Powder Core Applications in High Performance EMI Filters

Tim Slattery,
Applications Engineer
The Arnold Engineering Company
Marengo, Illinois
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The use of molybdenum permalloy, 50% nickel-iron alloy and sendust-type powder cores in power filter inductors is presented. Power line filtering to reduce differential-mode conducted EMI is the featured application. The article begins with a simple explanation of filtering and an example that demonstrates the advantages of using more than one inductor in a filter design.

In addition, power loss and inductance stability with respect to operating current frequency and magnitude is compared between inductors made with the three different core types. Graphs of equivalent series inductance, equivalent series resistance and impedance versus frequency are used to show the effects of winding distributed capacitance and core material eddy currents.

This paper is a companion to “Powder Core Applications in Switching Amplifier and High Performance EMI Filters,” an article written by Donald E. Pauly and sponsored by The Arnold Engineering Company. It also complements “Power Supply Magnetics” (a three-part article) by Mr. Pauly and published in the January, February and March, 1996 issues of *PCIM Magazine*. Copies are available from The Arnold Engineering Company.

Multiple Pole Filters – Advantages

Filters as they apply to electrical and electronic power conversion systems are circuits with inductors and capacitors as elements. The arrangement and sizes of these elements are chosen so that only relatively low frequencies of electrical energy are allowed to pass. This creates a “low-pass filter.”

Filter design is quite complicated, requiring considerable knowledge of mathematics and computer-aided engineering as well as practical experience. The term “pole” refers to a theoretically infinite output response to input at a particular frequency. For the two filters that will be considered here, it is sufficient to identify the single capacitor and single inductor arrangement as a two-pole or single-stage filter and the combination of two capacitors and two inductors as a four-pole or two-stage filter. See Figure 1. The number of poles corresponds to the number of elements.

The nature of the circuits which are attached to the filter input and output (source and load impedances) have a profound effect on the frequency response. The filter poles are not seen as infinite responses because of damping

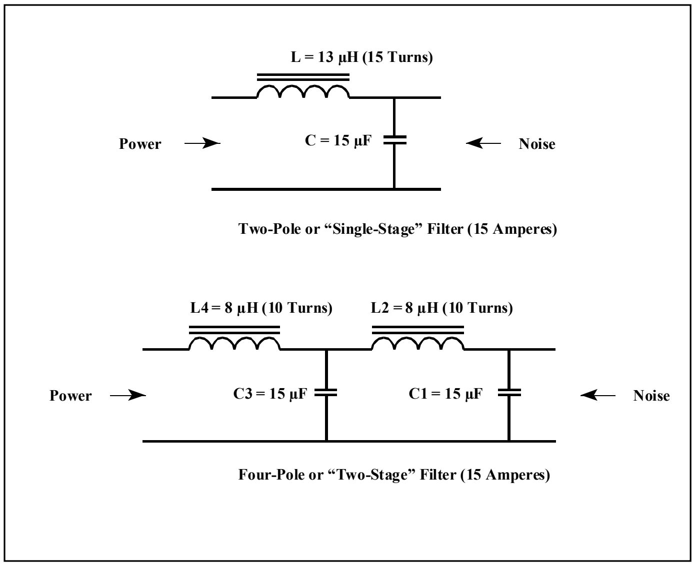

Figure 1. Two-Pole and Four-Pole Filters.

by the load and source. In practice, the filter elements include resistance associated with inductor winding and core losses as well as capacitor lead, electrode and dielectric losses. Higher frequency loss provides additional damping that is desirable for stability.[1] Also, parasitic elements such as capacitor lead inductance and inductor winding distributed capacitance influence filter performance. These parasitic elements are shown in Figure 2 along with the equivalent series resistance of the inductor, Rs, and capacitor, Rc.

Stand-alone constructions of the two types of filters for testing are shown in Figure 3 and Figure 4. The single-stage filter uses a 15 μF polypropylene capacitor and a 13.2 μH inductor. The inductor core is Arnold Engineering part number MS-130060-2, a sendust-type core with a permeability of 60. (Arnold manufactures and sells this type of core under the trade name Super-MSS™.) The conductor is made from three strands of 18 AWG magnet wire and results in a DC resistance of 4.5 mΩ.

The two-stage filter uses two of the same 15 μF capacitors as in the single-stage design. Each of the two inductors has a value of 7.95 μH and is based on a smaller core of the same material and permeability, Arnold part number MS-106060-2. The conductor is the same size as for the larger inductor but only ten turns are used. The total resistance for the inductors

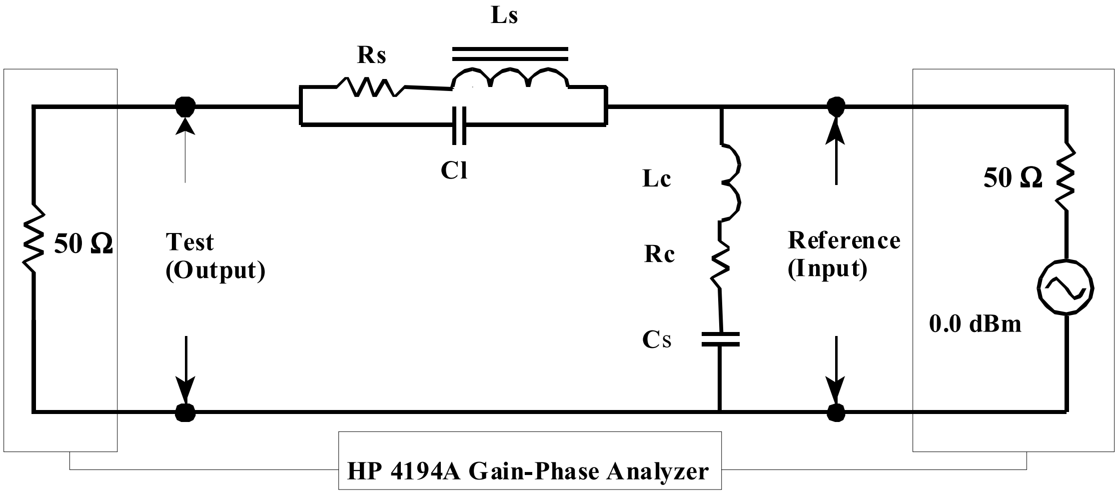

Figure 2. Single-Stage Filter Model Showing Parasitic Elements and Test and Source Load.

