"Common Mode Filter Inductor Analysis"

Author:	Len Crane	Date: 1985
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COMMON MODE FILTER INDUCTOR ANALYSIS

Leonard F. Crane and Steven F. Srebranig
Coilcraft, Inc.
Cary, Illinois

ABSTRACT

Recently, the tightening of noise limits by regulatory agencies has made solutions to common mode EMI a necessary consideration in the manufacture and use of electronic equipment. Common mode filters are generally relied upon to suppress line conducted common mode interference; when properly designed, these filters successfully and reliably reduce common mode noise. However, successful design of common mode filters requires foresight into the non-ideal character of filter components--the inductor in particular. It is the aim of this paper to provide filter designers with the knowledge required to identify those characteristics critical to desired filter performance.

INTRODUCTION

The filtering of common mode noise is typically not as well understood as its differential counterpart and this paper will deal with the practical aspects of common mode filters as related specifically to the common mode inductor.

Common mode noise occurs simultaneously on both lines of a conductor pair with respect to a common ground, whereas differential noise occurs between conductor paths. The frequency response characteristics of filters incorporating different common mode choke constructions will be examined. The filter designer should then have a better understanding of common mode inductors and be able to choose the common mode inductor construction which will yield the required attenuation characteristic without the additional cost of over designing or the failure of under design.

I. TYPES OF NOISE AND NOISE SOURCES

Power converters are often major sources of noise in any equipment. Power converters normally produce common mode and differential mode noise at harmonics of the switching frequency while some wide band differential mode noise is usually also produced.(1)

Conducted emissions from power converters are attributable to a number of causes. The nature of converter operation (the rectification of the line frequency, and switching waveforms, for example) and circuit magnetics contribute several unique types of noise; also, the capacitive effects of components and overall mechanical structures, such as cases, and the semiconductor components themselves add their own disruptive voltages.

An input L-C smoothing filter is generally required in off-line switching regulators, but these inductors and capacitors may themselves be sources of EMI. If the inductor is constructed with a relatively high Q material, it will display subtantial ringing and produce spectral noise energy. Also, switching noise of the converter may be coupled back into the line through the distributed capacitance of the inductor. The power transformer may also ring and couple in ways similar to the filter inductor and produce its own EMI.

There are semiconductor noise sources associated with temperature (thermal noise), within the junction of differing materials (contact noise), and electron-hole movement in junction devices (shot noise). There exists low frequency noise attributable to dc current carrying electronic devices (modulation, flicker, or 1/f noise), due to the non-ohmic behavior of semiconductors at high fields (hot carrier noise), the generation and recombination of charge carriers (generation-recombination noise), and induced noise at the gate of an FET due to the alteration of the source to drain currents by the induced charge at the gate.(2)

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gauge wire (i.e., the 'perfect' coil).

At frequencies above self-resonance, an inductor begins to display the full effects of its parasitic components, particularly the distributed capacitance (Cd).

The Cd describes the effective capacity across an inductor and is caused by individual turns of wire in close proximity (Figure 4). It is the distributed capacitance that gives the inductor its characteristic self-resonant frequency ($1/2\pi\sqrt{LC}$).

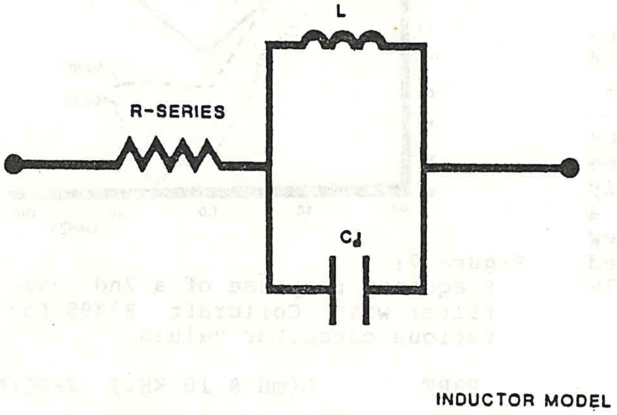

Figure 4:
Model of an inductor (one common mode inductor winding).

