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.

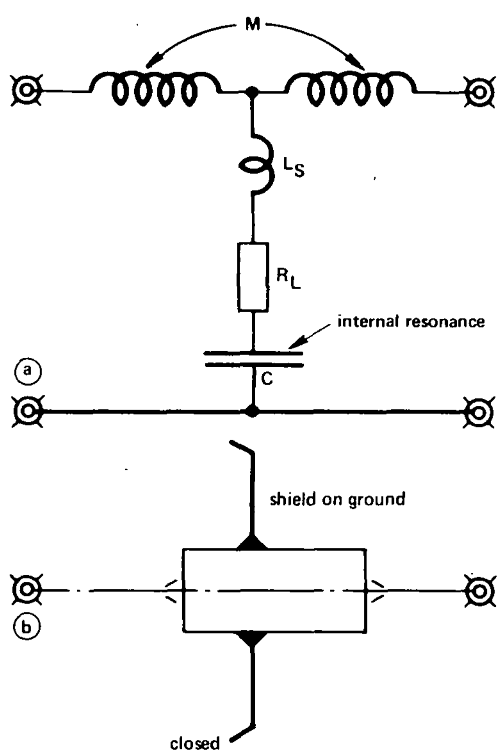

Figure 1

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

(b) Feed-thru configuration.