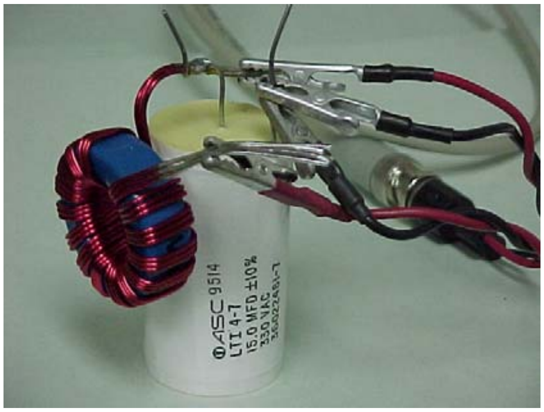

Figure 3. Single-Stage Filter Construction and Test Leads.

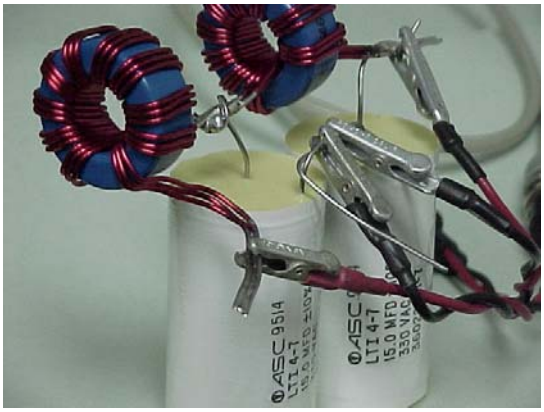

Figure 4. Two-Stage Filter Construction and Test Leads.

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[1] See Mitchell, Daniel M., *DC-DC Switching Regulator Analysis*, McGraw-Hill, New York, 1988, ISBN 0-07-042597-3, Chapter 7, "Effects of EMI Input Filtering."

connected in series is 5.4 mΩ. Because of the fewer turns, the magnetizing force on the smaller cores is 14.5% less for the same value of current.

Figure 5 shows how the equivalent series inductance and resistance varies with frequency for each type of inductor. The larger one self resonates at about 26 MHz whereas the smaller one is still inductive beyond 40 MHz. A wider frequency range is typical of smaller inductors. There will be more on inductor characteristics at high frequency in the next section.

A similar graph for the capacitor is shown in Figure 6. In this case, parallel capacitance and resistance are plotted against frequency. Note that the capacitor resonates with the inductance of its leads at about 250 kHz.

All of the frequency response graphs in this paper are based on data from a Hewlett-Packard 4194A Impedance/Gain-Phase Analyzer. For each inductance and capacitance measurement, the test signal voltage used was nominally 0.5 V rms.

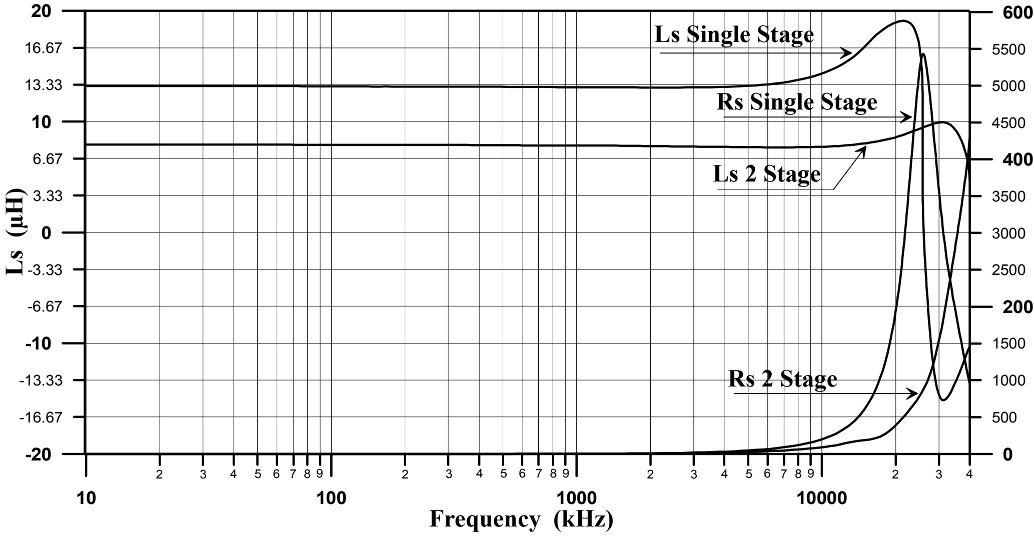

Figure 5. Equivalent Series Inductance and Resistance versus Frequency for Single and Two-Stage Inductors.

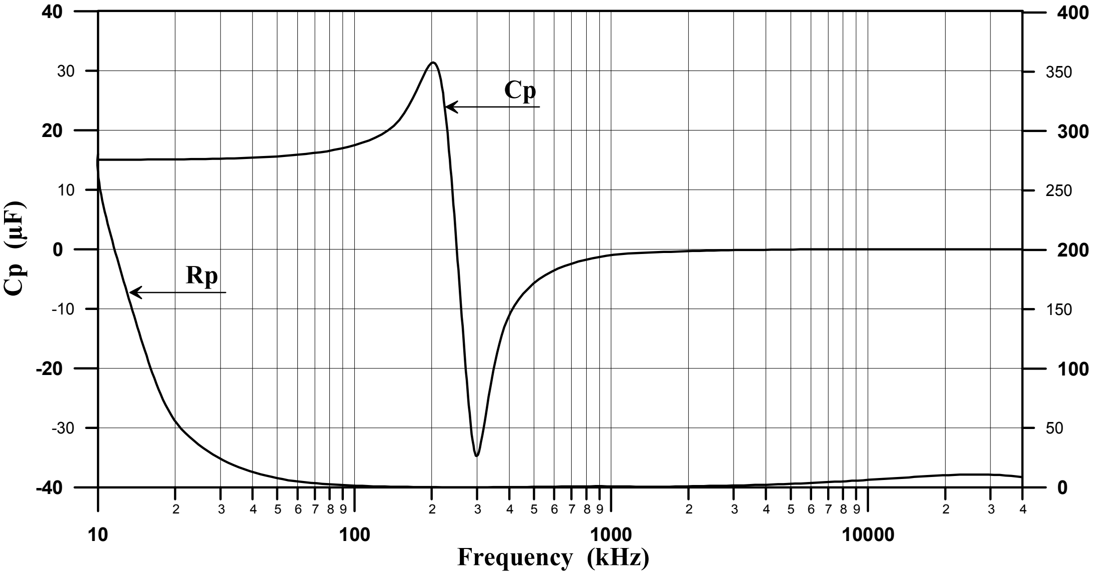

Figure 6. Equivalent Parallel Capacitance and Resistance versus Frequency for the 15 μF Capacitor.

