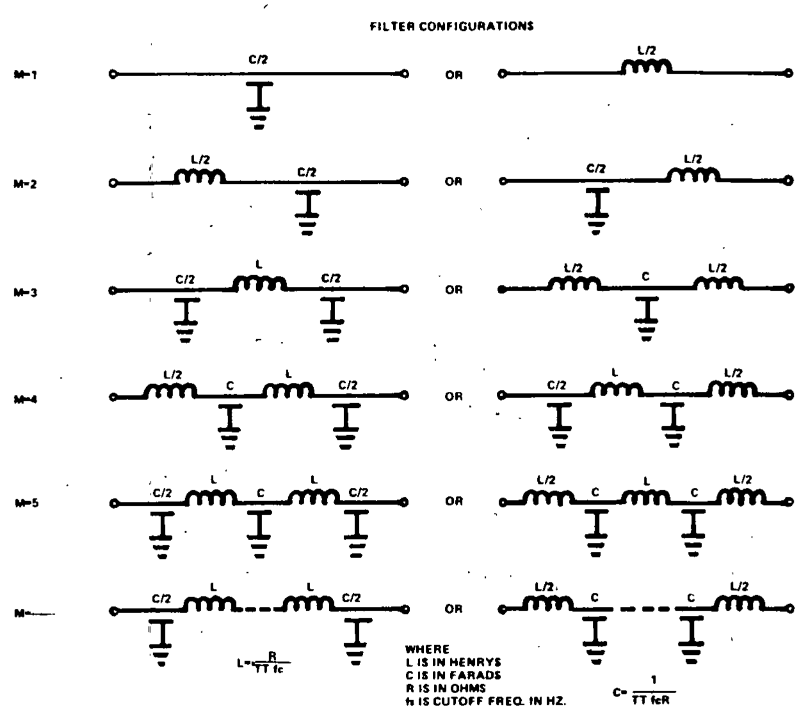


Figure 8

Figure 11 shows a direct comparison of the insertion loss of the two filters. Both meet the passband and the reject band requirements.

It would appear from this discussion that it is a relatively simple matter to design filters. Unfortunately, there are many other factors that must be considered in the area of filter design. To best illustrate some of these factors, examine another filter requirement that is widely used throughout the military/government structure, as follows:

100 dB from 14 KHz to 10 GHz per MIL-STD-220A with modified buffer networks to allow measurements down to 14 KHz.

277 VAC 60 Hz, 100 Amp rms

2 V rms max. voltage drop at rated voltage, current and frequency with a unity PF load.

Note on Figure 12 that there are two defined areas, namely the passband from DC to approximately 100 Hz and the reject band from 14 KHz to 10 GHz. The transition area between the passband and the reject band is not defined, and therefore the rate of attenuation (or the I.L.) is left to the choice of the filter designer.

Looking at a "π" filter as shown in Figure 13 the cutoff frequency would be approximately 200 Hz, which would yield an inductance of approximately 80 milli henry and two capacitors of approximately 16 mf each. Needless to say, this value of inductance is not practical at a current of 100 amps.

In order to lower the value of inductance required to a somewhat more reasonable value, the cutoff frequency must be raised. When doing this, the number of elements employed in the filter must be increased for higher rate of insertion loss as depicted in Figure 14.

