The Use Of Ferrites In EMI Suppression

Properties Of Ferrites

Introduction

Ferrites are a class of ceramic *ferromagnetic* materials that by definition can be magnetized to produce large magnetic flux densities in response to small applied magnetization forces. Originally referred to as "magnetic insulators," ferrites were first used as replacements for laminated and slug iron core materials in low loss inductors intended for use above 100 kilohertz (kHz). At these frequencies, laminated and slug iron are plagued by excessive eddy current losses whereas the high volume resistivity of ferrite cores limit power loss to a fraction of other core materials. Today, Steward ferrites are the core material of choice for modern high density switch mode power supply and pulse transformer design.

Fundamental Properties

While frequently nicknamed "magic beads" in marketing literature, EMI suppression ferrites are actually well understood magnetic components. Ferrites intended for EMI applications above 30 MHz are mixtures of iron, nickel and zinc oxides that are characterized by high volume resistivity (10^7 ohm-cm) and moderate initial permeability (100 to 1500). 600 ohms, and becomes essentially resistive above 100 MHz. When used as EMI filters, ferrites can thus provide resistive loss to attenuate and dissipate (as minute quantities of heat) high frequency noise while presenting negligible series impedance to lower frequency intended signal components. When properly selected and implemented, ferrites can thus provide significant EMI reduction while remaining "transparent" to normal circuit operation! For high frequency applications, ferrites should be viewed as frequency dependent resistors. Since they are magnetic components that exhibit significant (and useful) loss over a bandwidth of over 100 MHz, ferrites can be characterized as high frequency, current operated, low Q series loss elements. Whereas a purely reactive (i.e., composed only of inductors and capacitors) EMI filter may induce circuit resonances and thus establish *additional* EMI problem frequencies, lossy ferrites cannot. In fact, ferrites are often used in high frequency amplifier design and power supply design to prevent or significantly reduce unintended high frequency oscillations.

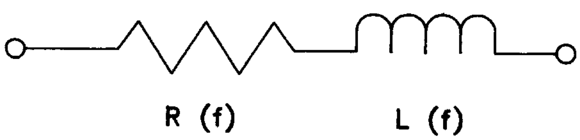

FIGURE 10: Simple equivalent circuit model of a two terminal ferrite bead

Ferrites are most frequently used as two terminal circuit elements, or in groups of two terminal elements. The unique high frequency noise suppression performance of ferrites can be traced to their frequency dependent complex impedance, as shown in Figure 10. At low frequencies (below ~10 MHz), a Steward type chip bead presents a small, predominately inductive impedance of less than 100 ohms, as shown in Figure 11. At higher frequencies, the impedance of the bead increases to over

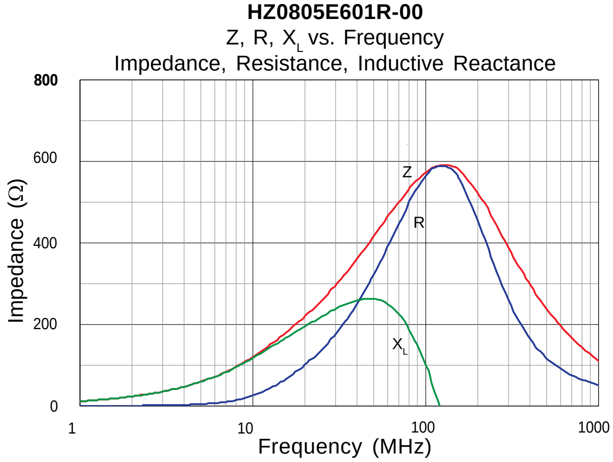

FIGURE 11: Typical impedance versus frequency characteristics of Steward high impedance chip bead

A Closer Look At Ferrite Impedance

The previously described complex impedance of ferrites can be analyzed further if the situation considered is limited to small applied magnetization forces (i.e., small forward current, few turns of conductor around/through the core). In such cases, the application of incremental increases in magnetizing force **H** to a ferrite will result in a corresponding increase in magnetic flux density **B** in the core. This operation typically displayed graphically via a devices **B-H** curve, as shown in Figure 12.

dependent series complex relative permeability

$\mu''(f)$ = the imaginary component of the frequency dependent series complex relative permeability

K = a constant corresponding to the number of windings and the core dimensions

μ_o = permeability of free space

ω = radian frequency = $2\pi f$

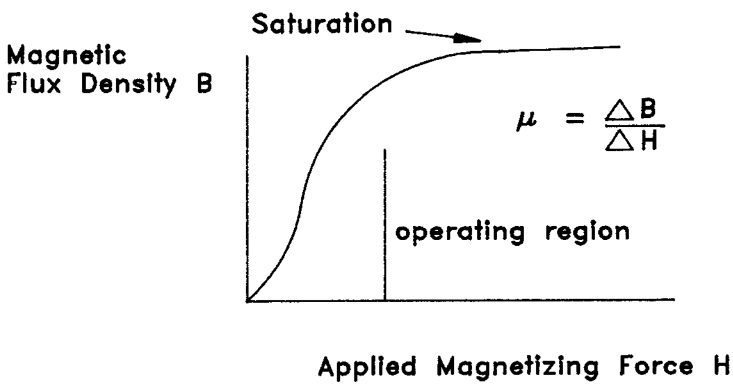

FIGURE 12: Virgin B-H curve for a typical ferrite

With the previously mentioned restrictions, the impedance of a given ferrite bead or core can be expressed as:

$$Z = R(f) + j\omega L(f)$$

The frequency dependent loss term arises from the loss of energy incurred as a result of oscillation of microscopic magnetic regions (called *domains*) within the ferrite. The loss and the ferrite impedance can be expressed in terms of a complex permeability as:

$$Z = K\{j\omega\mu_o\,[(\mu'(f) - j\mu''(f))]\}$$

$$= K\omega\mu_o\mu''(f) + jK\omega\mu_o\mu'(f)$$

$$= R(f) + j\omega L(f)$$

where:

$\mu'(f)$ = the real component of the frequency

The loss tangent (tan d) of a ferrite material can be defined as the ratio of the imaginary part to the real part of the material's relative permeability.

$$\tan d = \frac{\mu''(f)}{\mu'(f)}$$

Figure 13 gives a graphical representation of the loss tangent. As is true with the permeability, the loss tangent is frequency dependent. The loss tangent is an intrinsic property of a given ferrite material formulation. Choosing a particular ferrite material corresponds to choosing a particular loss tangent and an associated impedance versus frequency characteristic.

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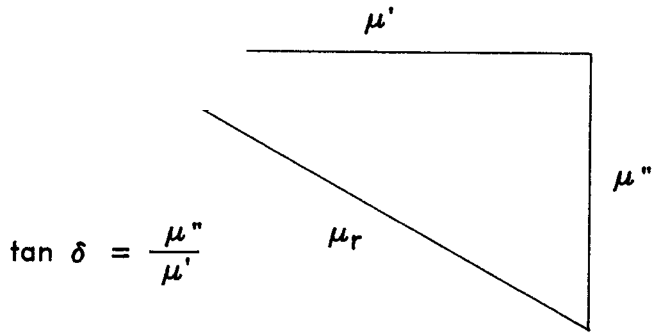

FIGURE 13: Graphical representation of the loss tangent

DC & Low Frequency AC Bias Effects And Saturation

The performance of any magnetic material will be degraded if it is operated under large DC or low frequency AC bias. Under "small" bias conditions, increasing the applied magnetomotive force F applied to a magnetic core device induces a corresponding increase in magnetic flux F in the core. At some value of F the magnetic flux F stops increasing; increasing F beyond this value results in a rapid decrease in the permeability of the part. For this condition magnetic theory terms the device's core *saturated,* as it is unable to support further increases in magnetic flux with increasing magnetomotive force input.

To illustrate, saturation may occur if a ferrite core is placed around a single output wire of a DC power supply as shown in Figure 14. In this situation, the core will experience a large DC magnetizing force. If the current is sufficient, the core will operate in the *saturation region* of its **B-H** characteristic, as shown in Figure 12. Since the slope of the **B-H** curve is nearly flat (=0) in saturation, the instantaneous relative permeability (equal to the slope at the operating point) of the core will drop to a value of approximately 1, or that of free space. Since the desirable lossy characteristics of EMI suppression ferrites require core permeability >>1, the core will provide little noise attenuation if operated near or in saturation.

When operated at DC bias currents greater than zero but less than the saturation bias value, EMI suppression ferrites will maintain a large lossy impedance. Since high frequency EMI filter applications depend on the lossy component of a ferrite's impedance, it is possible to use a ferrite effectively even with a significant net DC or low frequency magnetomotive force input. Many Steward EMI suppression ferrites maintain useful lossy impedance with forward bias currents in excess of 4500 milliamperes. Empirical impedance versus forward DC current information is provided for several Steward ferrite part families to aid applications requiring operation under large DC bias and/or low frequency AC bias.

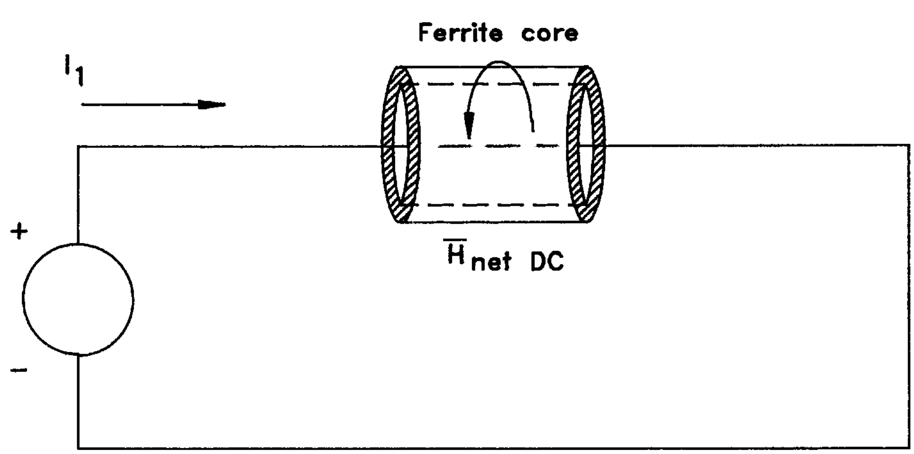

FIGURE 14: Ferrite core under DC Bias

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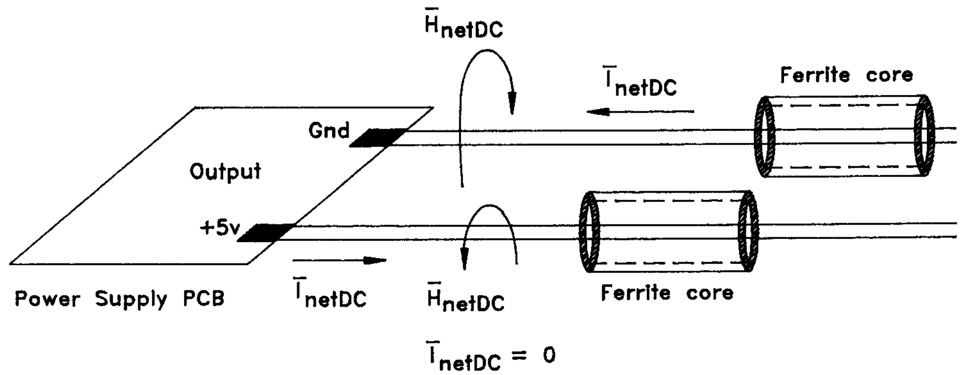