To show the advantage of multiple-pole filtering, the frequency response for the single-stage (two-pole) and two-stage (four-pole) examples are presented in Figure 7 and Figure 8. The most significant departures from a power circuit application are the 50 Ω source impedance and 50 Ω load, which are provided by the "gain-phase" part of the Hewlett-Packard 4194A Analyzer. In a typical switching-type power supply, the impedances are variable, not matched and usually much lower in value at low frequencies. The test does provide useful information for comparison even though the application conditions differ.

For example, the maximum attenuation (minimum gain) for each filter is the result of series resonance of the capacitor and its lead inductance. It is especially noticeable at about 175 kHz for the single-stage filter. The importance of minimizing lead length is apparent. Attenuation decreases at higher frequency because lead inductance is impeding the flow of return current through each capacitor.

Another important observation with regard to filter behavior is the lower damping of the two-stage configuration around 20 kHz. Theoretically, the four poles are two double poles at

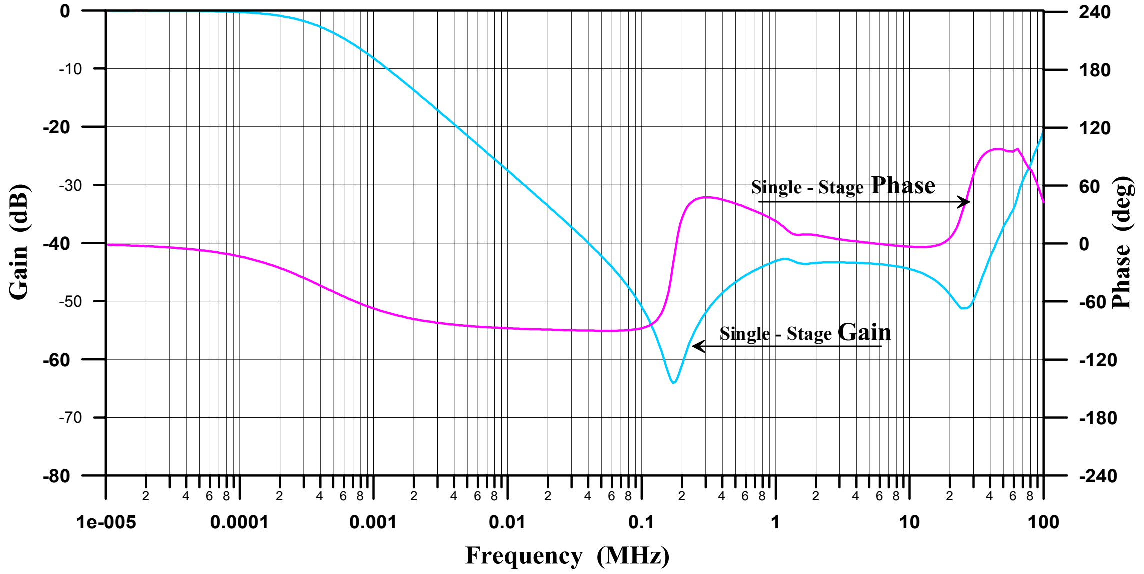

Figure 7. Gain and Phase versus Frequency for the Single-Stage Filter.

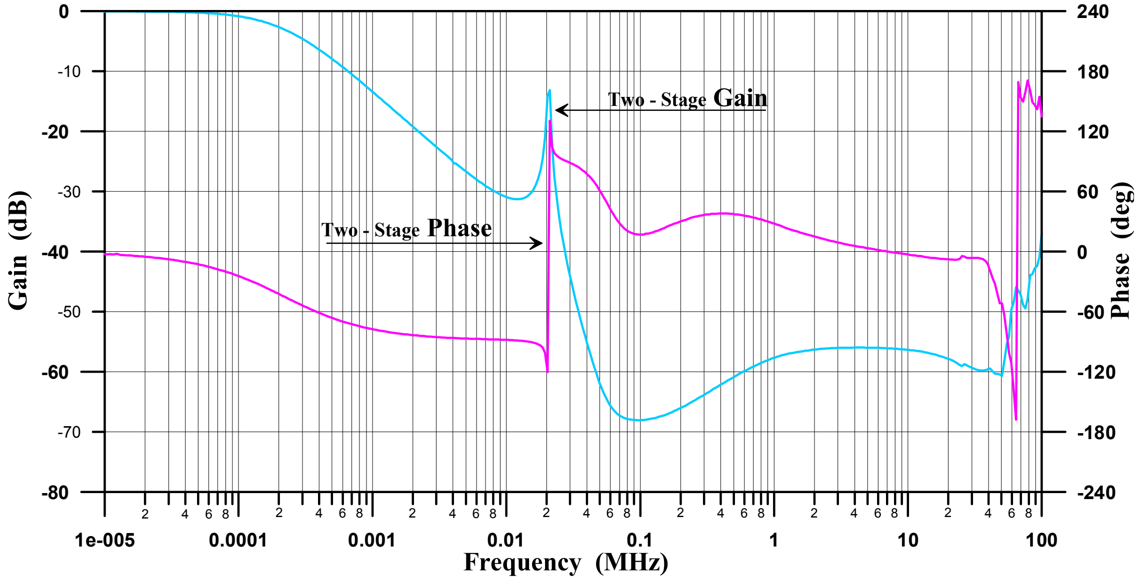

Figure 8. Gain and Phase versus Frequency for the Two-Stage Filter.

