Introduction

Inductors and ferrite are dual element of capacitors. They work by increasing the loop impedance of the circuit (Fig. 1), the device impedance, $Z_X = 2\pi f \times L$, must be larger than the series combination of $Z_S + Z_L$.

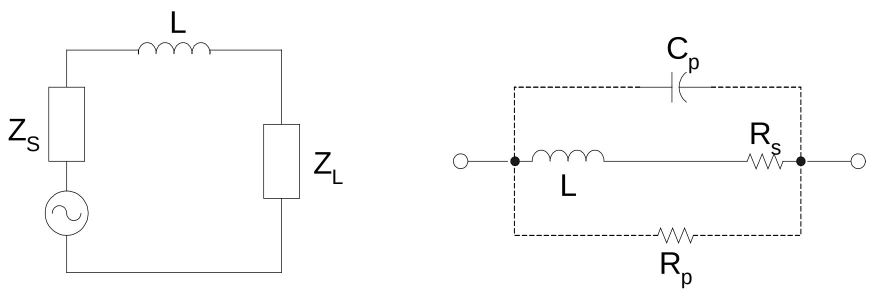


Fig. 1. Inductor filtering circuit and equipment elements.

The cutoff frequency of such lowpass filter is given by

$$F_{off} = \frac{1}{2\pi R_S L}$$

Where R_S = series resistance of Z_S, Z_L.

The attenuation at any frequency above IL_{dB} is given by

$$IL_{dB} = 20\log(1 + \frac{Z_X}{Z_S + Z_L})$$

If $Z_X >> (Z_S + Z_L)$

$$IL_{dB} \approx 20\log(\frac{Z_X}{Z_X + Z_L})$$

Again, as for capacitors, one must be careful to use the actual values of Z_S, Z_L at the calculation frequency, if these are not pure resistances.

APPLICATION

INDUCTOR

Since inductors are dual elements of capacitors, they suffer a mirror kind of limitation: While with capacitors a resonance is created with the leakage inductances of the terminal leads, an inductor will have a leakage resonance produced by the interturn capacitance of its winding.

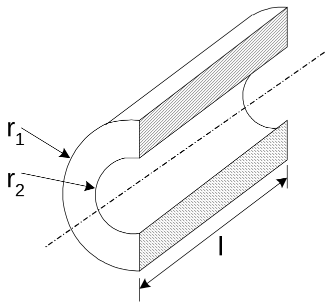
The inductor being placed in series in a power supply and signal circuit, the device must be:

- Capable of carrying the functional current without overheating or unacceptable voltage drop.
- Unaffected, not driven into magnetic core saturation, by the through current.

Ferrite Inductor

Introduction

Ferrite inductors has been regarded as the miracle remedies that the EMC magician pulls out of his sleeve, resolving in seconds a problem that was lingering for months. (Fig. 2)



Magnetic flux

$$\Phi = B \times l\,(r_1 - r_2)$$

$$I_{(\max)}(saturation) = \frac{B_{\max}\, l\,(r_2 - r_1)}{L}$$

$$B_{\max}(typ.) = 0.1 \ to \ 0.2 \ tesla$$

Fig. 2. Basic parameters of a ferrite core.

The most interesting characteristic of an EMC ferrite core is its impedance vs. frequency curve. The impedance of the ferrite bead is a complex one, which can be expressed as

$$Z_{bead} = R + j\,2\pi\, f\, L$$

In the above equation, R, the resistive term, depends on the material resistivity and is related to the eddy currents losses. Therefore, it is a frequency-dependent term. L, the inductive term, depends on μ_r, the relative permeability of the material. It corresponds to the reactive behavior, which is the one primarily sought in magnetic application below the megahertz level. It is given by

$$L = 0.2\,N^2\,\mu_r\,l\ln(\frac{D_1}{D_2})$$

Where N = number of times passes through the ferrite bead

l = bead length

D_1, D_2 = outside and inside diameters

Quite often, Manufacturer catalogs provide the AL value for a given toroid size and material. AL is measure, in nanohenries, for one turn such that, for N turns,