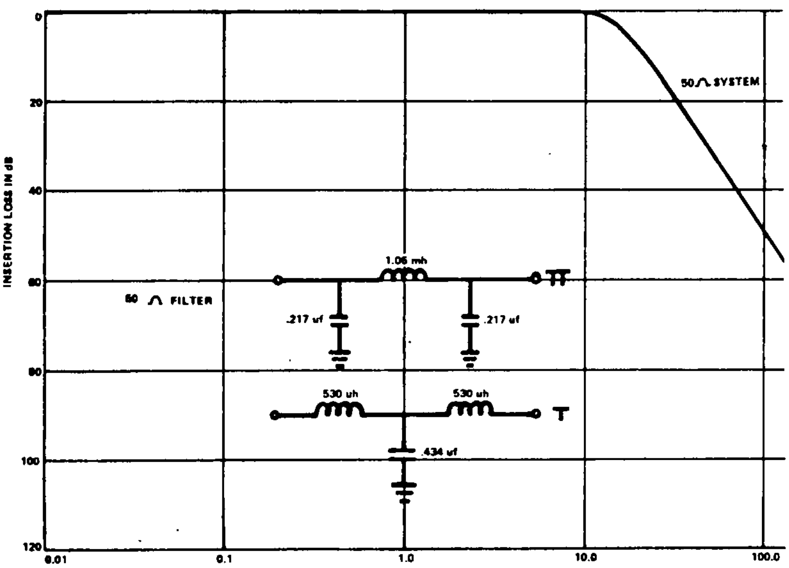


Figure 9

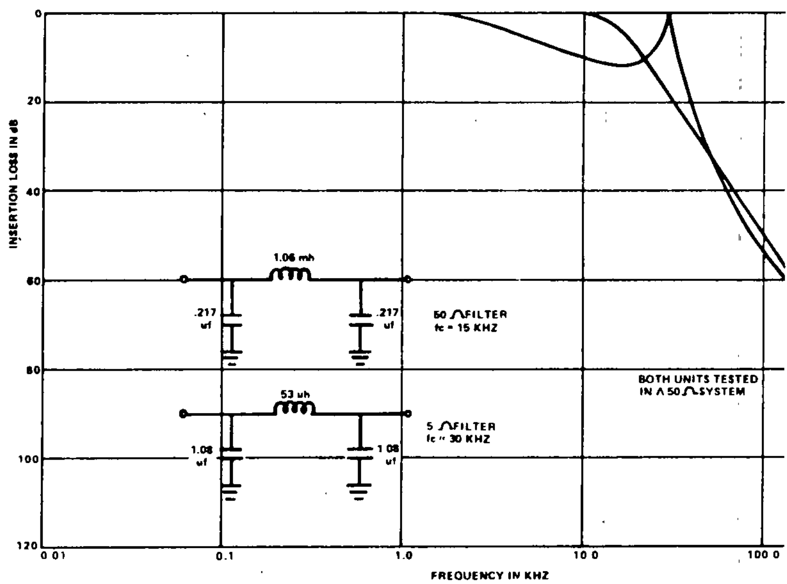


Figure 11

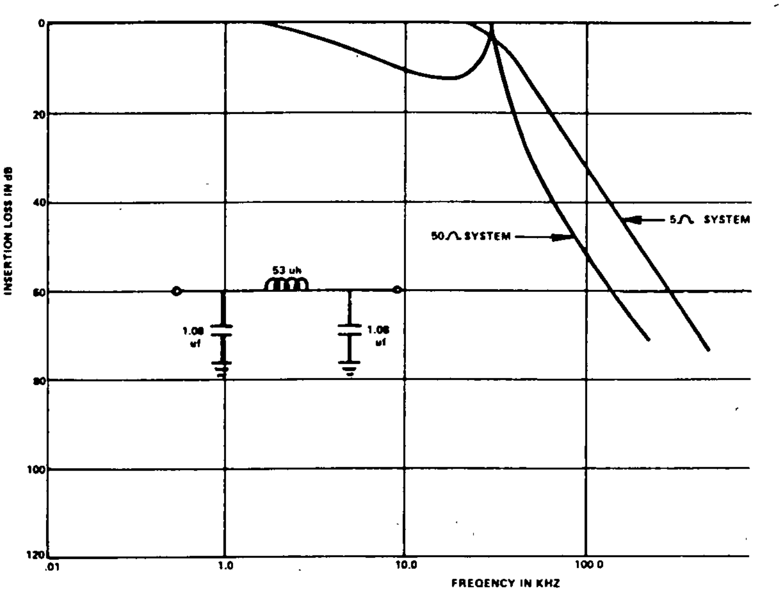


Figure 10

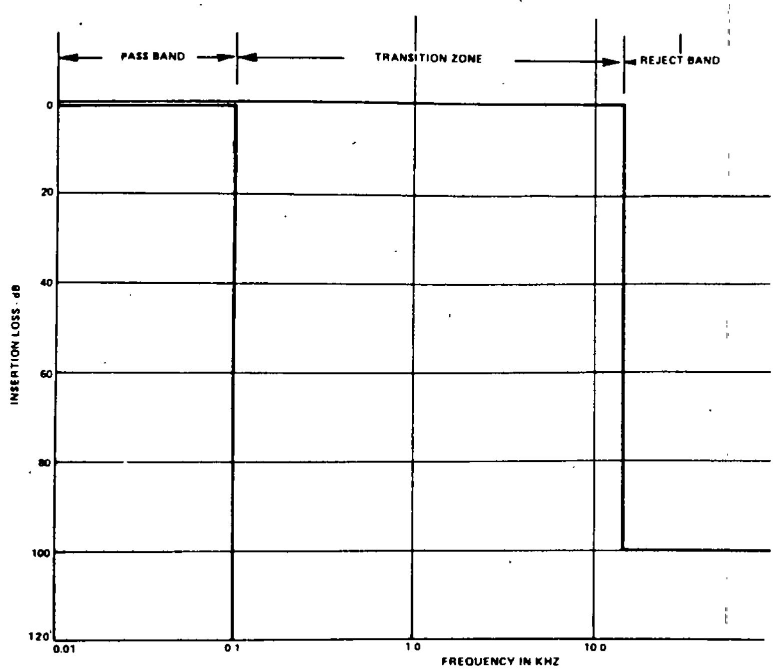


Figure 12

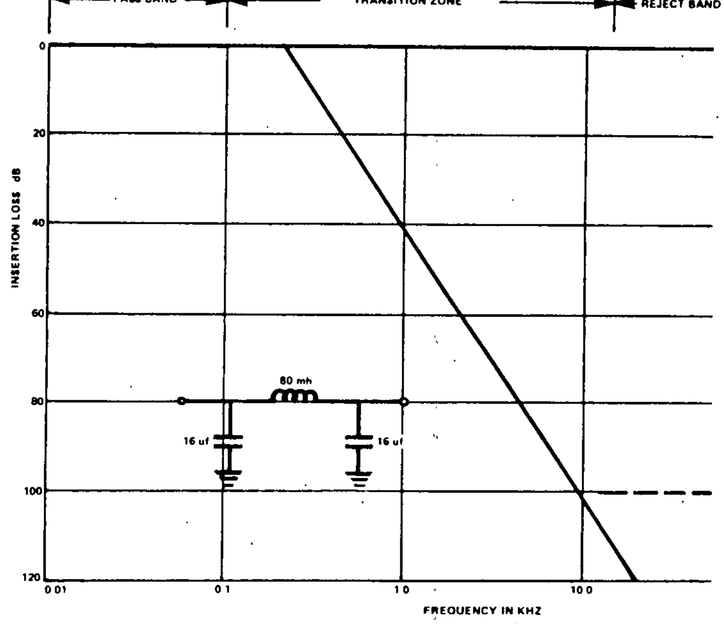


Figure 13

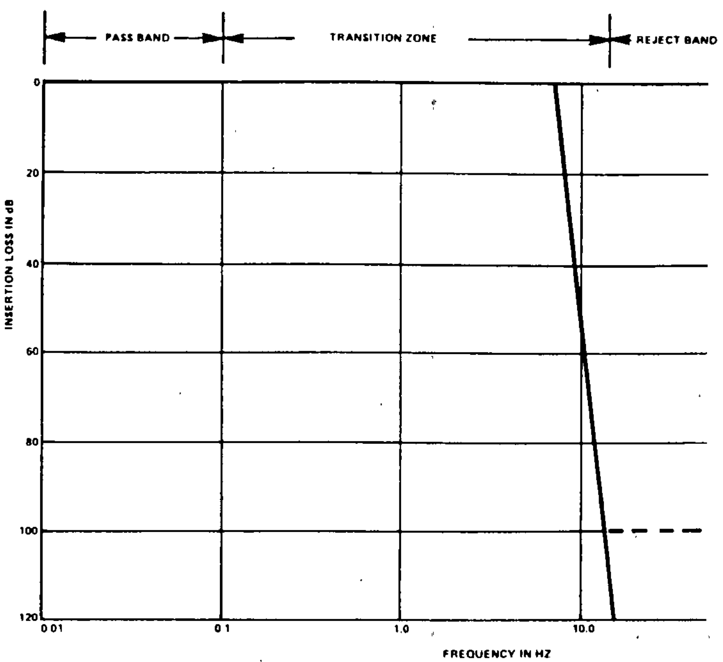


Figure 14

To arbitrarily select a cutoff frequency of 7 KHz, a 9 element filter would be required. The value of each inductance being 2.3 mh and capacitor values of .91 uf and .45 uf. A quick evaluation of this design indicates that while the values of capacitors are certainly reasonable, the inductance values are still not, and the filter would have excessively high voltage drop at 100 amps.

mismatch and employ reasonant circuits to meet the specification requirements. Without going into detail concerning the methods of arriving at the component values, suffice to say that a typical design might be as shown in Figure 15. The inductance must be designed to provide the value indicated with full load current flowing and the value of inductance must be maintained up into the 100 KHz range, as a minimum. Taking into account the copper losses (wire resistance) and core losses, this design would meet the maximum voltage drop at 60 Hz, approximately 1.5 V rms, and provide the required insertion loss from 14 KHz up when tested in a 50 ohm system as indicated in Figure 16.