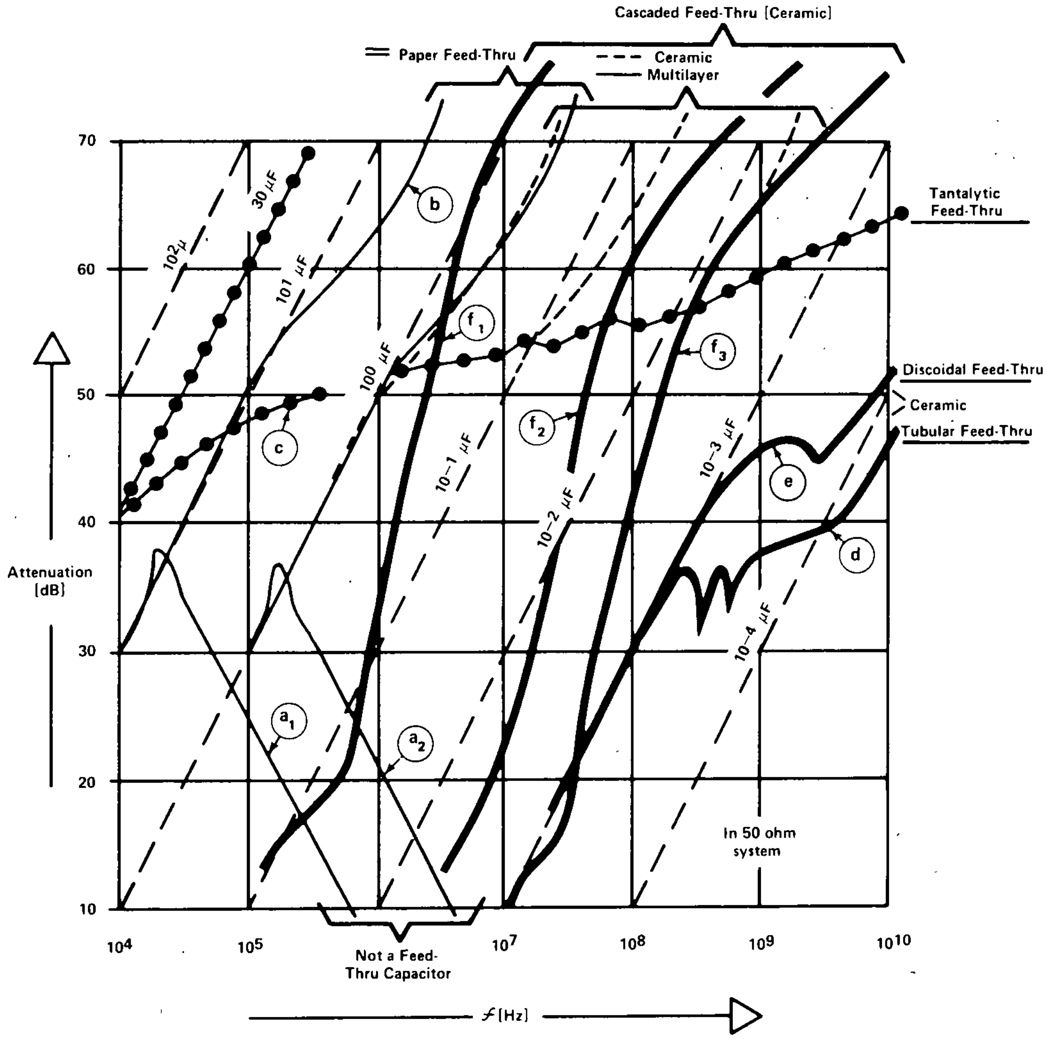

Figure 2 Attenuation of So-Called Capacitors

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. Figure 3 portrays the spread of actual filter performance as caused by the variation of the interface impedances encountered. It may be +3 dB's to -40 dB's, in some cases even quite a bit more, different from the value predicted by MIL-STD-220A.

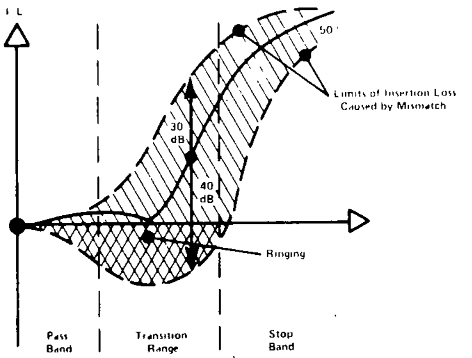

Figure 3 The Effects of Mismatch

The shaded area in Figure 3 is bounded by the upper and lower limits of insertion loss (attenuation under the influence of mismatch). At high attenuation levels, the bounds of insertion loss do not differ much from the attenuation curve. Hence, for high attenuation, the filter prediction made in a 50 ohm system can be considered somehow realistic. But, it is the transitional range and the pass band where mismatch can play a deleterious role.

Even insertion gain, or a negative insertion loss, can result because of interfacial and eigen-(self) resonances. This insertion gain is also called ringing of the filter. Such resonances can be quite annoying. For instance, ringing, normally in the audio or ultrasonic frequency range, can be so pronounced (Figure 4) that SCR's misfire. It is often advisable to include small resistors (preferably carbon composition resistors for long term stability under pulse conditions) to dampen such resonances. Lossy inductors are suitable, too. Unfortunately, lossy filters for lower frequencies are not yet commercially available. Rather, it will be shown that proper filter selection is often sufficient to reduce ringing to acceptable levels.

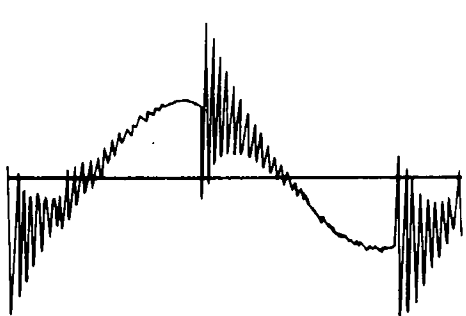

Figure 4 Typical Ringing

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). From this source, Figure 5 is reproduced, which describes the basic diagram of a DC line filter that reduces randomly switched load current pulses in the order of 10 milliseconds and amps to wiggles in the milliamp range on the supply side.

c. Quasi-RC-Filtered Switches: Electro-optical isolators (Figure 9a) for which the light path is interrupted or opened by a movable, isolated obstruction and for which the light sensor consists of slowly reacting cadmium-sulfide, act as bounce- and interference-free switches having moreover the advantage of isolation.

