TESTING AND TROUBLESHOOTING THE COMMON MODE INDUCTOR

The great advantage of the common mode choke, compared to the DM choke, is that very high values of inductance can be achieved on a small magnetics structure.

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BACKGROUND

Power line filter design is always done in common mode (CM) and differential mode (DM) sections. A vital part of the CM filter is the CM choke. Its great advantage, compared to the DM choke, is that very high values of inductance can be achieved on a small magnetics structure. One of the major design considerations with the CM choke is leakage inductance, i.e., DM inductance. The traditional method of calculating leakage inductance was to assume it was 1 percent of the CM inductance. Actual measurements show that leakage inductance can vary between 0.5 percent and 4 percent of the CM inductance. This considerable margin of error can be significant when designing optimum chokes.

IMPORTANCE OF LEAKAGE INDUCTANCE

What causes leakage inductance? A toroidal structure which is closely wound over its full circumference contains all the magnetic flux within the "core" of the structure, even if the core is air. If, on the other hand, the structure is not wound over its full circumference or if it is not wound closely, then the magnetic flux may leave the core. This effect is proportional to the relative size of the gap left in the winding and to the permeability of the core material. The common mode choke has two windings arranged so that the currents conducted around the core flow in opposite directions resulting in an H field of zero. If the cores are not bifilar wound, for safety reasons, there will be two fairly large gaps in the winding. This physical arrangement automatically gives rise to magnetic flux "leakage" indicating that the H field is not really zero at all points as had been intended. The leakage inductance of a CM choke is a DM inductance. In fact, the flux associated with the DM inductance must leave the core at some point. In other words, the magnetic flux path is closed outside the core, rather than totally within the toroid.

If the core has a DM inductance, DM current will cause a flux swing in the core. If the flux swing is too high, the core will saturate. This saturation leaves the CM inductor with essentially the inductance of an air core solenoid. The CM emissions will thus be at as high a level as if the choke were not in the circuit. The flux swing in the CM core caused by the DM currents is:

$$\Delta\Phi = \frac{L_{dm} \bullet \Delta I_{dm}}{n} \qquad \textbf{(1)}$$

where

$\Delta\Phi$ is the flux swing in the core.

L_{dm} is the measured DM inductance.

ΔI_{dm} is the peak DM current.

n is the total number of turns of the CM core.

Since it is desirable to prevent saturation in the core by keeping B_{total} less than B_{sat}, the criteria is that

$$I_{dm} < \frac{B_{max} \bullet A}{L_{dm}} \qquad \textbf{(2)}$$

where

I_{dm} is the peak DM current.

B_{max} is the maximum flux swing desired.

n is the total number of turns on the core.

A is the cross sectional area of the core.

L_{dm} is the DM inductance of the core.

The DM inductance of the core may be measured by shorting the ends of one leg together and then measuring the inductance of the other two ends.

CONCLUSIONS ABOUT CM CHOKES

Filters are designed with CM and DM sections which are assumed to be independent; however, the sections are not truly independent since significant DM inductance may be contributed by the CM choke. This DM inductance may be modeled as a discrete DM inductor.

To take advantage of the DM inductance in filter design, the sections should not be designed simultaneously, but sequentially. First the CM noise should be measured and filtered. By using a differential mode rejection network, the differential mode can be excluded, and the common mode noise can be measured directly. When a CM filter is designed which keeps DM noise within limits, the composite noise, CM and DM, should be measured. Since the CM component is known to be beneath the limits, above the limits emissions are differential mode, attentuated by the DM leakage inductance of the CM filter. On low-power supplies, the DM inductance of the CM choke may be sufficient to correct DM emissions problems because DM emissions have a low source impedance, so even small amounts of inductance are effective.[1]

Although some DM inductance can be very helpful, too much DM inductance may result in saturation of the core. A simple calculation using Equation 2 should be done to avoid this saturation.