$$L = AL \times N^2 \ (nH)$$

This N^2 dependency is a theoretical ideal that generally is not met except at near-zero current. More realistically, practitioners found that

$$L \approx AL \times N^{1.5 or 1.8}$$

Combining equations:

$$AL = 0.2\,\mu_r\,l\ln(\frac{D_1}{D_2})$$

The value of μ_r, in general, is more modest than for a purely magnetic component such as a transformer or a choke. Typical values of μ_r for EMC ferrites are in the 50 to 1000 ranges. But, in contrast with magnetic materials used at 50/60Hz and up to few tens of kHz, the μ_r for ferrites keeps a stable value across a very wide frequency range, e.g., 0.1 to 10 MHz, and even beyond 100MHz for some materials. The upper limit of ferrite bead impedance is reached by either core saturation (too many ampere-turns) or too high an EMI frequency where leakage capacitance starts to bypass bead impedance.

As the current increases, inductance L, tends to decrease, but so does the "R" term. Typically, for a small or medium size ferrite bead, this decrease starts for current in the ampere range; with a 0.5 times decrease in bead impedance for a few amperes of DC bias.

It is interesting to note that the upper region of the bead impedance vs. frequency curve is dominated by the resistive term R; i.e., the upper-frequency portion of the EMI spectrum is dissipated into heat.

Attenuation of a ferrite bead

The ferrite performs as a loss inductor, whose insertion loss is approximately.

$$A(dB) \approx 20\log(1+\frac{Z_{bead}}{Z_S+Z_L+Z_W})$$

where Z_S, Z_L = source and load impedance of the circuit

Z_W = wire impedance between source and load

Conversely, if source and load close to each other, becomes simply.

$$A(dB) \approx 20\log(1+\frac{Z_{bead}}{Z_S+Z_L})$$

These equations reveal several things that should be considered when choosing the ferrite as a possible solution:

1. Ferrite has little effect in high-impedance circuits.
2. Increasing N, the number of turns, ideally will multiply bead impedance by N^2.
3. If the wire impedance connecting source impedance and load impedance is already large (very resistive conductor, high self-inductance), the attenuation may be disappointing because of the wire impedance term.

Differential Mode and Common Mode Inductors

Inductors used for EMC purposes are low-loss, core-wound components, for use typically up to a few MHz, beyond which self-resonance makes them progressively less efficient. Their most typical application is for filtering the AC input of switch-mode power circuits, the output of switch-mode power supplies (SMPSs). Beside their use as stand-alone devices, they are also commonly incorporated in most EMI filters. Just like their dual element, the capacitor, they can be used against DM or CM interference. (Fig. 3.)

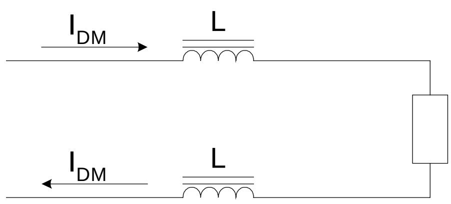


Fig. 3-1 Differential Mode Choke

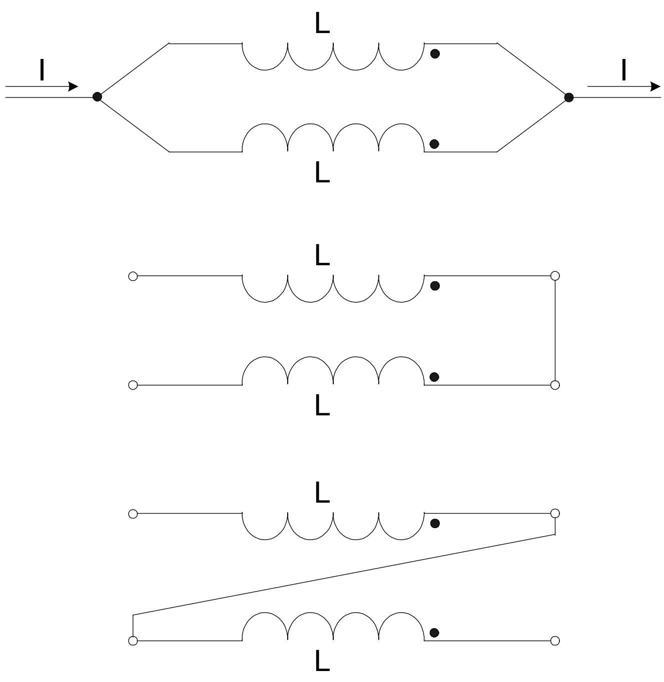


Fig. 3-2. Common Mode Choke

Fig. 3. Differential Mode and Common Mode Choke.