Other non ideal aspects of inductors include leakage inductance, which acts as inductance in series with each winding. All multiple winding chokes display leakage inductance. The leakage inductance of a winding is the amount of inductance which is not coupled to any other windings through a shared core and is undesireable in transformers because it stores energy without transforming it to other windings in the structure. In a low pass filter, however, leakage inductance should add to the attenuation of the filter (also in line frequency common mode chokes, i.e. where the differential signal passes unattenuated due to coupling of the winds, the uncoupled leakage inductance will aid in the suppression of high frequency differential noise).

Resistive losses such as copper (I^2R) and core loss may also be expected to affect attenuation. The diameter of wire used in a choke is determined by the amount of current which it will be required to handle. The larger the current, the larger the wire. For example, at a line frequency current of 1 ampere, 26 AWG wire is required to provide 250 circular mils to support the current. As frequency increases, the amount of cross sectional area (for a single strand of wire) used by the current decreases (skin effect). For frequencies above about 100 KHz, multi-stranded wire (litz wire, with each strand insulated) should be used if the high frequency current is to be supported. For a low pass inductive filter which needs to pass only the line frequencies, further attenuation due to skin effect may be desirable.

Capacitors exhibit parasitics of their own. For filter applications, mylar, mica, and ceramic capacitors are the most useful because they exhibit high self-resonant frequencies due to minimization of their parasitics (series inductance and resistance, and parallel resistance).

IV. WINDING CONFIGURATIONS

Three winding configurations for inductors are shown in Figure 5. Simplest and least prone to distributed capacitance of all the standard configurations is the single layer wind. The starts and finishes of a single layer wind are as far from one another as possible, thus reducing capacitive coupling. A multilayer wind (two or more single layers) provides capacity between layers as well as from the start lead to the finish lead (which are generally close to one another with the finish lead ending where the start lead began). The multilayer configuration displays the greatest capacity of the winding configurations (thus the lowest attenuation at higher frequencies for an inductive low pass filter).

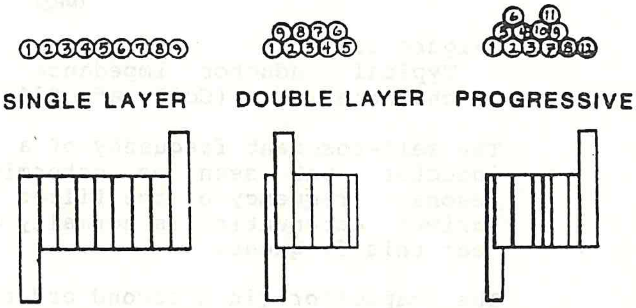

Figure 5:
The three winding configurations examined.

For similar constructions, self-resonance (the useful and theoretically predictable frequency limit of inductance) generally decreases as initial inductance (measured between 10 KHz and 20 KHz) increases. Moreover, the self-resonant frequency of a layer wound inductor decreases as the number of layers are increased (while maintaining the same turn count).

The progressive or banked windings (-P) of the table display the same self-resonance as the single layer (-S) versions. Progressive winding allows the increased turns of a multilayer wind while maintaining the optimum characteristics of a single layer wind.

Because our examination was to determine the attenuation effected by a typical EMI filter configuration due to differing chokes and choke constructions, we used the circuit of Figure 8, maintaining all circuit components constant except for the inductive element.

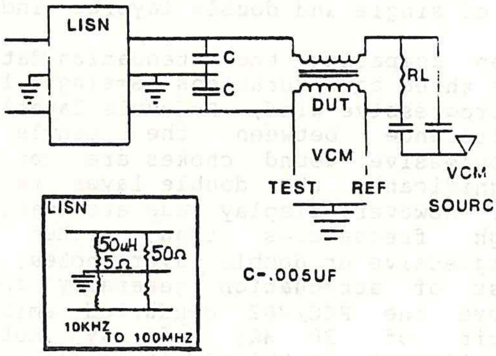

Figure 8:
Test circuit used to measure common mode signal attenuation.

We initially felt it necessary to determine whether differential power (60 Hz) applied to the common mode circuit would affect the high frequency common mode attenuation of the filter. Presumably, the differential operation of the common mode circuit, with inductors coupled to each other and their relative polarity such that their equal and opposite (differentially produced) flux lines cancel, no inductive reactance should be encountered by the differential signal and saturation of the core should therefore not occur from the differential signal. To prove this we used the circuit of Figure 9 with a load, RL, to provide the rated current through the choke.