DETECTION OF SATURATION OF A CM CHOKE IN LISN-BASED TESTS

Detecting saturation of the CM core (total or partial)is often difficult. A simple test can show how much the CM filter attenuation is affected by a decrease in inductance caused by 60 Hz bias currents. The test requires an oscilloscope and a differential mode rejection network (DMRN). First, the line voltage is monitored with the oscilloscope. Proceed with input for channel A of the oscilloscope as follows. Set the oscilloscope time base to 2ms/div. Then the oscilloscope is triggered on channel A. Line currents will flow during the peak portion of the AC voltage waveform. During this peak a decrease in filter effectiveness is anticipated. The inputs of the DMRN are connected to the LISNs. The output of the DMRN is terminated in 50 ohm and connected to channel B of the oscilloscope. When the CM choke is operated in the linear region, the emissions monitored on channel B should increase by no more than 6 to 10 dB during the input current surge. Figure 1 shows the oscilloscope display of this test set up. The upper trace is common mode emissions; the lower trace is the line voltage. During the periods of peak line voltage, the bridge rectifier is forward biased and conducts the charging currents.

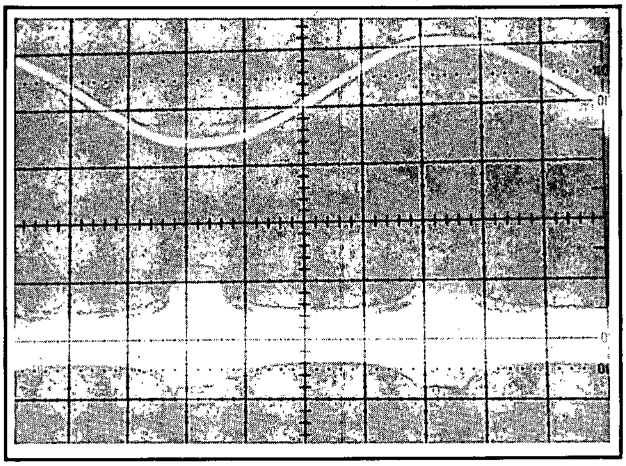

Figure 1. Oscilloscope Display of Degradation Factor of Common Mode Choke due to 60 Hz Charging Currents.

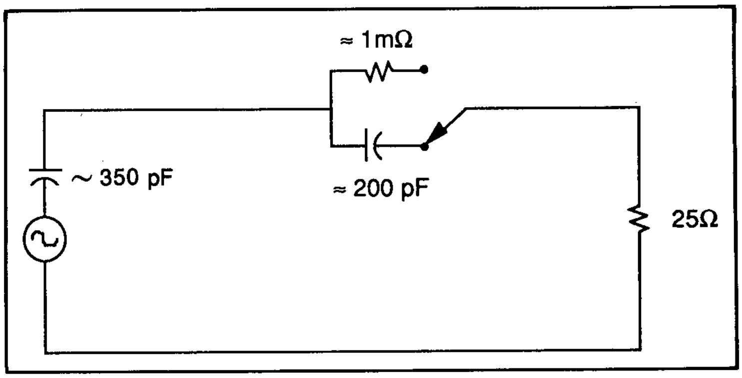

Figure 2. CM Emissions Equivalent Schematic.

If the CM choke is driven into saturation, the emissions during the input surge will increase. If the CM choke is driven into hard saturation, the emissions will be at virtually the same level as without a filter, i.e., easily 40 dB higher.