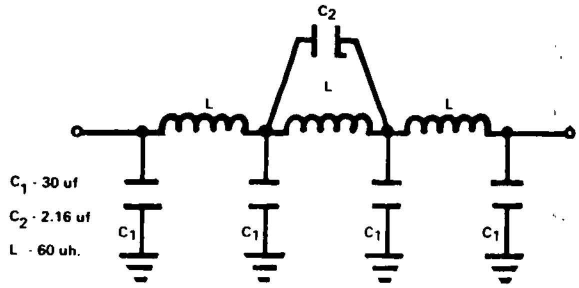


Figure 15

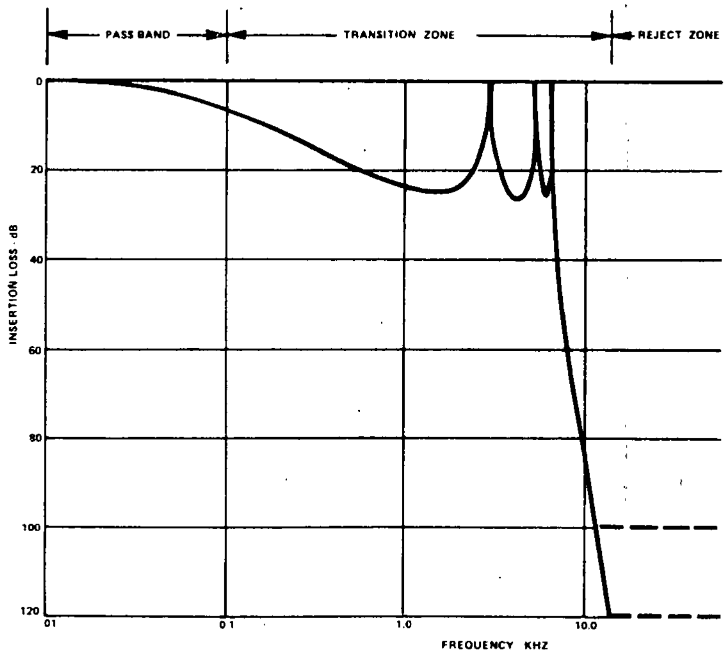


Figure 16

Of significant interest are the resonant points in the transition band. While these do not appear to give a rise when tested in a balanced 50 ohm system, they become areas of concern when the filter is operated in real world impedance environment as shown in Figure 17. It is important to point out that this same filter, when theoretically evaluated in impedances more closely approximating the actual, does not provide the 100 dB insertion loss at 14 KHz.

Thus far only line to ground type filters have been considered. In recent years that has been more emphasis placed on line to line type filters due to the low leakage current requirements of commercial applications, both domestic and foreign. A typical filter of this type might be as shown in Figure 18.

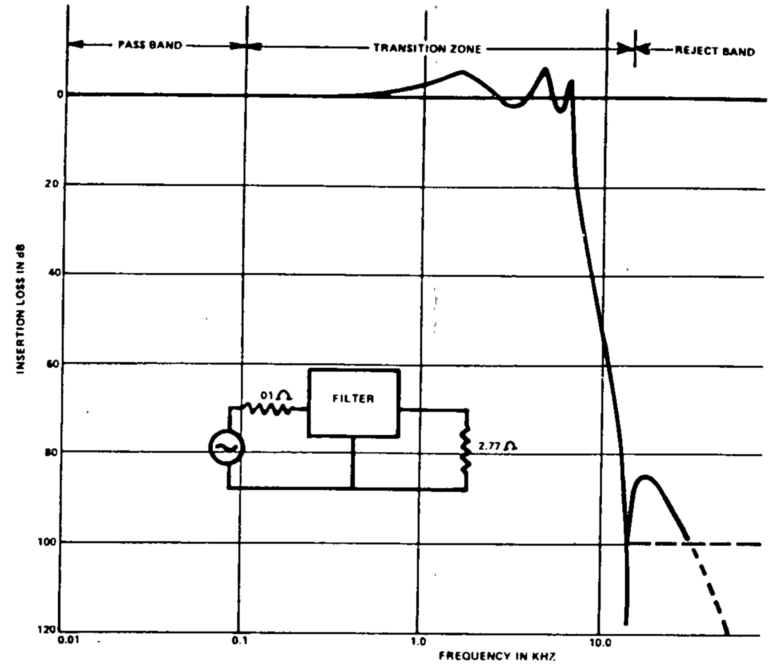


Figure 17

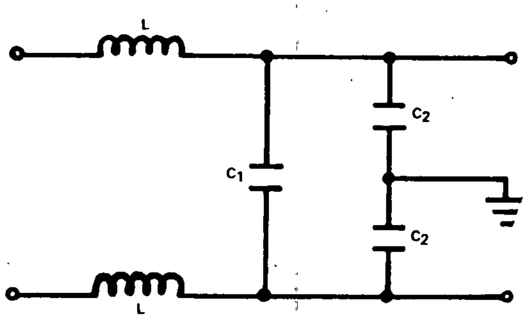


Figure 18

They function quite well in reducing line to line noise, but due to the small value of C_2 as determined by the allowable leakage current, the value of L must be quite large to reduce line to ground noise. Values of 1 mh are not uncommon for this type filter, and the current rating is generally in the lower values. Typical values of C_1 may be up to 2 uf, while C_2 values generally do not exceed 0.01 uf. Due to the fact that C_1 is a by-pass type of capacitor, the performance tends to fall off at high frequencies.