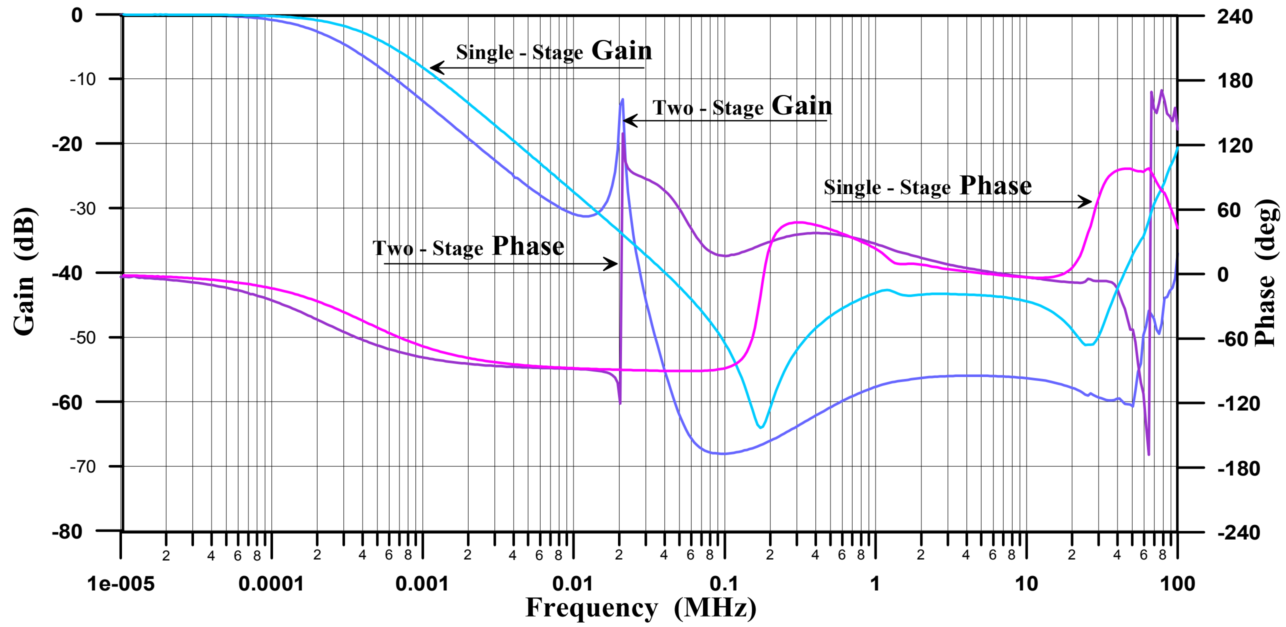

Figure 9. Composite Gain and Phase versus Frequency for One and Two-Stage Filters.

14.6 kHz and their effect is apparent because of the lack of damping between C1, L2 and C3. About 30 dB of attenuation is lost at 20 kHz. Above that frequency, the filter recovers and outperforms the single-stage design by a remarkable 20 dB at 60 kHz. See Figure 9.

Finally, note that the two-stage filter maintains a 10 dB advantage from 300 kHz to 1 MHz. The additional inductor and capacitor reduce the capacitor lead inductance effect.[2] In the United States, because the AM broadcast band is from 540 kHz to 1.6 MHz, improved filter performance in this range of frequencies is of particular benefit.

The filters were tested with the input or reference channel on the capacitor side and test channel on the inductor. It was observed that the frequency response was very similar with the inductor side connected to the reference channel and the capacitor side tied to the test channel. Therefore, the observations above also apply to the filters treated as the inductor-input type.

Power Line Filters

The term filter usually applies to an electrical circuit or portion of a circuit that prevents electromagnetic interference (EMI). Without filtering, unwanted electrical signals could travel from one device to another along the power line or bus bar that they share. The conducted interference can also be subsequently radiated since a power line is an antenna for higher frequencies. The purpose of the filter is to prevent this electrical “noise” from being conducted to the line from the device while allowing the desired electrical power to pass.

For equipment connected to a public utility, government agencies regulate the maximum conducted noise voltage over specific frequency ranges. For example, in the United States, the Federal Communications Commission specifies a conducted radio frequency interference (RFI) limit of 48 dBµV from 450 kHz to 30 MHz.[3] The purpose is to prevent interference with radio, television and telephone services used by the general public.

Noise limits for the outputs of power supplies within an electronic system are determined by the requirements of the attached loads. In most cases, sufficient noise filtering is accomplished with the same power filter elements (energy storage inductor and output capacitor) that

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[2] See Don Pauly’s article “Power Supply Magnetics,” page 16 of the reprint available from Arnold Engineering or “Part III” in the March, 1996 issue of *PCIM* on battery line filters.

[3] FCC Part 15 Class B, devices for home or consumer use. “dBµV” stands for decibel microvolt; 48 dBµV is 0.00025 volt; “kHz” is kilohertz or thousand cycles per second and “MHz” refers to megahertz or million cycles per second.

control the output voltage ripple. However, some designs include a second stage of filtering to control EMI on the output of the supply.[4]

Equipment that contains continuously switching components, such as the power transistors and diodes of a switched-mode power supply, require conducted EMI filtering on the input side. The abrupt changes of current in the circuit cause brief voltage rises or "spikes" either across the input conductors or on both conductors to ground. ("Ground" includes ground return wires, ground planes and grounded enclosures.)

EMI voltage between input conductors is called differential-mode noise. Noise from both conductors to ground is termed common-mode. An inductor for common-mode noise utilizes the opposing currents in the input conductors (two windings on one core) and a high permeability core material.

In contrast, a differential-mode inductor requires a core material that can maintain permeability with a bias field. Refer to the graphs in Figure 11 showing inductor current, voltage and core magnetic fields. Note that the source in Figure 11 is either a power line (via a wall outlet, for example) or a battery such as the 48 volt battery for telephone central office equipment. In a battery system, the magnetizing current is a constant DC. For an AC system with high power factor, the magnetizing current is nearly sinusoidal. With a low power factor AC system, the current is a series of alternating pulses.

Powder cores are appropriate for differential-mode, sometimes referred to as "series-mode," inductors or "chokes," because of their extraordinary capability to maintain inductance with bias. The 50% nickel-iron alloy powder is particularly useful at high flux densities. (Arnold Engineering's trade name for this material is Hi-Flux™.) For comparison, permeability versus DC bias curves for the three types of powder cores are shown in Figure 12.

The test data in Figure 12 and the data that follows came from the same three cores. Each has a permeability of 60 and is the same size as the core used in the single-stage filter. For reference, the Arnold part numbers are A-291061-2, HF-130060-2 and MS-130060-2, representing the molybdenum permalloy (MPP), 50% nickel-iron and sendust-type powders, respectively.

An example of a "fully" wound core is shown in Figure 10. Fully wound means that one-half of the core inside diameter remains. Usually, at least this much room must be provided for a hook or shuttle to place the last turn. In this case, the inductance value is 1.9 mH and is typical for power line applications. Inductance requirements generally range from a few microhenries to several millihenries.

Low core loss at power line frequency is necessary to take advantage of the core material's high saturation flux density. Measurements are presented for Hi-Flux in Figure 13. Hi-Flux has the most loss so it can be used as a worst-case reference. Even at 400 Hz and 9000 gausses, the core loss density is low at 200 mW/cm^3. For 50 and 60 Hz applications, the flux density limit is determined by the change in permeability as shown in Figure 14.