This experimental data may be interpreted in another way. The minimum value of emissions (during 0 line current periods) is the filter's effectiveness with a 0 current bias. The ratio of peak emissions to minimum emissions, the degradation factor, is a measure of the effect of line current bias on the filter's effectiveness. A high degradation factor suggests a less than original use of the core. A "natural degradation factor" on the order of 2 to 4 will be observed with a good filter in place. Two phenomena contribute to this degradation factor. First there is a decrease in inductance caused by 60 Hz charging currents. (See above.) Secondly the bridge rectifier is forward and reverse biased. The equivalent schematic for CM emissions consists of a voltage source with an impedance on the order of 200 pF, the diode impedance, and the common mode impedance of the LISNs. This schematic is shown in Figure 2. While the bridge is forward biased, voltage division occurs between the source impedance and 25 ohm, the LISN's common mode impedance. When the bridge is reverse biased, voltage division occurs between the source impedance, the bridge reverse bias capacitance, and the LISNs. When the diode bridge reverse bias capacitance is low, it contributes to the filtering of CM emissions. When the bridge is forward biased, the bridge has no influence on the filtering of CM emissions.

Because of this voltage division, a natural degradation factor on the order of 2 is expected. Actual values will vary considerably depending on the actual values of source impedance and diode bridge reverse bias capacitance. In a circuit patented by Flugan[2], this concept was employed to reduce conducted emissions from a ballast.

DETECTING SATURATION OF A CM CHOKE IN CURRENT-BASED TESTS

If a tester uses considerable caution, a similar technique may be used to detect saturation of a CM choke in a MIL-STD-461 test setup. The concept is employed as follows. Two current probes are used with the low frequency probe monitoring the line input current and the high frequency probe measuring only CM emissions currents. The line current monitor is used as the trigger. A potential problem with using current probes is that the DM current rejection is a strong function of wire symmetry in the core. With careful consideration of wire placement, roughly 30 dB of DM current rejection can be obtained.[3] Even with this rejection, the DM component measured may exceed the CM component intended for measurement. Two techniques can be used to overcome this problem. First, a high-order, high-pass filter with a 6 kHz corner frequency can be used in series with the oscilloscope. (Remember to terminate with 50 ohm.) An alternative is to use a discrete wire from each 10 μF capacitor to the power bus. To measure CM emissions, the current probe is clamped around these wires, which contain very small line currents.

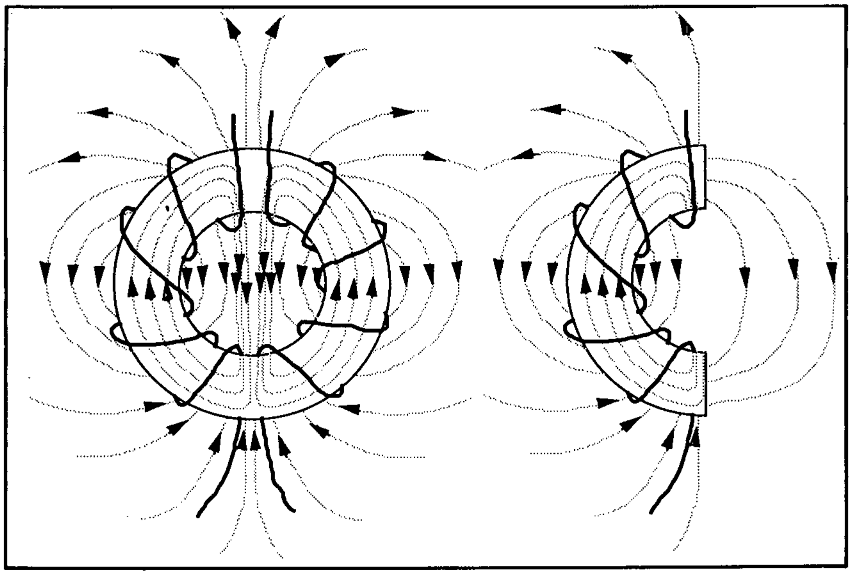

Figure 3. Drawing of DM Flux Path in a CM Core.