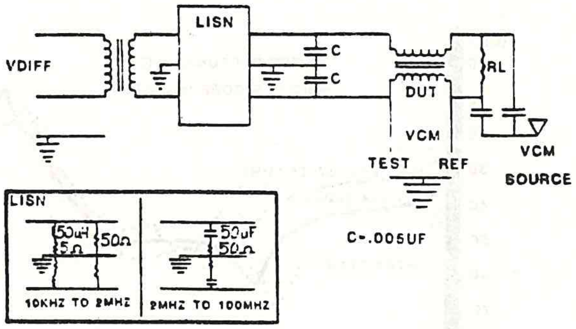

Figure 9:
Test circuit used to apply common mode signal and differential (60Hz) power simultaneously.

The LISN (see Appendix B) of the 'power' circuit was split at 2 MHz between the standard 50 uHenry/5 Ohm arrangement (below 2 MHz) and the 50 uFarad/50 Ohm arrangement (providing 50 Ohms above 2 MHz to the noise source). Splitting the LISN (and later splicing the attenuation curves at 2 MHz) provided a more accurate composite LISN than either arrangement alone would have with the required power components.

Neglecting measurement error (approximately 4 decibels), the differential input did not appear to affect the common mode attenuation of the circuit even at high frequencies (through 10 MHz).

Figures 10 and 11 show the common mode attenuation by second order filters with the standard chokes and .005 microFarad capacitors and using the LISN load .

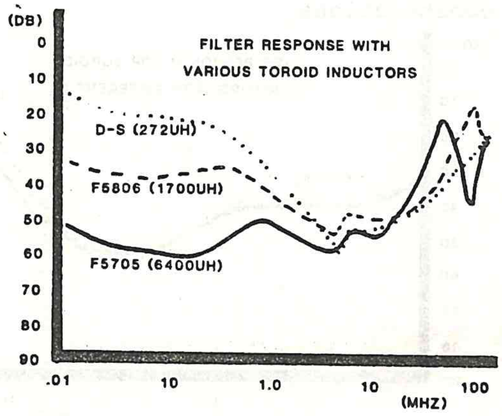

Figure 10:
Common mode attenuation of second order filters with .005uF capacitors and various inductors.

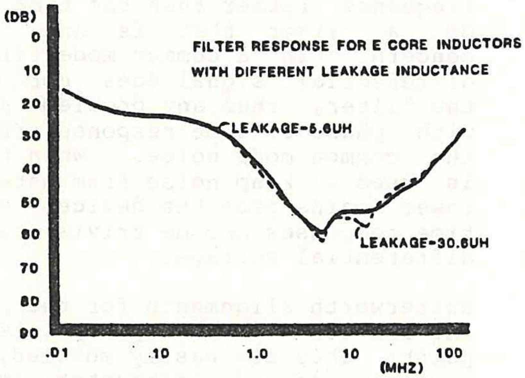

Figure 14:
The affect on attenuation due to leakage inductance.

VI. DISCUSSION

The data taken can be used in the following ways:

1. The data show that common mode filter response is the same as that expected for the more familiar differential mode L-C filter; common mode filter response can be fairly accurately predicted using standard L-C calculations except where the components used exhibit non-ideal characteristics. For example, Figure 2 shows the theoretically calculated frequency response for an L-C filter using a 3.3mH common mode choke, a .005uF capacitor, and the LISN load. With these component values one would expect a high frequency rate of attenuation of 20 dB per decade. It can be seen from the actual response of the same filter (shown in Figure 3) that the measured rate of attenuation for frequencies below resonance (within an octave of resonance) agrees quite well with the expected slope and approximate value. This is useful in that for frequencies below inductor self-resonance, the component values necessary to achieve a desired level of attenuation may simply be calculated.

2. The data also show that common mode filters achieve a maximum value of attenuation at the self-resonant frequency of the common mode inductor. The self-resonant frequency of the inductor thus becomes an easily used indicator of whether one should adjust the capacitor value or the inductor value to achieve greater attenuation at a specific frequency or frequency band. For example, Figure 7 shows the differences in attenuation caused by changing the filter capacitor value. If one were interested in attenuation at 4 MHz, it is seen that the attenuation can be increased from 55dB to 85dB by increasing the capacitor value from 50nF to 100nF; whereas even a relatively large change in inductance would have negligible affect.