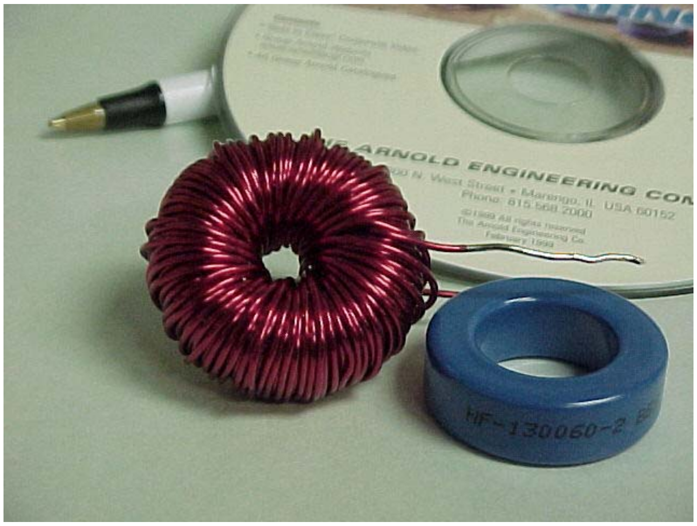

Figure 10. Example of "Fully" Wound Core

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[4] See Billings, Keith H., *Switchmode Power Supply Handbook*, McGraw-Hill, New York, 1989. ISBN 0-07-005330-8. pp. 1.151 and 1.152.

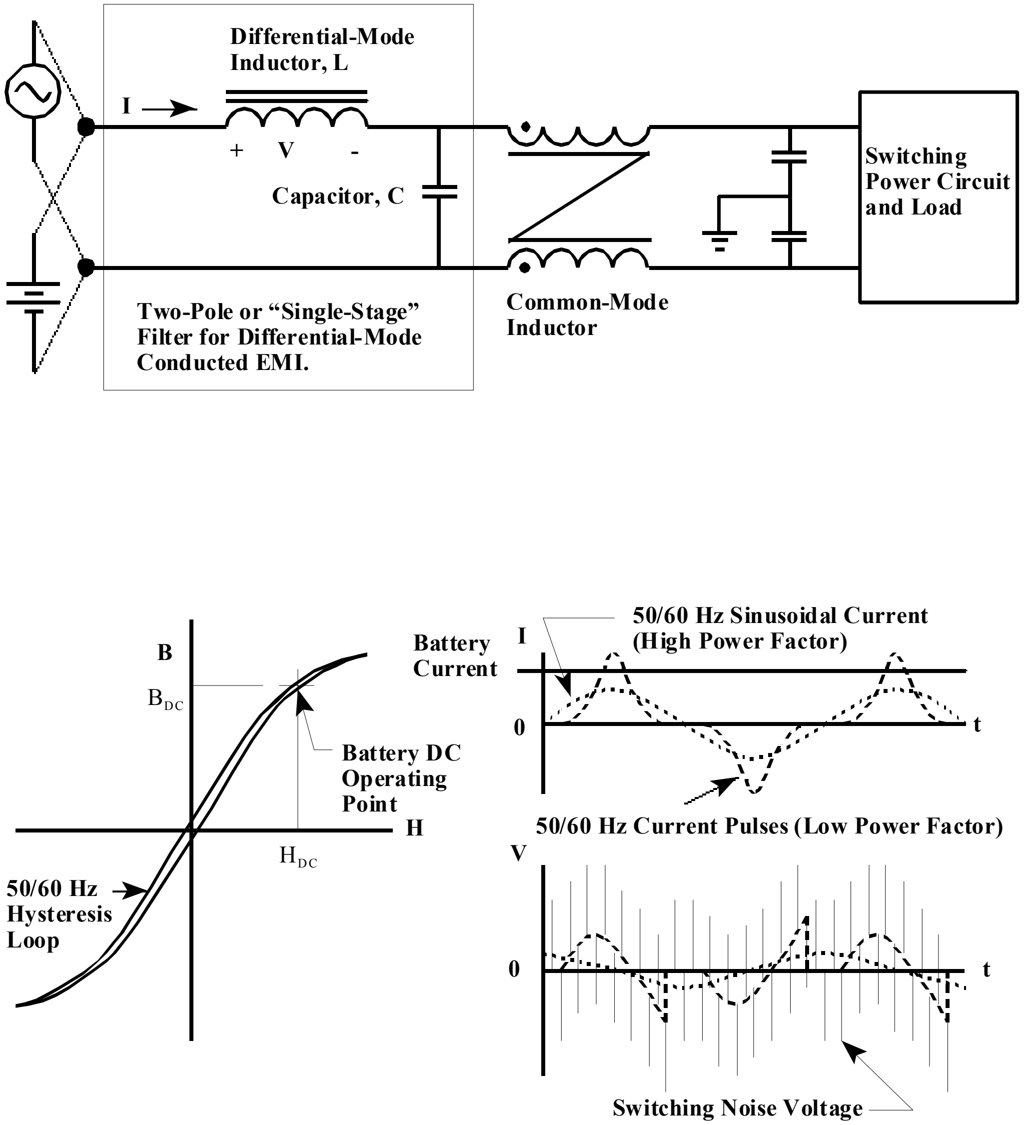

Figure 11. Typical EMI Filter Configuration and Differential-Mode Inductor Voltage, Current and Magnetic Waveforms.

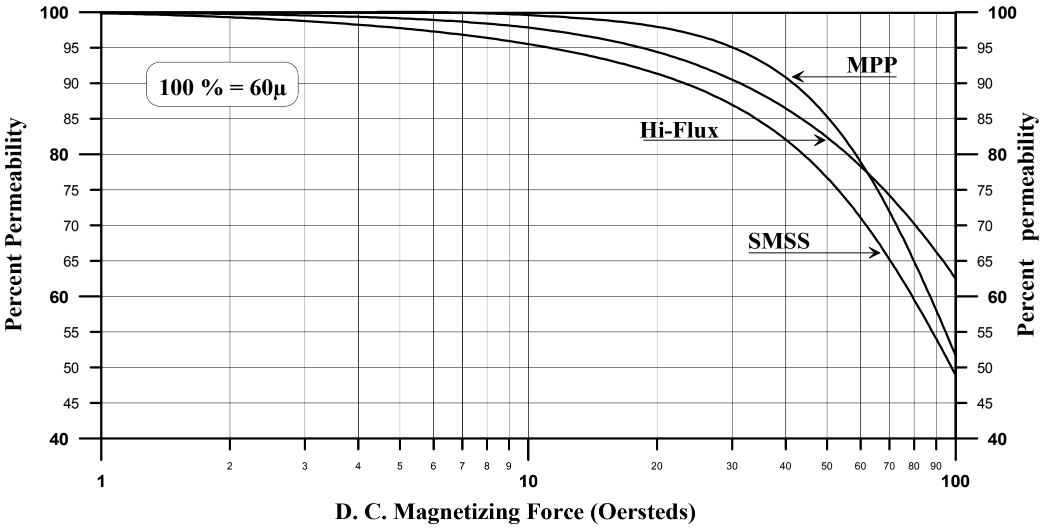

Figure 12. Permeability versus DC Bias.