FIGURE 15: Incorrect usage of cable ferrites to filter conductors carrying large DC components

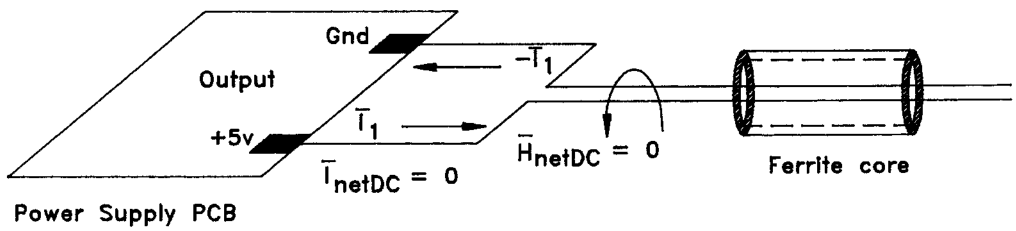

FIGURE 16: Correct usage of cable ferrites on DC carrying conductors

DC & Low Frequency AC Bias Effects in a Board Level Application

Steward ferrites deliver maximum series impedance under zero DC and low frequency AC bias; i.e., when zero net flux is induced into the device by circuit bias currents. Since EMI suppression ferrites are frequently used to filter common mode EMI on conductors carrying DC or AC power, they should be applied so as to encircle pairs or groups of conductors that carry equal and opposite (balanced) low frequency (e.g., 60 Hz) alternating and direct currents. For example, suppose an EMC engineer wishes to reduce the high frequency noise on a DC power supply output cable. The engineer proposes two solutions. The first implementation, shown in Figure 15, employs two ferrite cores, one for the +5 volt conductors, and one for the “ground” or power return conductors. In this case, each ferrite will be subject to a large net DC bias, which will result in a large reduction in the high frequency impedance of the ferrite, and a corresponding reduction in EMI suppression performance. In the second implementation, displayed in Figure 16, equal numbers of +5 volt and “ground” conductors are passed through a single ferrite. In this instance, the ferrite “sees” equal and opposite DC currents and thus zero net magnetic flux density. The ferrite will be able to provide maximum series impedance for high frequency common mode currents and remain unaffected by the DC operation of the encircled conductors.

Some applications may not permit a ferrite to operate under zero bias. While ferrites can still function as lossy elements with non-zero DC and low frequency flux densities, the user must be aware that the impedance of the device will decrease under such bias. This drop in impedance can be easily compensated by increasing the mass of the part. To aid the designer with non-zero bias applications, Steward provides impedance versus DC bias current information for all applicable component families. Figure 17 shows the impedance versus DC bias behavior of the Steward Part Number HZ0805E601R-00.

The Use Of Ferrites In EMI Suppression

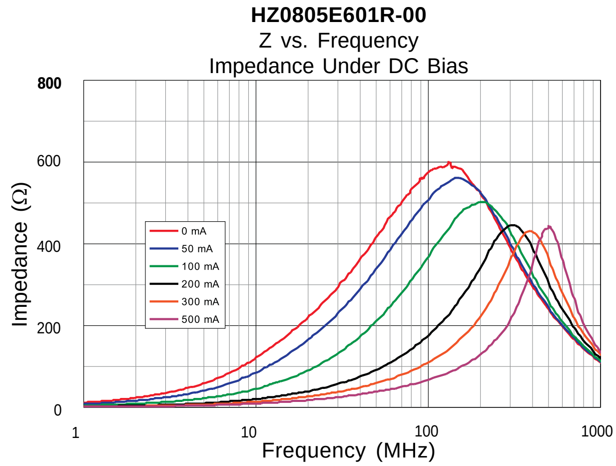

FIGURE 17: Impedance versus DC bias behavior

Ferrites For EMI Suppression On PCBs

Attacking EMI Problems At The Source

A fundamental EMC design principle requires that EMI be attenuated at its source on the PC board. This strategy confines noise to the small regions of a given PC board and reduces the possibility that high frequency noise will couple to other circuits (often called receptor or victim circuits) that may radiate the noise more efficiently through interconnecting wires or openings in a product's shielding. Attacking EMI at the source generally provides the most cost effective design approach, since filtering is targeted only to a few specific noise generating circuits, rather than to every single possible noise receptor in the entire product. Effective source filtering also helps limit overall EMC design costs by reducing the need for additional shielding that would otherwise be necessary to confine unfiltered high frequency noise components.

Noise On The PC Board Power & Ground Distribution Network

PC board generated EMI originates from the periodic switching of digital circuits. A simple noise model of a digital integrated circuit (IC) is shown in Figure 18. Each time the IC output switches state, it causes high frequency current to flow from the PC board power distribution bus (Vcc and "ground"). This action will introduce a small differential noise voltage drop, or "sag," across the board's power bus. Since this process will repeat with each transition of the IC's output, the noise that is induced on the PC board power and "ground" will oscillate at a frequency equal to the operating frequency of the IC. Additional IC's that reside on the PC board will "see" this noise voltage and couple it to other areas of the system. Power supply and data cables that are connected to the PC board power and ground bus will also transport and radiate the IC switching noise throughout and outside of the system.