Effects Of A Filter On A System

The following is a detailed examination of the power line filter, not so much as it relates to the control of emissions entering conducted paths but rather some of the effects this device may have on the power line and/or the system for which it is supposedly providing protection. The principal concern in this regard is of course filter performance at the power line fundamental frequency.

Power line filters are impedance sensitive devices and though it is common to evaluate interference rejection performance while terminating these filters in 50 chm source and load impedances in accordance with MIL-STD-220A, it can be disastrous to overlook the effects of impedances other than 50 chms on the performance of the filter at the power line fundamental frequency. More often than not these impedances will be complex and will have values ranging from a fraction of an ohm to several hundred ohms.

An example is a typical 5th order power line filter. Figure 19 shows the filter schematic along with the associated element values. The insertion loss performance of this filter, when terminated in 50 ohm source and load resistances, over the frequency range of 10 KHz to 100 KHz, is shown in Figure 20.

Since power line filter terminating impedances are usually not resistive, it is of considerable interest to examine the performance of this filter when terminated in impedances which more nearly resemble those of the real world. In order to accomplish this the computer simulated performance of the filter is shown in Figure 21, when driven by a source of essentially zero impedance and terminated in load impedances with varying power factors ranging from 0.5 inductive to 0.5 capacitive. We are interested in the difference between input and output voltage, expressed as voltage drop or gain, as a function of load power factor.

The filter under these conditions is delivering full rated current to the load. It may be observed that resistive and inductive loads result in voltage drops and that capacitive loads with power factors less than approximately 0.9 result in voltage gains.

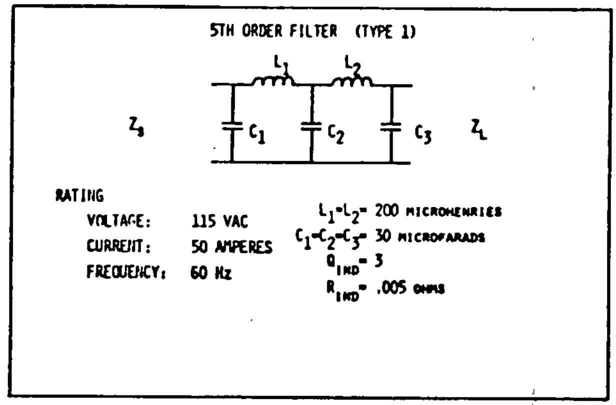


Figure 19

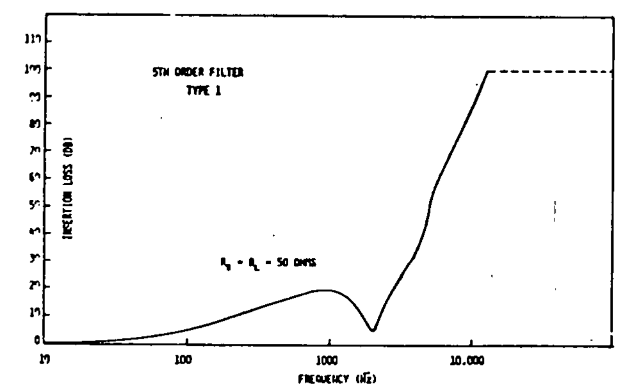


Figure 20

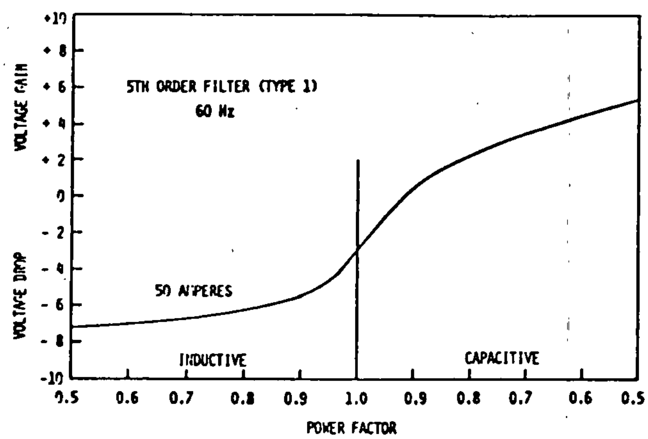


Figure 21

Since filters are often operated at something less than rated current, observe the 5th order filter's performance when terminated under the same power factor conditions as previously stated but when delivering only one tenth of the previous value of current to the load, as shown in Figure 22.