Another important consideration is the variation of inductance with frequency. The frequency responses of single layer 60 µH inductors made with each type of core are shown in Figure 15 through 17.

The absence of the series inductance peak for the Hi-Flux inductor indicates that its core permeability is dropping with frequency. Higher eddy current loss in the 50% nickel-iron powder is responsible. As mentioned before, loss at higher frequency can be an advantage in filters because of the additional stability the damping provides. Greater detail regarding series inductance and resistance in the frequency range of 100 kHz to 1 MHz is given in Figure 18. The relatively low eddy current loss in Super-MSS is apparent.

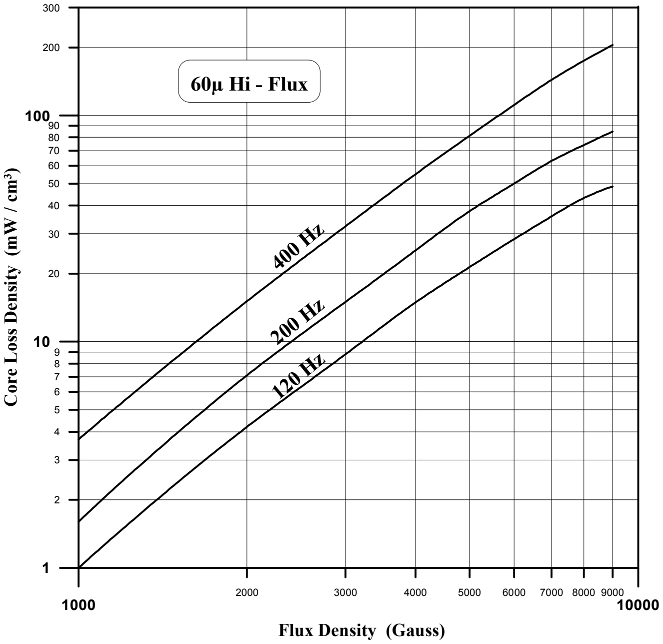

Figure 13. Core Loss versus Flux Density.

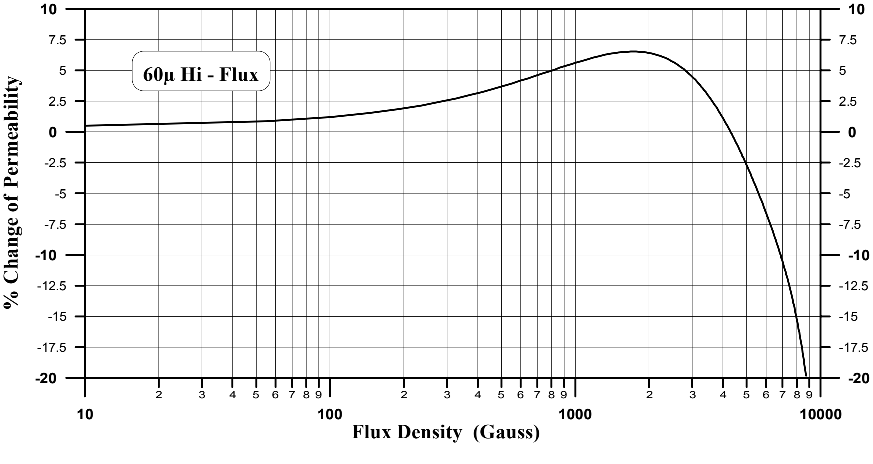

Figure 14. Modulation of Permeability with Flux Density.

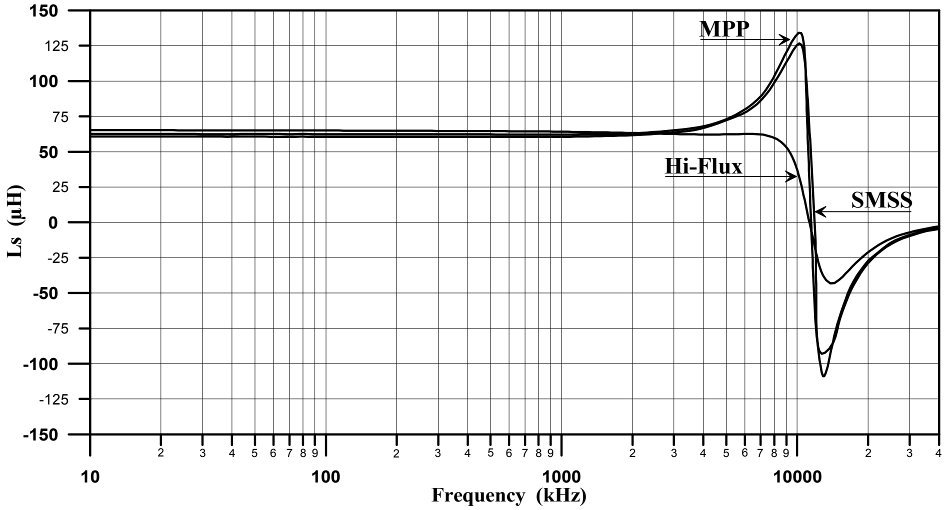

Figure 15. Equivalent Series Inductance versus Frequency, Single-Layer Winding.