The Use Of Ferrites In EMI Suppression

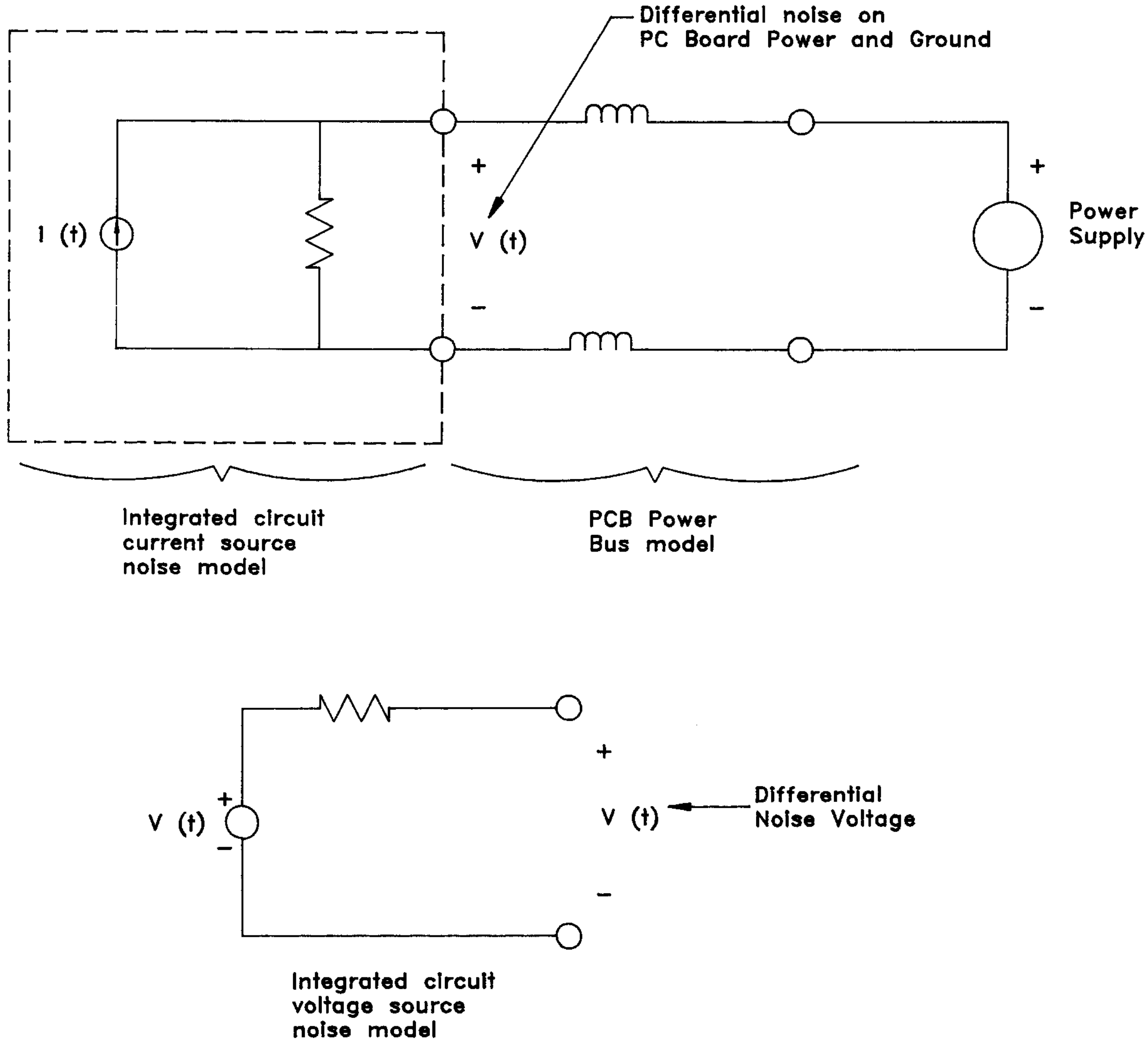

FIGURE 18: Noise voltage and current source models of an integrated circuit on a PC board

We can generalize this power bus noise voltage problem by modeling the PC board power bus as a lumped impedance through which active devices (integrated circuits, for example) draw high frequency current. An ideal board impedance would have a value of zero ohms, i.e., an active device could draw infinite switching current yet introduce no significant differential noise voltage to the PC board bus. This ideal situation is never achieved in

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practice. To reduce the magnitude of the board impedance, circuit designers add decoupling capacitors across the power and ground conductors of the PC board in an attempt to provide a "local" source of charge for each active device. This technique can also be viewed as placing a high frequency "short circuit" across the active device's power and ground pins, as shown in Figure 19.

While decoupling capacitors may provide adequate noise filtering at frequencies up to 75 MHz, their performance at higher frequencies will be dramatically reduced by the presence of circuit resonances. These resonances arise from the interaction of the decoupling capacitors with device lead and interconnect inductance in essence, capacitors become functional inductors at higher frequencies. Many EMC engineers have observed and solved frustrating noise problems that arise unexpectedly from unique combinations of noise frequencies, PC board layouts and decoupling capacitors.

Filtering The Power Input Pins Of Active Devices With EMI Suppression Ferrites

While the resonant behavior of decoupling capacitor arrangements limits their effectiveness at higher frequencies, the performance of Steward ferrites actually *improves* with increasing frequencies. Since Steward EMI suppression ferrites present an essentially resistive (lossy) impedance at high frequencies, they cannot by themselves introduce performance limiting circuit resonances. When used in conjunction with decoupling capacitors, ferrites can provide additional EMI source suppression by blocking and dissipating power bus noise generated by high speed logic devices. Note that a capacitor still must be used at the power input pin of the active device, since the ferrite by its nature will block the high speed switching current that the device requires to operate. Figure 20 shows an example of a ferrite bead and capacitor filter that is often used in personal computer clock oscillator circuits.