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. Figure 6, taken from bibliography (1), marshals the regulation and filtering performance of 3 types of ferroresonant transformers: alpha is an optimized ferroresonant filter-regulator having excellent regulation and filtering in contrast to the conventional ferroresonant transformer gamma. Beta is a somehow improved ferroresonant transformer, having high reactive current and poorer regulation and, also, as does beta behaving very poorly (collapsing) by half cycle interrupts (curves e with 1/2 cycle interruption, meaning that 1/2 cycle is clipped off the primary voltage, as it may happen, for instance, with lightning arrestors). This 1/2 cycle interruption is an extreme case of notching as, for instance, caused by SCR switching which is also eliminated only satisfactorily with version alpha.

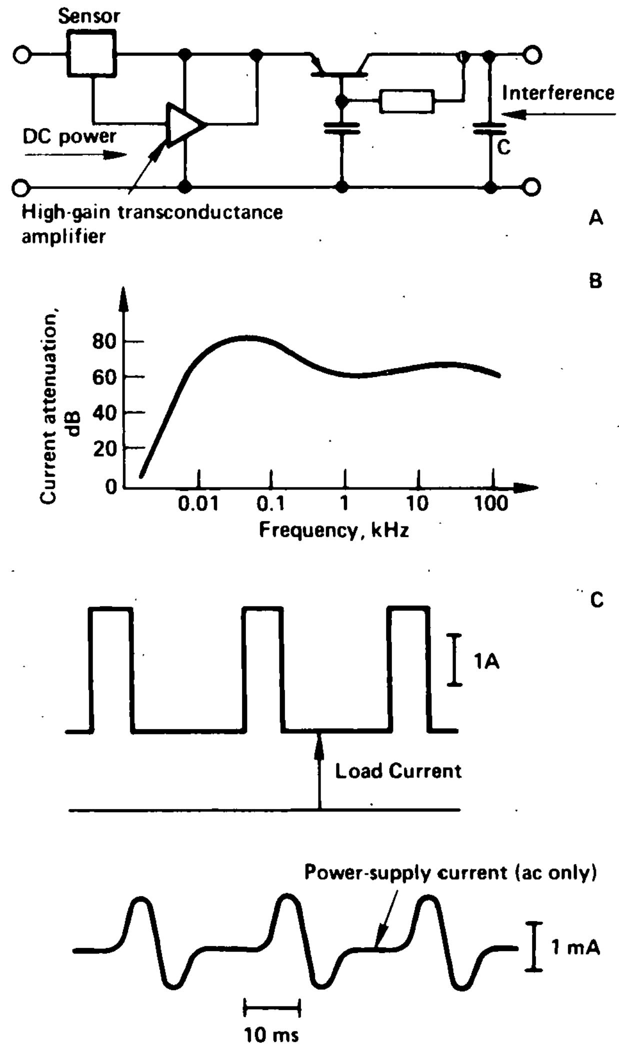

Figure 5. Randon-Pulse Filter A—Basic Circuit for wide-band attenuation. B—Current-attenuation curve. C—Attenuation of 20 Hz, 2.5 ampere current pulse.

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 nonlinear 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.