The filter under these conditions is delivering 5 amperes to the load. From a voltage drop or gain standpoint, 5 amperes appears to be almost an ideal operating condition for this filter. Cost, of course, is one of the principal reasons why 50 ampere filters are not used for 5 ampere applications.

Now take a look at a filter of slightly different design and see if it offers any improvement in performance under the same previously stated conditions. Figure 23 shows the filter schematic along with the associated element values.

The insertion loss performance under 50 ohm conditions over the same frequency range is shown in Figure 24. It may be noticed that the filter begins its transition from pass band to reject band at a somewhat higher frequency than that of the 5th order filter. To better see this, Figure 25 superimpose the two curves. This filter's voltage drop and gain as a function of load power factor and the same two previously stated load current conditions is of interest.

Figure 26 shows that the magnitude of voltage drop or gain is considerably less for the 7th order filter. In other words, the 7th order filter offers better regulation than the 5th order filter. Figure 27 shows that the voltage drop and gain performance of the 5th order filter when operated at 400 Hz may be totally unsatisfactory. Particularly at full rated load current conditions and at load power factors very far removed from unity. Figure 28 shows the performance of the 7th order filter under the same conditions. The 7th order filter has a generally improved performance over that of the 5th order filter and its performance at 400 Hz is tolerable over a wider range of load power factor values.