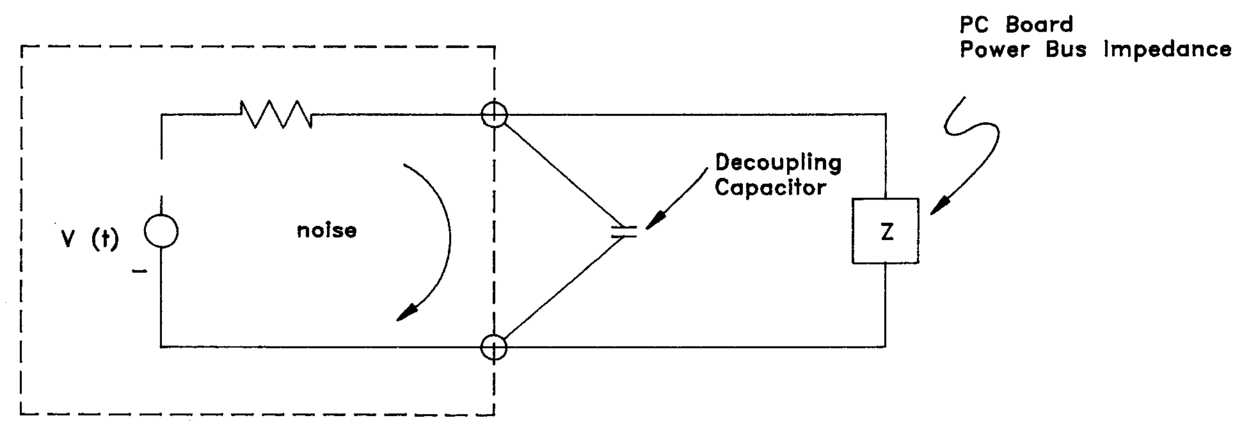

FIGURE 19: PC board noise model with board impedance, integrated circuit, and decoupling capacitors

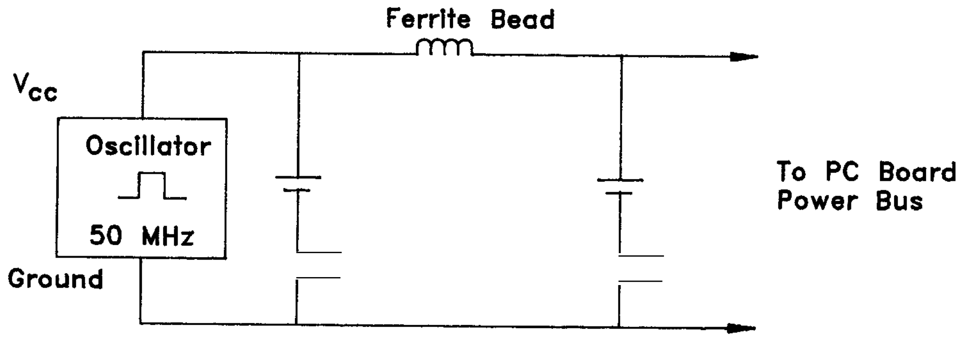

FIGURE 20: Ferrite and decoupling capacitors for high frequency DC power filtering

Note that this application subjects the ferrite to a net DC bias current. As discussed in the previous section, the impedance and resulting noise attenuation of a ferrite drops with increasing net DC or low frequency AC bias current; therefore, the amount of attenuation obtained from a ferrite DC filter circuit will depend upon the current requirements of the active device and the impedance versus forward DC current characteristic of the ferrite. Complete information on impedance versus DC bias current characteristics is provided for the Steward part families that are subject to DC bias in typical applications.

Filtering DC Power To Multiple & Individual PC Boards

Time-to-market design pressures have inspired a new generation of modular electronic products whose features can be easily upgraded with cost-effective interchangeable PC boards. For successful EMI control of such product architecture, EMC engineers must design in a type of "configuration independence" in which any possible combination of product features and hardware options will always pass mandatory U.S. and international EMI requirements. Since high frequency noise is often produced on and conducted through a PC board's power distribution bus, the tendency of interchangeable circuit boards to create EMI problems can be substantially reduced by filtering the power input to each circuit board, as shown in Figure 21.