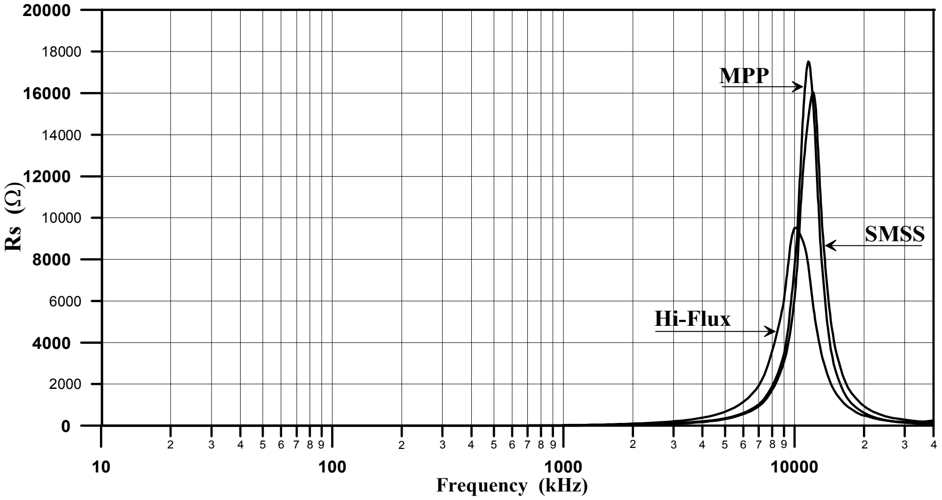

Figure 16. Equivalent Series Resistance versus Frequency, Single Layer Winding.

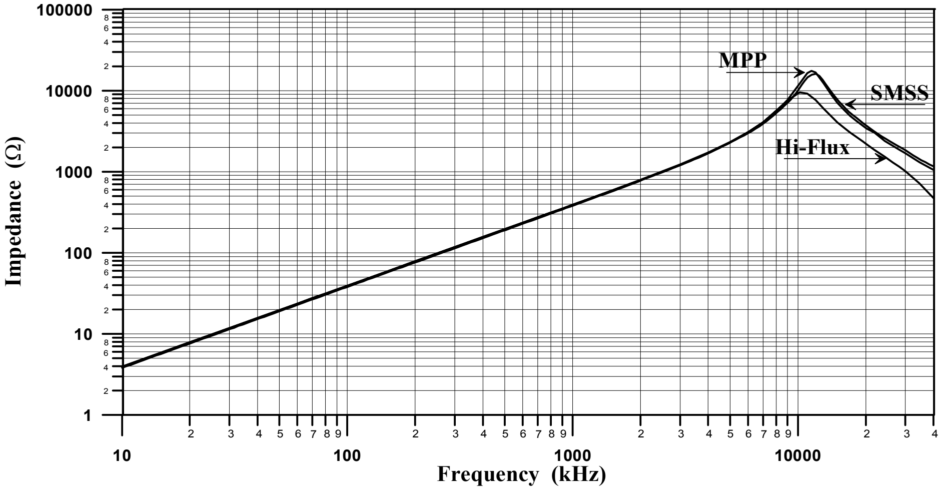

Figure 17. Impedance versus Frequency, Single Layer Winding.

Finally, the effect of greater distributed capacitance with overlapping conductor turns (multiple layers of magnet wire) is shown graphically in Figure 20 and Figure 21. Beyond 1.6 MHz, this stray capacitance actually causes the high-value, multiple-layer inductor to have a lower impedance than the low-value single-layer inductor.[5]

In conclusion, each of the powder core types is applicable to power line filtering. The 50% nickel-iron material performs the best because of its ability to sustain inductance with higher magnetizing current. It also provides some desirable damping at higher frequencies.

Another important consideration is acoustic noise caused by magnetostriction of the magnetic metal alloy. A 50% nickel-iron alloy core can make a humming sound at high 50 or 60 Hz flux levels. Of course, DC magnetizing current does not cause audible noise so the 50% nickel-iron is usually the best material for battery power line filters.

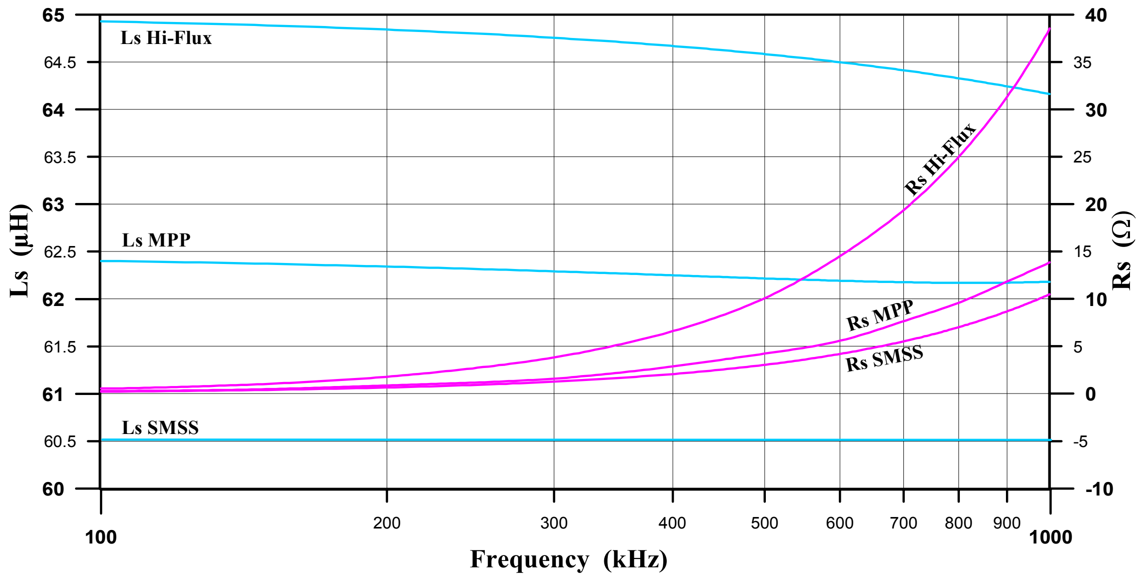

Figure 18. Equivalent Series Inductance and Resistance versus Frequency, 100 kHz to 1 MHz.