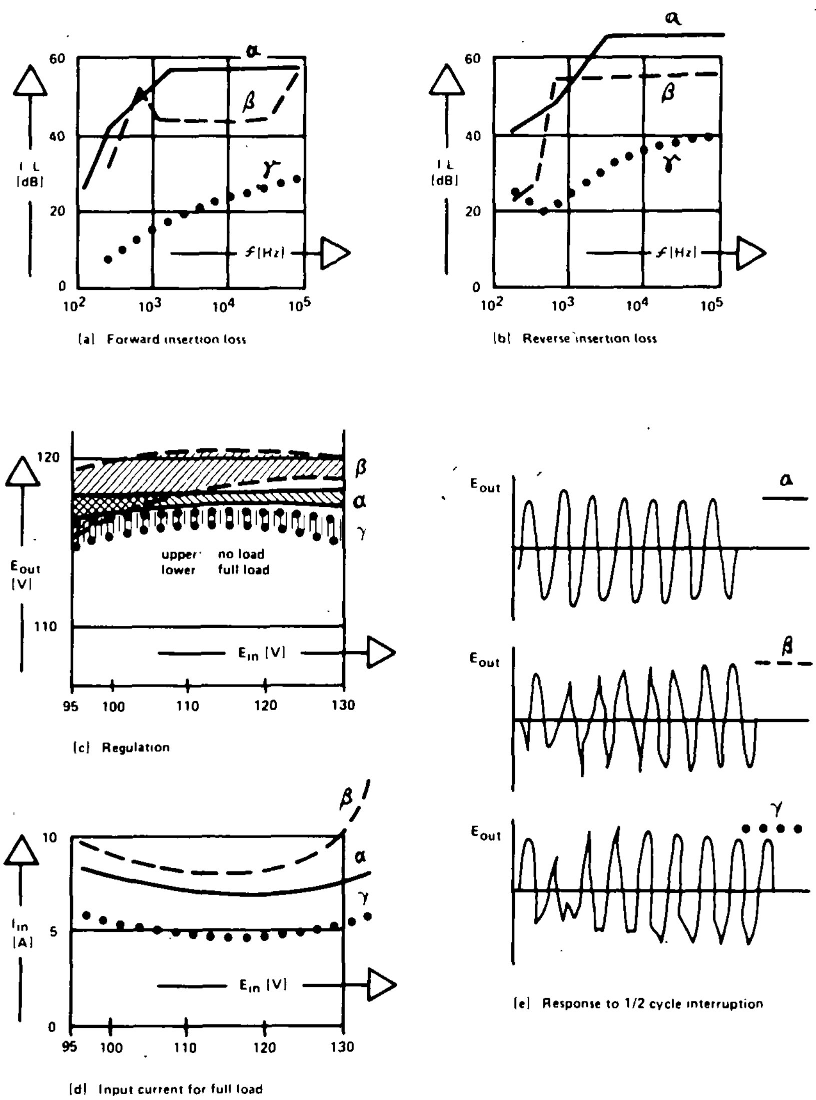

Figure 6 Juxtaposition of Key Data of Three Magnetic Core Filter-Regulators

To remove signals from completely masking noise, with signal and noise power spectrum completely overlapping, one exploits, expressed very simply, the fact that noise averaged in time or for different ensembles or if correlated (compared at different times) cancels out to zero (assuming white noise). The signal, in contrast, if averaged or correlated (with itself: auto-correlation or with a co-periodic other signal: cross-correlation) either reveals its original shape (averaging) or at least its presence and period (missing phase relations changes signal appearance in correlation analysis).

For digital signals, matched filters are matched to the signal form and respond essentially only to the signal for which the filter is matched, telling whether or not the signal is there.

Whenever something is known about the signal, phase-locked loops can detect signals 30-40 dB's below the noise level. And if one takes sufficient time, averaging or correlating filters can extract signals from noise of unbelievably poor signal to noise ratio.

Just to give an example: Figure 7 shows a signal completely emerged in noise. After a thousand averaging at proper timing (required prior knowledge of signal: periodicity), the extracted signal becomes quite obvious, to become essentially perfect with an increase in time.

Impulsive noise in digital systems (with the exceptions of cases discussed before) is difficult to suppress once it reached critical signal or control lines. Hence, coupling into critical lines must be avoided (see also isolators for suppressing common mode spikes).

If operation in a high noise environment is to be expected, it is best to select from the very beginning, a system into which "filtering" has been designed as a systems mode. Typical examples are the incorporation of redundancy, error correcting codes, etc., which serve to minimize the probability of error.

DIRECTIONAL OR MODE FILTERS

In lines (wire pairs) one normally talks about a forward and a return wire (normal mode). Quite often, however, one encounters common mode (c.m.) propagation, mostly caused by multiple grounds, and consisting of noise current flow in the same direction for both wires. Figure 8 depicts the common mode as contrasted to normal mode and also some effective remedies to suppress the common mode propagation.

Since the current flow provided by the normal mode does not create any biasing effects for the inductors, the common mode filters, baluns, or ferrite slugs do not become saturated and, hence, can be held quite small.