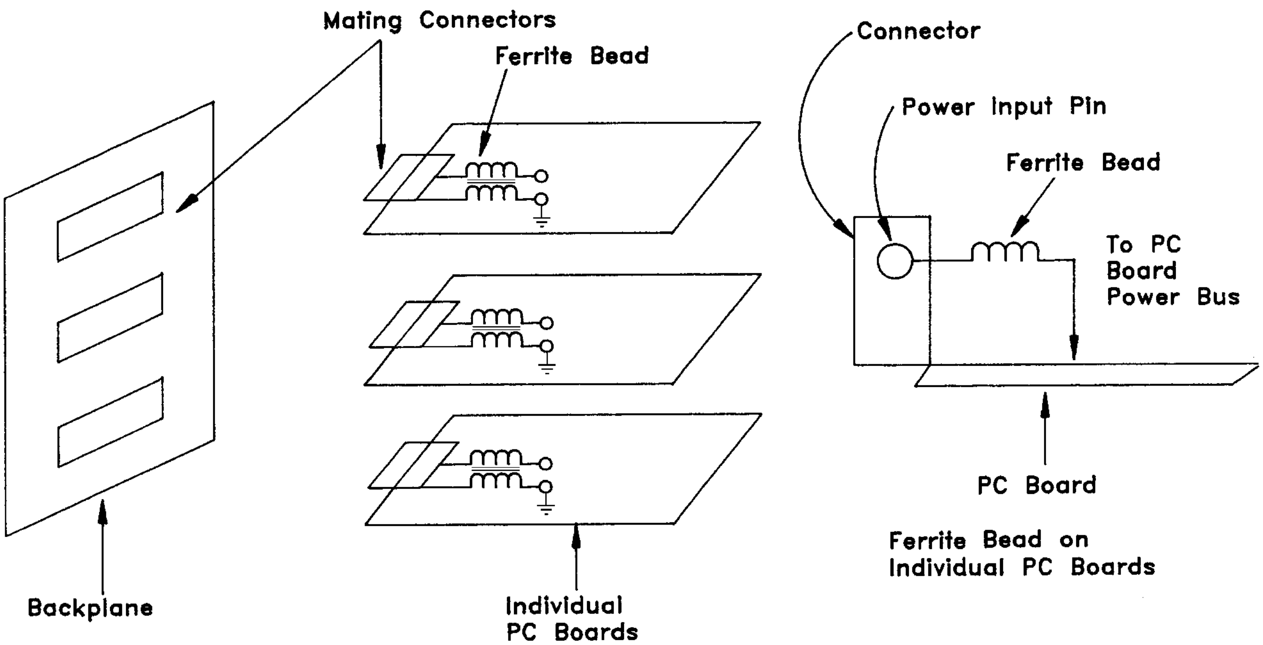

FIGURE 21: Using ferrites to filter the DC power input of interconnected PC boards

The Use Of Ferrites In EMI Suppression

This design approach can also substantially reduce "common frequency" type problems where the noise output of multiple circuit boards with identical operating frequencies combine at one or more frequencies to create large radiated emission test failures. Examples of DC power filtering can be found in notebook computers, where external battery packs, AC adapters, and facsimile, printer, and other communication options must connect to an "EMI-noisy" main system module. Other applications include backplane/daughter board arrangements as found in low cost computer network hardware, where multiple PC boards receive power and data from a single high frequency backplane arrangement.

Since the described DC filter applications will subject the ferrite components to DC bias current, the maximum in-circuit impedance (and hence maximum noise attenuation) achieved will be less than that obtained under zero bias conditions. For acceptable performance in power applications, the larger, higher current Steward common mode multi-line devices and multiple aperture devices are recommended for PC board power filtering. In applications involving DC bias above 300 milliamperes, the greater cross-sectional area and higher zero bias impedance of these devices will provide better performance than smaller radial and surface mount devices.

A common mode choke is a superior solution, due to it's independence from DC/AC bias effect over a single line differential mode product. For example, the CM4545Z131R-00 retains 96% of its performance from 0 to 10 amps.

Filtering Of Input/Output (I/O) Data Conductors

One of the most common and cost effective applications of ferrites is the filtering of conductors that must bring signals into and out of an EMI noisy environment such as the inside of a high speed personal computer enclosure. For example, energy radiated from a central processor (CPU) integrated circuit (IC) may couple into the "driver" IC that sends to and receives data from the system's external keyboard and mouse, as shown in Figure 22. The long external cables of these devices then radiate the noise that previously was confined to the shielded enclosure of the computer. Steward ferrites can be used between the driver IC and the keyboard and mouse connector to insert a large signal loss in series with the high frequency CPU noise on the data lines. Since the keyboard and mouse signals have essentially zero signal energy above 1 MHz, they will pass through the ferrite filter undisturbed. As shown in Figure 23, Steward multiline suppressor ferrites, CM3032 series, provide a compact means of filtering up to 8 data lines simultaneously, thus minimizing filter part count and assembly time as compared with that required for single data line filters.