1. For DM suppression, there must be one inductor per wire; therefore the winding carries all of the DC or low-frequency components and the undesired higher frequencies. As a result, the magnetic core can be easily saturate and, for staying

within a reasonable volume and cost, the value of L is rather limited, as soon as the normal DM current exceeds a few amperes.

2. For CM suppression, the inductor has a double winding. The four terminals are to be connected in such a way that the DM current produces opposing magnetic fluxes in the core, hence the other name for these chokes.

To the contrary, as the CM currents flow in the same direction, their fluxes also have the same direction, and the core behaves as a single inductance with "two-wires-in-hand"(so called CM chokes). Since the normal DM current does not saturate the core, this allows more filtering capability (more L) in a given core size.

3. Combined DM + CM chokes. By letting a certain leakage flux take place in the device, a CM inductance with a certain DM value is created Typically, with such chokes, L_{DM} = 1 to 5% L_{CM}. (Fig. 3.)

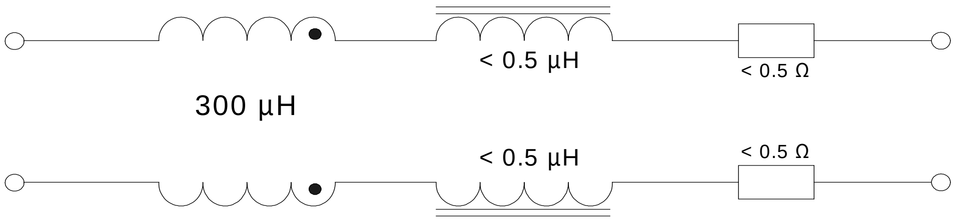


Fig. 3. Common mode choke with associated leakage inductances.

Indication method

1. For conducted EMI suppression (CM and DM) in all sorts of switch-mode power circuits (SMPS, variable speed drives, DC/AC inverters, etc) on mains input side
2. For DM chokes, when the EMI sources is a low-Z, high-current (typically above 0.5A) circuit
3. For ripple and EMI suppression on the output side of switch-mode power circuits

Installation method

1. Select an inductor with a generously rated current handling. Selection based on rms current can be misleading when the peak current has a high crest factor.
2. Install as close as possible to the switching source.
3. Check that the leakage resonance frequency, Fres, is sufficiently above the DM or CM noise frequencies and definitely well above the SMPS switching frequency, F_s; typically.

$$F_{res} > 5F_S$$

4. Prefer the packaging style with terminal lugs on opposite sides rather than side by side.
5. Do not install near susceptible circuits or components (e.g., sensors, A/D converters, feedback loops, op amps, and analog instrumentation amplifiers).
6. Beware of inductive kick at power-off. It may require a voltage transient protection device if there are fragile components on the same line.
7. Check that the resistive voltage drop (for CM and DM chokes) caused by the current stays within acceptable limits.

Ground Chokes

A ground choke is a special, low-value inductor put in series in the safety wire to artificially increase the ground-loop impedance, thus reducing the circulation of ground-loop currents via the interconnecting cables. The choke must have a value small enough to remain practically a short at power line.

Indication method

1. Use against EMI in the range of a few kHz to a few MHz when either of the following is the case:
   - The current probe shows similar CM currents in interconnecting cables and safety wire or ground straps.
   - Interconnected equipments are grounded to safety line at different points that may not be equipotent.
2. Use when the building or system safety ground bus is very polluted.
3. Use to decrease ground currents injected by the first harmonics of a switch-mode power supply.
4. Use when it is impossible to float either the PCB zero volt or the chassis from ground-loop problem is in the kHz to MHz region.

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