DM AND CM FLUX IN A CM CHOKE

For a quick and easy way to introduce the operation of a common mode choke consider the following explanation: "The fields from both sides of the core cancel out and there is no magnetic flux to saturate the core." Although this argument does embody an intuitive explanation of the operation of the CM choke, it is not physically true.[4]

Consider the following argument based on Maxwell's equations:

- Given that a current density J will produce an H field, one must conclude that another close-by current cannot cancel or prevent the presence of an H field, or the resulting B field.
- Another nearby current can cause an alteration of the path taken by the magnetic field.
- In the specific case of a toroidal common mode inductor, the DM current density found in each leg is assumed to be equal and opposite. Therefore, the resultant H field must sum to zero around the circumference of the core, but not outside the core!

The core acts as if it had been broken in half at the gaps in the winding, each coil generates fields on each half of the toroid. $\Delta \cdot B = 0$ implies that the fields must close on themselves through the surrounding air.

Figure 3 is a drawing of the core and flux path of DM currents.

CONCLUSIONS ON LEAKAGE INDUCTANCE

CM chokes work because μ_{cm} is many orders of magnitude greater than μ_{dm} and because CM currents are normally small. Smaller values of μ_{dm} are achieved by maintaining low values of L/D.

To gain CM inductance while minimizing DM inductance larger cross-section cores are preferrable to the use of more turns. By using a larger core than necessary, significant DM inductance may be incorporated into the CM choke.

Since the DM flux leaves the core (toroidal structure), significant radiation may occur. Especially in the case of on-board filters, this radiation may couple to the power lines causing increased conducted emissions. Also if permeable materials are brought within the field (e.g., when the core is placed within a steel case), a significant increase in net DM permeability may occur, resulting in saturation of the core due to DM currents.

NON-RADIATING CM CHOKE STRUCTURES

To implement an effective filter design, the radiation problem caused by flux leaving the core must be overcome. Methods of overcoming the radiation problem include containing the DM flux within the magnetic structure (pot core) or providing a high permeability path for the DM flux (E-core).

THE POT CORE STRUCTURE

When a pot core is used for a CM choke, two bobbins are used. Figure 4 shows two bands of windings in the window of a pot core and the resulting flux path. It also shows the DM flux path for the same configuration. Note that to a first order, all the flux is contained within the core. With this configuration, the length of the air gap from the outer surface to the center post of the core determines the net reluctance. By using a washer with a permeability >10, the net reluctance may be controlled by varying the inner and outer radii of the washer (length of the air gap).[5] The DM inductance of the pot core CM choke may be calculated as

$$L_{DM} = N^2 \cdot (\text{Washer Permeance} + \text{Window Permeance})$$

Washer Permeance =

$$\ln \frac{2\pi\,\mu_o(l_5-l_4)}{\left[\left(\frac{r_2}{r_1}\right)\cdot\left(\frac{r_3}{r_4}\right)\cdot\left(1-\frac{1}{\mu_r}\right)\right]} \approx \frac{2\pi\mu_o(l_5-l_4)}{\ln\left(\frac{r_2}{r_1}\right)\cdot\left(\frac{r_3}{r_4}\right)}$$

Window Permeance =

$$2\pi\,\mu_o \frac{1}{\ln\left(\frac{r_2}{r_1}\right)}\left[\frac{l_1}{3} + (l_2 - l_1) - (l_5 - l_4) + \frac{l_3 - l_2}{3}\right]$$

The physical dimensions are defined in Figure 5.

Reducing the reluctance of the DM path will increase the DM inductance. The primary advantage with this implementation of a CM choke is the inherent "self-shielding" property of the pot core.