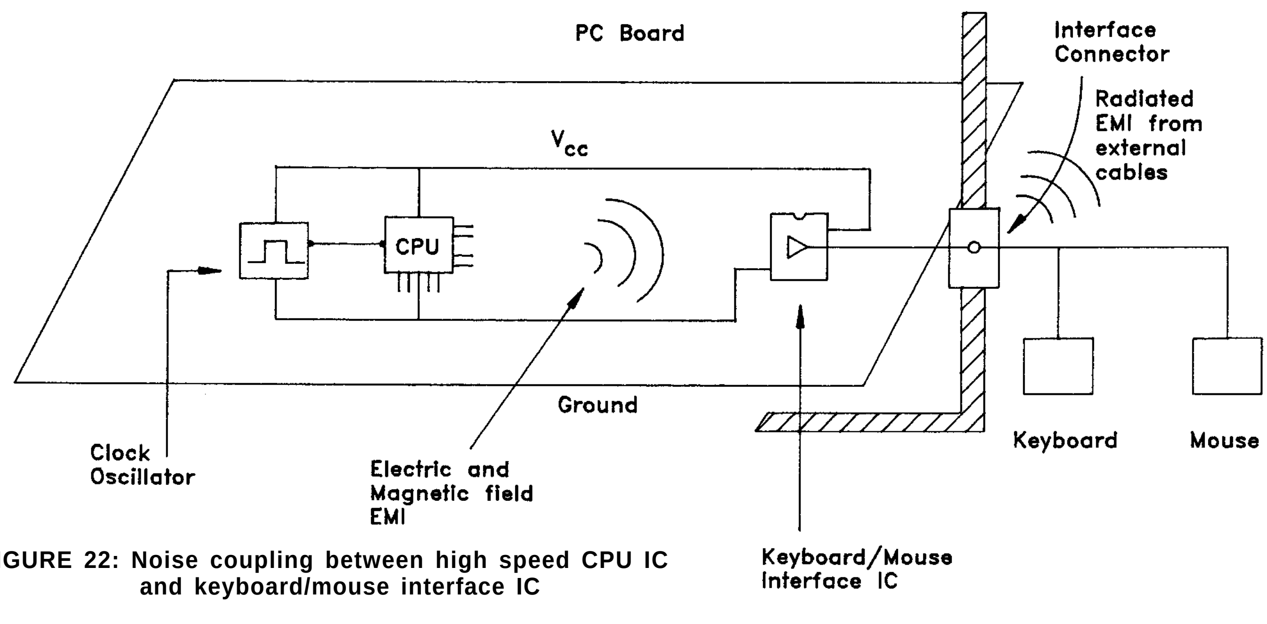

FIGURE 22: Noise coupling between high speed CPU IC and keyboard/mouse interface IC

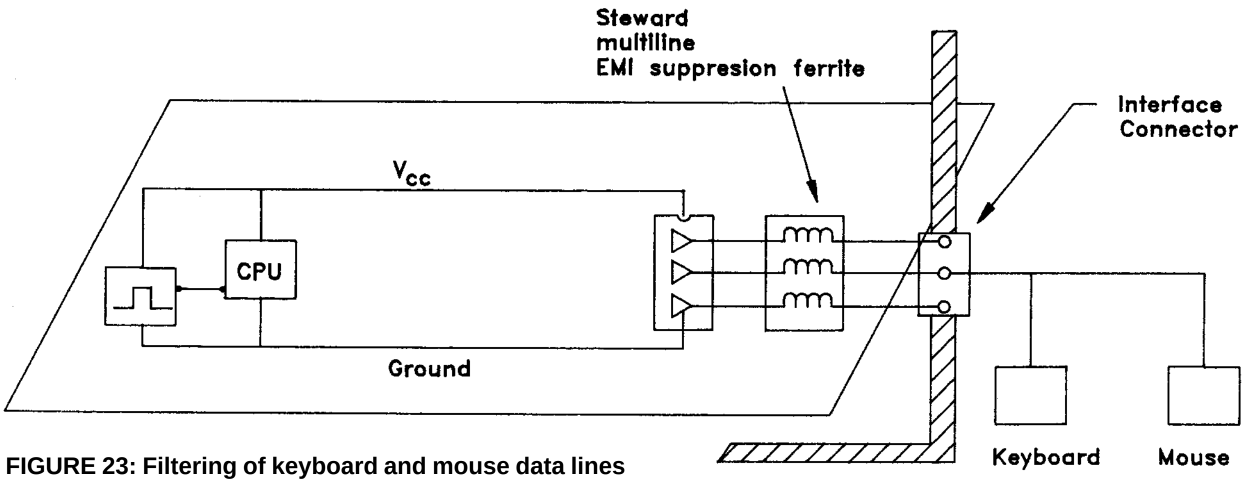

FIGURE 23: Filtering of keyboard and mouse data lines with Steward multiline ferrite

Ferrites For EMI Suppression On Cables

Introduction

Internal and external cable assemblies in computer equipment often act as miniature antennas as they transform noise voltages and noise currents into large sources of radiated EMI. Steward's line of ferrite beads for cable assemblies provide a cost effective approach to attenuate noise currents on flat and round cable bundles before they can be converted into radiated EMI.

Unshielded cable assemblies will radiate EMI due to the common mode noise that is present on their copper conductors. This noise is characterized by equal in phase high frequency currents that flow in the same direction along all the wires in the cables, as shown in Figure 24. These currents induce a net magnetic field with a specific magnitude and direction. Steward's cable ferrites attenuate the noise currents by "capturing" the magnetic field and converting a portion of its energy into heat. In terms of two terminal electrical device behavior, the ferrite is said to present a large lossy impedance to the common mode current. A Steward core used around a group of wires is common mode choke.

Internal Cable Assemblies

By reducing the EMI generated by cables inside the equipment, Steward ferrites can reduce the cost and amount of overall shielding required to confine EMI within a product's enclosure. Steward cable ferrites can be applied on internal power cables that carry direct current (DC), alternating current (AC), or analog and digital signals. Often, an upgrade will use a Steward common mode arrays (CM3032 series) as a replacement for an internal ribbon cable when it is desired to switch to a board mount solution.

External Cable Assemblies

Original equipment manufacturers (OEMs) use Steward ferrites to suppress EMI on external power and data cables for central processor units (CPUs), monitors, keyboards, printers, and other peripheral equipment. The long external power and data cables of these devices act as efficient antennas to transmit internally generated noise outside to the equipment's enclosure. By suppressing EMI on these cables, Steward ferrites can often reduce external cable shielding requirements, permitting the use of lower cost cables in many applications.