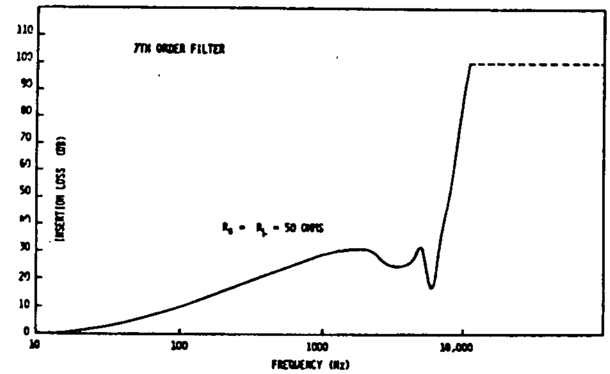


Figure 24

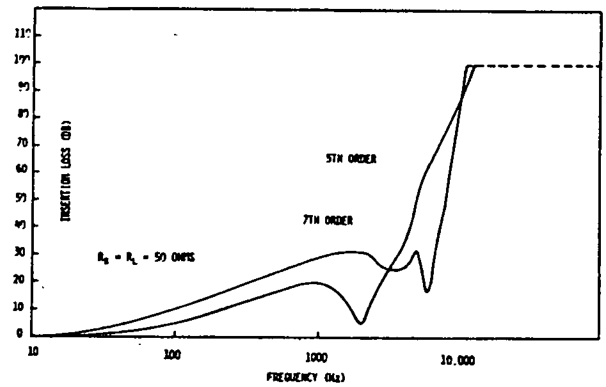


Figure 25

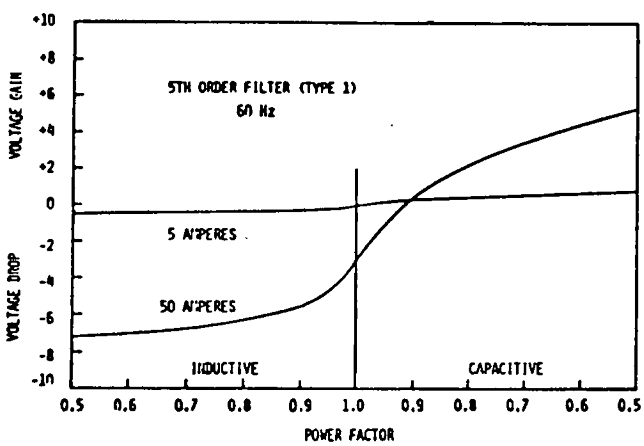


Figure 22

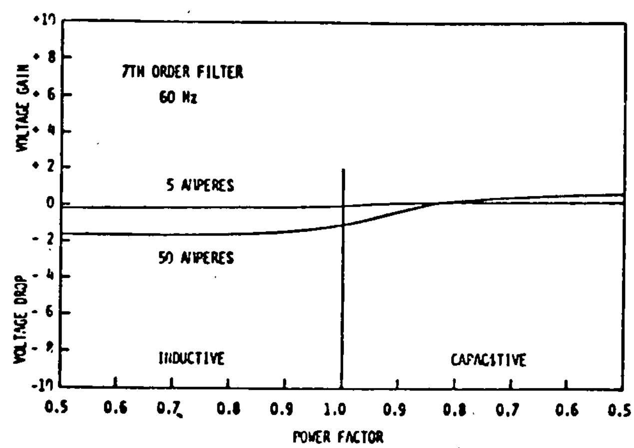


Figure 26

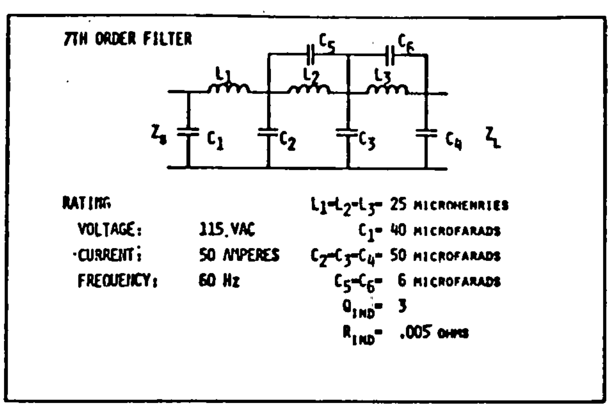


Figure 23

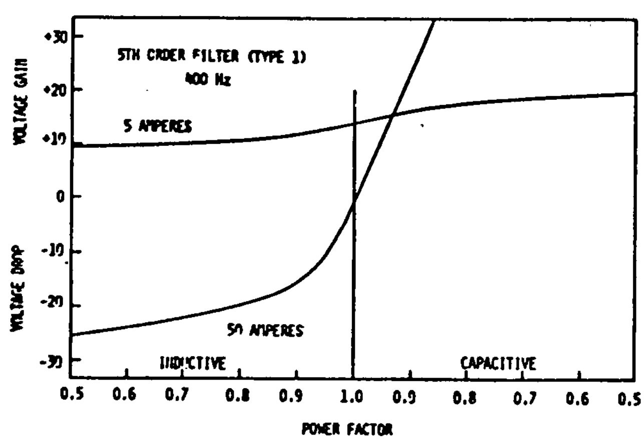


Figure 27

The better regulation of the 7th order filter is attributable to the reduction of the values of the series arm inductors in the filter. Since both the 5th order and the 7th order filters achieve 100 dB insertion loss at approximately the same frequency, the reduction in series arm inductance values in the the case of the 7th order filter are achievable primarily because of this filter's higher cutoff frequency. If less insertion loss could have been tolerated in the 10 KHz to 12 KHz region, a 5th order filter could have been designed with even better performance than the 7th order filter shown here. To show that this is in fact true, look at a 5th order filter designed to achieve 100 dB insertion loss at just over 20 KHz.

Note in Figure 29 that the series arm inductors are of the same value as those of the 7th order filter.