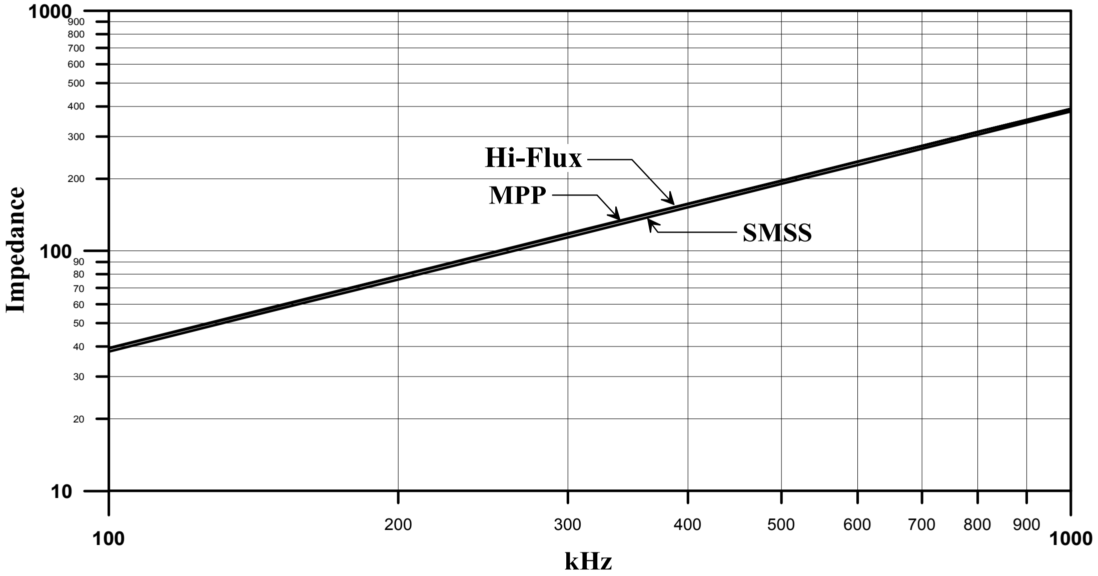

Figure 19. Impedance versus Frequency, 100 kHz to 1 MHz.

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[5] The multiple-layer winding is 170 turns of 18 AWG magnet wire.

Both MPP and Super-MSS have exceptionally low magnetostriction and either could be used to minimize audible noise. MPP has the advantage of better incremental permeability with DC bias. The 50 or 60 Hz current is essentially DC compared to the frequency of electrical noise. Incremental permeability versus DC bias curves can be used to predict the inductance at any point of the 50/60 Hz current waveform.

The sendust-type core has the lowest cost per unit volume and is a good choice where the highest possible performance is not required. The difference in cost of molybdenum permalloy powder and the 50% nickel-iron alloy powder is negligible.

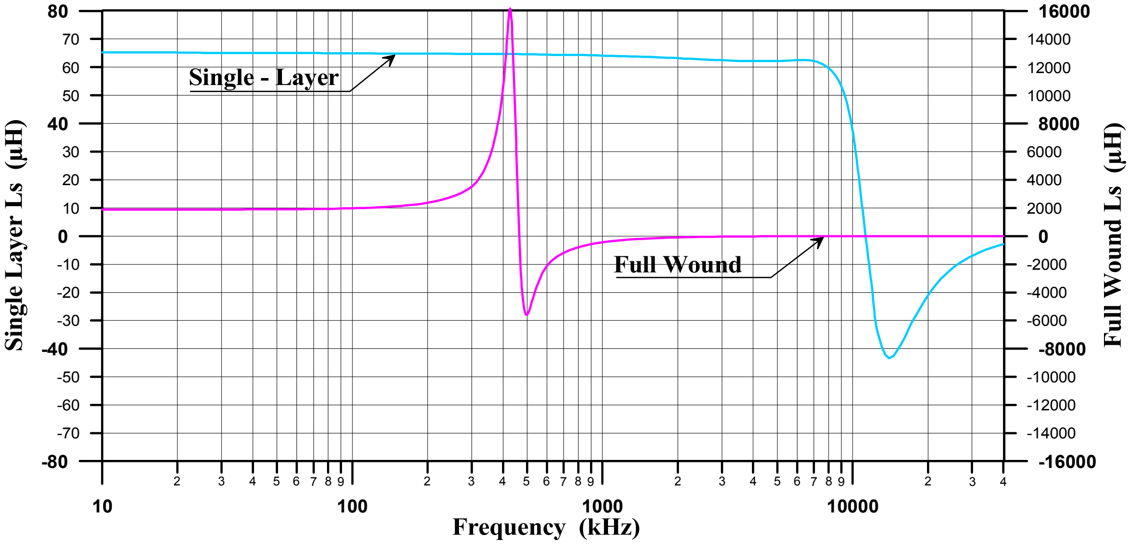

Figure 20. Equivalent Series Inductance versus Frequency for Single-Layer and Fully Wound Designs.

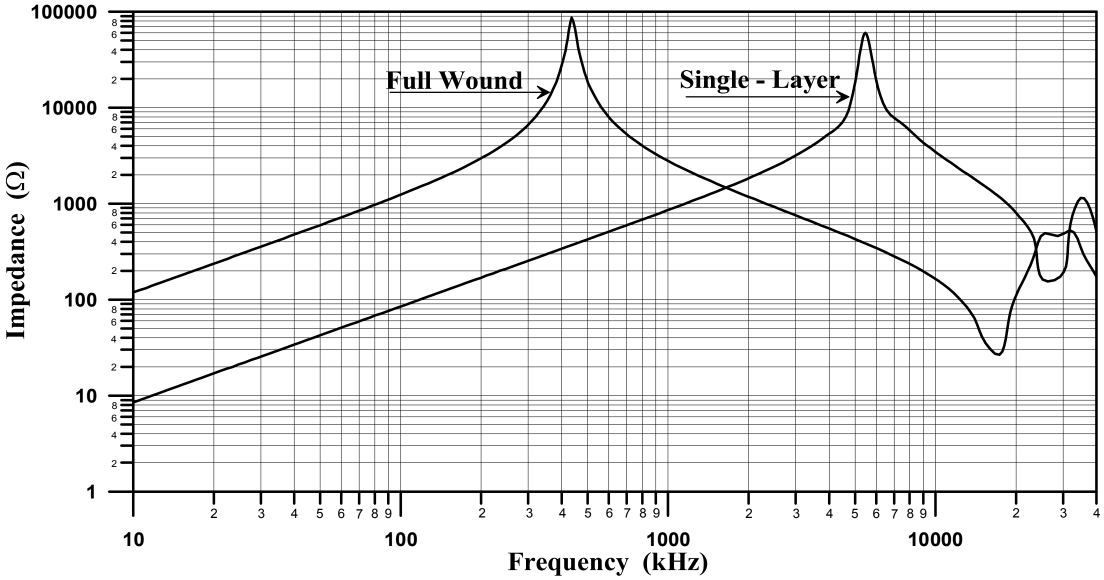

Figure 21. Impedance versus Frequency for Single-Layer and Fully Wound Designs.

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