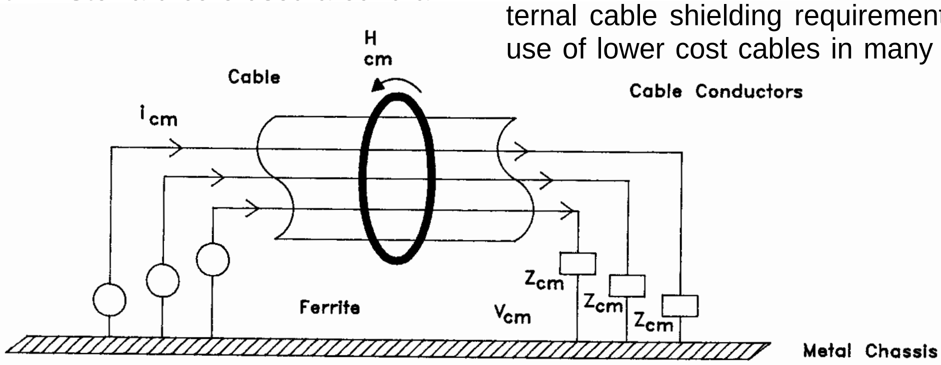

FIGURE 24: Ferrite on cable with common mode EMI

The Use Of Ferrites In EMI Suppression

Selecting Cable Ferrites For Optimum Performance

Precision electronic components such as Steward EMI suppression ferrites should be selected with consideration of the intended application. In general, a cable ferrite should be selected to yield the highest in-circuit series impedance for the noise frequencies of greatest concern. For Steward type 25, 28 and 29 materials, this highest impedance will correspond to a maximum in-circuit loss and maximum EMI suppression.

Core Size and Volume

Once the ferrite material and approximate part dimensions are selected for a given application, in-circuit impedance and noise suppression performance can be optimized by:

1) increasing the length of the portion of the conductor surrounded by the ferrite
2) increasing the cross sectional area of the ferrite (especially for power applications)
3) selecting a ferrite with an inner diameter most closely matching the outer diameter of the wire or wire bundle to be filtered

In general, the "best" ferrite for a particular application is the longest, thickest device that can be accommodated and whose inner aperture is closely matched to the outer dimensions of the cable to be treated. When installed on flexible cable harnesses, ferrite cores of significant mass should be encapsulated by heat shrink tubing or otherwise protected and secured in place.

Number Of Turns

The series impedance of a high frequency ferrite device can be increased by running two or more turns of the treated conductor through the ferrite's core. Magnetic theory predicts that the impedance of the device will increase with the square of the number of turns. However, due to the lossy and non-linear nature of EMI suppression ferrites, a ferrite bead with two turns will yield somewhat less than four times the impedance of an identical part wound with only one turn of the conductor. Since interwinding capacitance will increase along with the number of added turns, Steward recommends that a maximum of two conductor turns be wound on a single part. Increasing the number of turns beyond two will tend to degrade performance at higher frequencies where interwinding capacitance dominates the characteristics of the device.

Placement At The EMI Source Location Or AT I/O boundaries

In most filter applications, the ferrite should be placed as close to the source as possible. This will prevent the noise source from coupling to other structures where filtering may be less effective or difficult to implement. For input / output (I/O) circuits, however, where conductors may enter and exit a shielded enclosure, the ferrite should generally be placed as close as possible to the shield penetration. This implementation prevents noice from coupling to the conductor at a physical location in the enclosure "after" the filter. Figure 25 illustrates both filter placement techniques.

Choice Of Material

For EMI suppression applications, Steward offers four unique ferrite materials with three distinguishing parameters:

- Operating frequency of maximum impedance
- Frequency selectivity or broadness of maximum impedance versus frequency
- Volume resistivity

EMI filtering applications are seldom narrowband; applications usually require noise attenuation and hence a large lossy impedance over a broad range of frequencies. Type 28 material is generally the best choice for the filtering of cables or single line applications with wideband EMI problems above 30 MHz. For applications where maximum attenuation and series impedance above 200 MHz is critical and lower signal frequency impedance is required (as in 100 Base-T applications), Steward's type 25 material is the optimum choice. Finally, type 29 material is specifically formulated for multi-line packages to achieve a high volume resistivity of 10^8 ohms or more. This material is designed for use in circuits with un-insulated conductors and where stringent leakage current and / or breakdown voltage requirements exist.

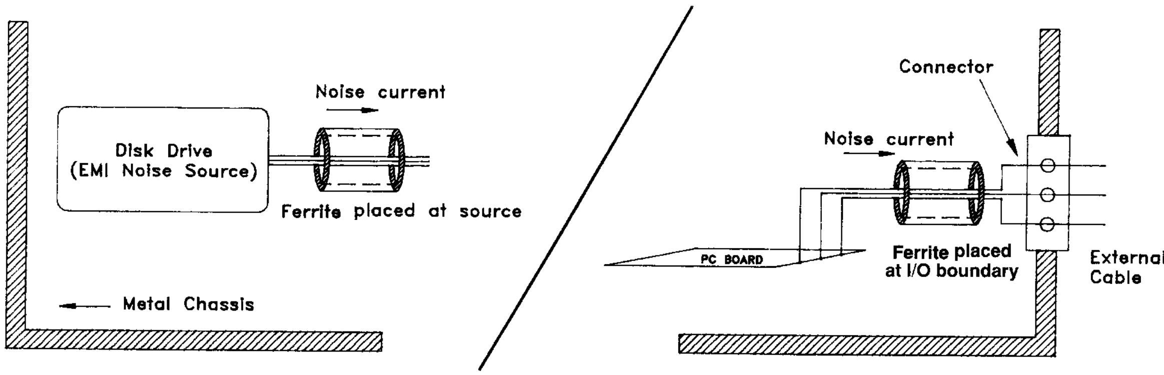

FIGURE 25: Placement of cable EMI suppression at the EMI source and at an I/O boundary

Protection From Shock & Vibration

Brittleness and vulnerability to physical shock are inherent characteristics of ferrites and other ceramic materials. Many customer applicatiions utilize EMI suppression ferrites in equipment that is subject to the shock and vibration of shipping, handling, and installation processes. When installed on flexible cable harnesses, ferrite cores of significant mass should be encapsulated by heat shrink tubing or otherwise protected and secured in place. Small surface nicks and chipping will not significantly degrade a ferrite's performance.

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