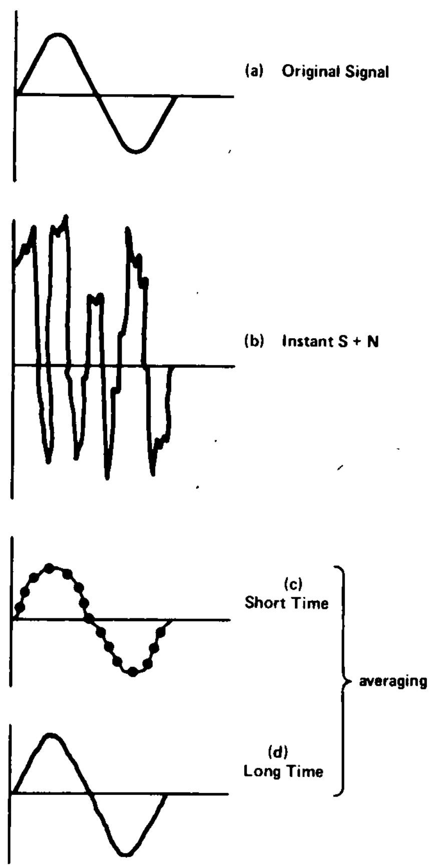

Figure 7 Extracting Signal by Averaging

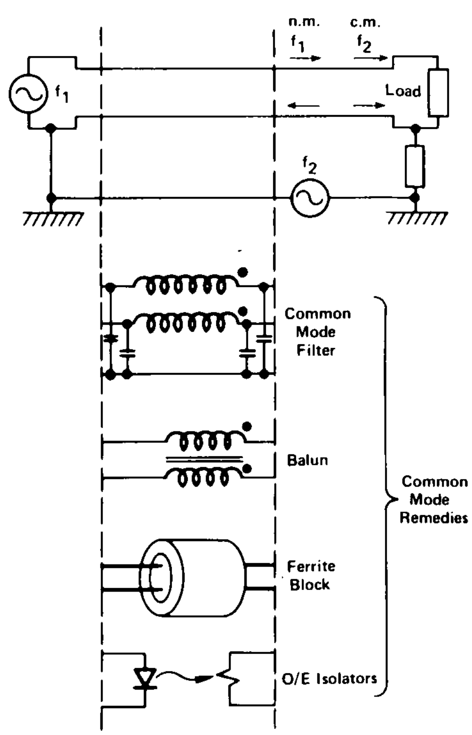

Figure 8
Common Mode Operation & Some Remedies

(Not shown are isolation transformers and high-common-mode-rejection operational amplifiers.) In this context, we refer to Figure 6a and b, which show the normal mode insertion loss of isolation transformers, the common-mode-rejection of which is extremely good particularly at the low frequencies.

Optoelectric isolators, Figure 9, quite often use light-emitting diodes for long life (in contrast to lamps) for the light source. Three basic light receivers are available: (a) for low speeds (for details see Figure 9) CdS sensors are most desirable because they also eliminate transients of the normal mode. For higher speeds, versions b and c using silicon receivers are indicated. Linearity, important in signal lines has to be checked.

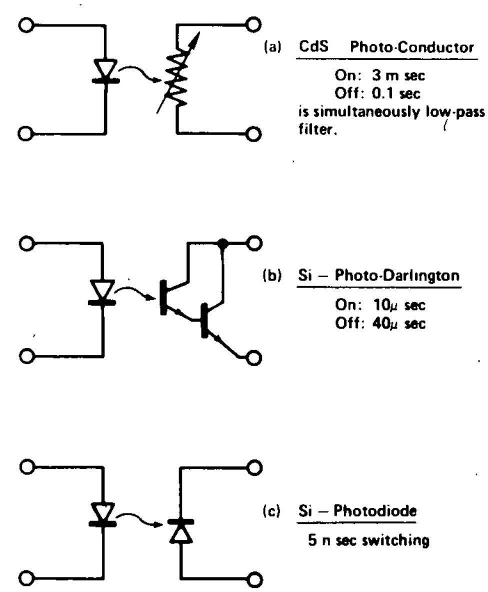

Figure 9
LED Operated Electro-Optical Isolators

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