3. In general it can be said that common mode filter response can be broken down into three frequency regions of interest: (A), the region below inductor self-resonance in which calculations based on component values hold true; (B), the region near inductor self-resonance in which the filter achieves the maximum attenuation; and (C), the region above inductor self-resonance in which the response is dominated by the filter capacitor.

CONCLUSIONS

Common mode filter response has been shown to differ substantially from theoretically predicted performance. Filter performance can be explained and successfully manipulated if non-ideal component response is taken into account.

The common mode inductor has been shown to be a primary component in determining the response of a typical filter circuit. The common mode inductor affects the magnitude (maximum attainable attenuation) and the shape (resonant frequency) of the frequency response of the filter.

A filter designer should carefully consider filter response from approximately 1 MHz to 30 MHz to determine whether the slightly diminished attenuation of a multiple layer inductor is acceptable. If one were to specify the inductor to be a single layer wind it may result in unnecessary cost and size penalties. It is seen from these data, that on an EE core or toroid core structure, the winding pattern of the individual windings (Cd) is far more significant than the relationship of the two windings (leakage inductance).

The distributed capacity of a choke decreases attenuation at high frequencies and multilayering increases the distributed capacitance of an inductor. Progressive winding allows the equivalent number of turns of wire as a multilayer wind, usually far more turns than a single layer wind could accommodate. A progressively wound inductor will display a distributed capacity similar to a single layer wind. To attenuate noise voltages which occur above the limits

For noise evaluations of OEM devices, the Line Impedance Stabilizing Network allows the normal power flow required of the device, while yielding a stable impedance to conducted emmissions. The LISN provides a low impedance at the line frequency, increasing impedance through the noise frequencies (5.4 Ohms at 10 KHz with 50 Ohms above about 400 Khz).

APPENDIX C

The following chokes were examined both to determine their inherent electrical characteristics and their affect on attenuation in a second order filter using .005 microFarad ceramic capacitors:

Coilcraft standard:

SAMPLE#	CONSTR	TURNS	L (mH)	Cd (pF)
E3490A	EE1/4"	92	10.9	19.0
E3499A	EE1/4"x1/2"	92	20.7	19.6
E3495A	EE1/4"	25	1.1	10.4
E3506A	EE1/4"x1/2"	16	.7	15.9
F5593A	EE3/8"	25	1.5	30.0
P104	EE1/4"	45	4.0	11.3
E3493	EE1/4"	42	3.3	13.6
G6252	EE3/16"	120	17.7	22.9
F5806	0.87"OD TOROID	15	1.7	6.6
F5705	1.0"OD TOROID	24	6.4	7.0

Additional samples tested:

A: (Toroid)
13 turns/10000 perm ferrite/.87"OD:
Single layer wound = 2.62mH 4.3pF
Double layer wound = 2.70mH 16.7pF
Progressive wound = 2.53mH 4.4pF

B: (Toroid)
13 turns/5000 perm ferrite/.87"OD:
Single layer wound = 1.24mH 9.1pF
Double layer wound = 1.15mH 9.8pF
Progressive wound = 1.21mH 9.3pF

C: (Toroid)
13 turns/125 perm molypermalloy/1.3"OD:
Single layer wound = 796uH 14.1pF
Double layer wound = 846uH 53.3pF
Progressive wound = 839uH 13.4pF

D: (EE core)
12 turns/2000 perm ferrite/ 1/4"x1/4"
Single layer wound = .272mH 5.8pF
Double layer wound = .273mH 7.6pF

E: (Toroid)
13 turns/2000 perm ferrite/.5"OD:
Single layer wound = 263uH 3.2pF
Double layer wound = 225uH 9.2pF
Progressive wound = 213uH 3.9pF

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AUTHOR'S BIOGRAPHY

Leonard Crane has been a Coilcraft employee since receiving his BSEE from the University of Illinois in 1979. He currently serves as Senior Product Engineer, specializing in switching power supply magnetics. Past opportunities have included the presentation of a switchmode tranformer design seminar in Hong Kong, Taiwan, and South Korea.

Steven Srebranig was graduated with a BSEE from the University of Wisconsin-Madison in 1984. He currently serves as a research and design engineer with Coilcraft.