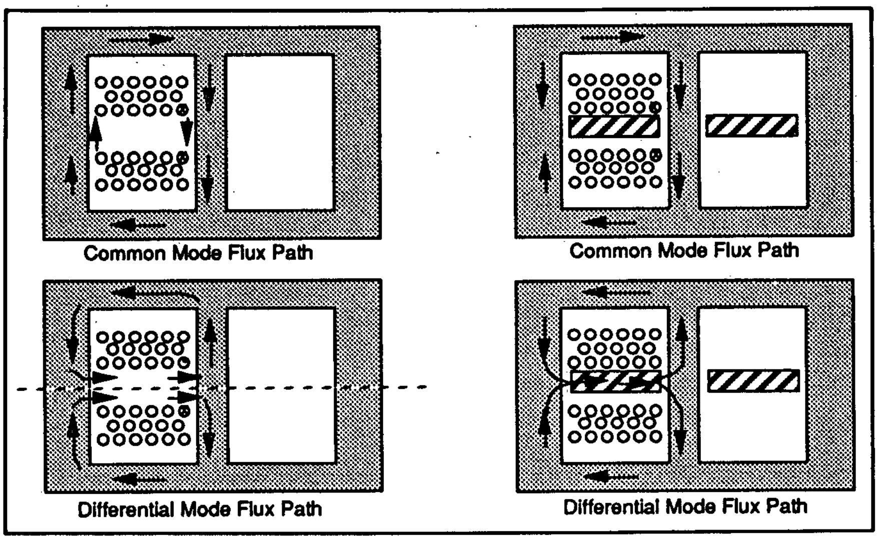

Figure 4. Flux Paths in a CM Pot Core Inductor.

E-CORE STRUCTURE

Another implementation of a CM choke which is easier to build than a toroidal core, but which has more radiation than a pot core, is the E-core as shown in Figure 6. Figure 6 shows that the CM flux links both coils on the outer legs. To achieve a high permeability, there should be no air gap in the outer legs. The DM flux, on the other hand, links the outer legs and the center leg. The permeability of the DM path may be controlled by gapping the center leg. The center leg is a primary area of radiation. ■

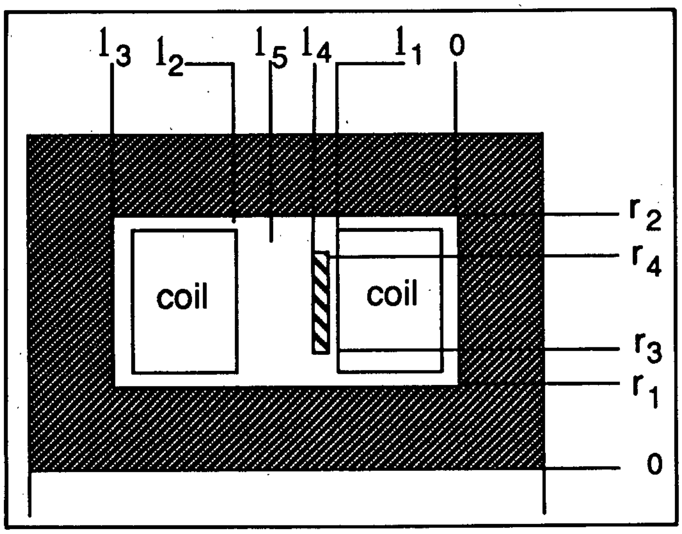

Figure 5. Pot Core Physical Dimensions for Calculating DM Inductance.

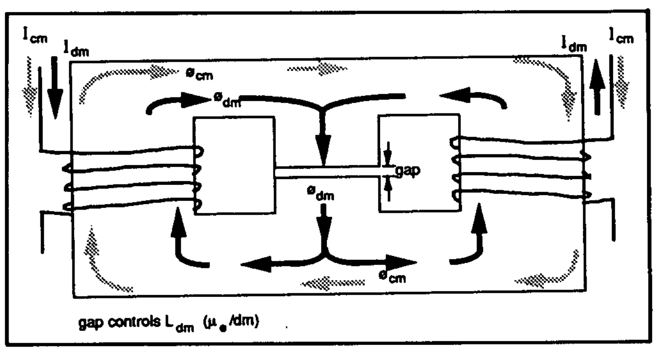

Figure 6. Flux Paths in a CM E-Core Inductor.

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