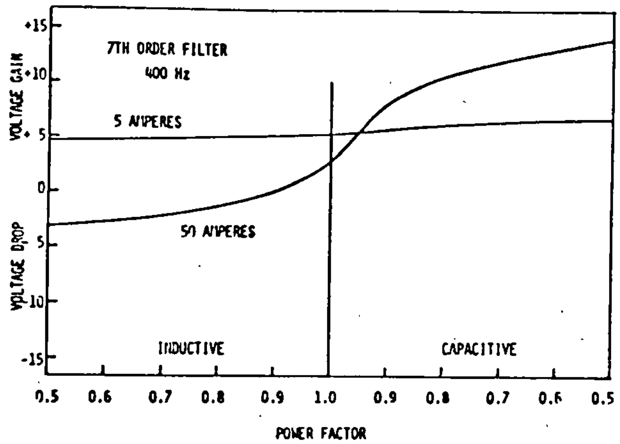


Figure 28

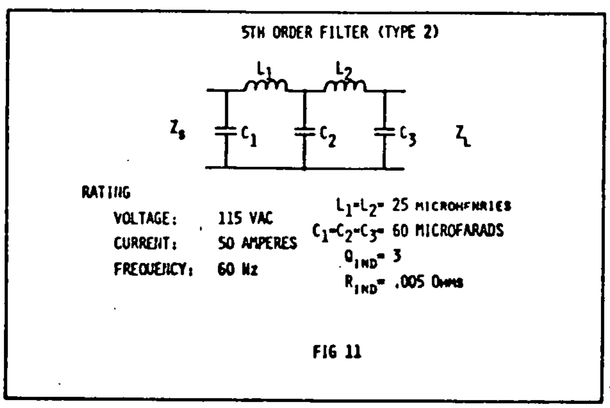


Figure 29

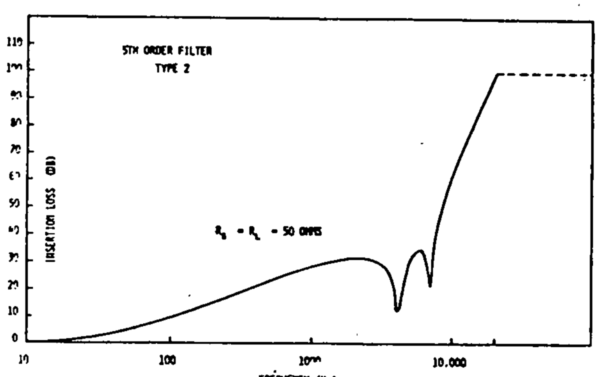


Figure 30

The insertion loss performance of this filter is shown in Figure 30. Note that its cutoff frequency is higher than that of the (type 1) 5th order filter thus allowing for the reduction in series arm inductance values. Observe what kind of performance this (type 2) 5th order filter gives under varying load power factor conditions. It is evident from Figure 31 that there is better performance under all conditions.

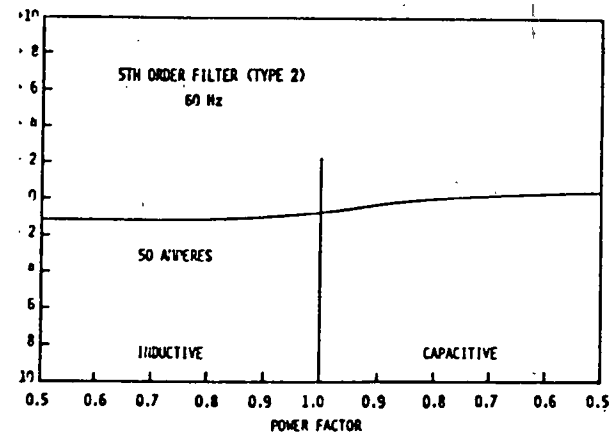


Figure 31

Though not shown here, this filter's 400 Hz performance is also better than previous filters discussed. One may be inclined to simply increase the capacity values of this last filter thereby causing the filter to exhibit the desired insertion loss in the 10 KHz to 12 KHz region. However, in order to achieve 100 dB insertion loss at approximately 10 KHz using a 5th order filter with 25 mh series arm inductors, would require 200 mf capacitors in each of the 3 shunt legs of the filter. Filter capacitors of this value for power line filter application are not practical.

In summary, the important points are:

1. A filter is an impedance sensitive device and exhibits certain unique performance characteristics under varying impedance conditions. If ignored, this performance can result in significant system damage and/or malfunction.

2. The user and more importantly the person specifying a filter should be aware of these performance characteristics. When in doubt, contact the Enginneering Department of a reliable and experienced filter manufacturer before specifying something that may not be achievable or may not be practical from a cost standpoint.

3. Examine carefully filter insertion loss needs before specifying. Try to relate insertion loss requirements to system needs rather than traditional needs. A great deal of money can be saved and better filter performance achieved by specifying lower insertion loss requirements in the 10 KHz to 100 KHz frequency range. These requirements, should be "in system" insertion loss requirements where possible which would mean evaluating the filter's insertion loss and regulation performance under more realistic impedance conditions. This can usually be accomplished without degrading system performance.

4. Most reliable, experienced filter manufacturers build filters in accordance with the environmental requirements of MIL-F-15733. More stringent requirements cost more money. It is easy to over specify especially if one is not thoroughly familiar with operational filter characteristics. Again, when in doubt, contact a reliable filter manufacturer.

The material on Filter Design was provided by Dale Knox, Engineering Manager, Filter Division, Cornell-Dubilier Electronics. The material on the Effects of a Filter on a System was provided by Stanley B. Clewell, Operations Manager, Cornell-Dubilier. Reprinted by permission. The remaining material on filters was excepted from Chapter 4.4 "Filtering and Buffering" of the proposed "Guide for the Installation of Electrical Equipment to Minimize Electrical Noise Inputs to Controllers from External Sources". The Guide is prepared by the Electrical Controlled Systems Sub-Committee of the IAS of the IEEE, chaired by George Younkin of the Gidding & Lewis Machine Tool Company. The technical material was written by Dr. Heinz Schlicke, Allen Bradley Company.