Calculating Parasitic Capacitance of Three-Phase Common-Mode Chokes

S. Weber[1], M. Schinkel[1], S. Guttowski[1], W. John[1], H. Reichl[2]

[1] Fraunhofer IZM, Gustav-Meyer-Allee 25, 13355 Berlin, Germany
[2] TU Berlin, Forschungsschwerpunkt Technologien der Mikroperipherik,
Gustav-Meyer-Allee 25, 13355 Berlin, Germany

stefan-peter.weber@izm.fraunhofer.de

Abstract

In this paper[1] the parasitic behaviour of CM-chokes with three phases is discussed in a frequency range up to 30 MHz. Therefore CM- and DM-impedances of three exemplars of eleven choke types are measured and calculated. The DM-inductance is 0.5 to 1% of the CM-inductance. Leakage inductance of one phase is $\frac{3}{2} L_{DM}$. Parasitic winding capacitances are in the range of 4 to 23 pF. The DM-capacitance is about 30% of the CM value. Furthermore the influence of the winding technology is quantified. Calculation of parasitic capacitance is accurate if the winding's geometry is well defined.

1 Introduction

Unfortunately, fast switching of high current and high voltage, the basic principle of every power electronic system, has got a high potential in emitting electromagnetic interference. The challenge of electromagnetic compatibility is a crucial aspect regarding the reliability of power electronic applications. State-of-the-Art in assuring electromagnetic compatibility in the radio frequency range are low-pass-filters with passive components.

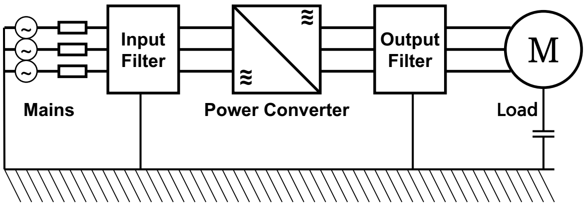

Fig. 1: Filter Design for a compatible Electric Drive System

The rapid advances in the semiconductor technology have enabled an ongoing volume shrinking of systems for energy conversion. Consequently, other devices like energy storage and filter elements become more and more the important factor regarding the system volume. In order to be able to fulfill the request for reduced volume, new packaging concepts are being investigated. Circuit components are arranged extremely closeby, sometimes in a real three-dimensional structure yet leaving the conventional PCB technology. The proximity of components can cause significant field coupling problems. In the past years, the systematic investigation of electromagnetic coupling effects caused by high density assemblies in power electronic systems has become another key aspect. [3]

The common way of assuring EMC according to CISPR 16 is, to determine filter components and topology for the necessary insertion loss at the lowest frequency, for example 150 kHz. After prototyping and measurement of the filter's performance, a working solution for the whole frequency range up to 30 MHz is found by an iterative trial and error process. [1]

A more efficient design process would take the parasitic behaviour of the components into account, if those were known [4]. A lot of work was done to calculate parasitics of EMI-filters' capacitors [3, 4] and inductances [6, 7]. The first calculations on parasitics can be found in papers from the early radio days in the 1930s [14]. Then electronic components were as big as power components are today.

2 Ferromagnetic Materials for CM-Chokes

Toroid cores are used to design chokes because they are made of one piece. Therefore they are much cheaper and provide a higher relative permeability than other core shapes. As the number of turns is small, the disadvantage of higher winding costs is not fatal and toroids are nearly always used for high power common-mode chokes.

In the frequency range above 10 kHz ferromag-

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Fig. 2: A 2.2mH choke with massive wire for 10A, a 2.4mH with Litzwire for 18A and a multi-layered choke with 0.85mH for 25A

	Ferrites (Ni-Zn, Mn-Zn)	Iron Powder	Nanocristal-line Iron
Permeability	+	-	++
Saturation	−	++	+
Conductivity	+	+	+
Price	++	+	−

Tab. 1: Comparison of ferromagnetic materials for high frequency applications

netic materials with reduced conductivity provide high permeability up to very high frequencies. The main types of materials, nickel-zinc and manganese-zinc ferrites, iron-powder-cores and nanocristalline-iron-cores with resistivities higher seven orders of magnitude than that of iron, are compared in Table 1. Although nanocristalline-iron-cores have the best performance they are very seldom used because of their high price. Applications with very high saturation currents are equipped with iron powder cores but the main material for common-mode chokes are the cheap ferrites.

3 The Current Compensation Principle in Terms of CM- and DM-Impedance

The CM-choke is a transformer which provides a high inductance to CM signals and a very low inductance to DM signals. This function is called current compensation because the high power DM current does not saturate the core.

The CM impedance of a three phase CM choke is the impedance of its three coils connected in parallel. While the mutual magnetic coupling adds to the impedance for CM signals, the magnetic flux of DM signals cancel each other out. Only the leakage inductance is magnetized by DM currents.

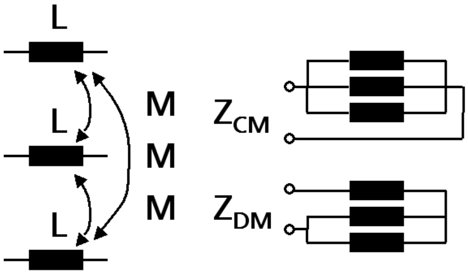

Fig. 3: CM- and DM-impedance of three phase CM-chokes.

$$\begin{aligned} L_{lk} &= L - M \\ L_{CM} &= L - \frac{2}{3} L_{lk} \approx L \\ L_{DM} &= 1.5\, L_{lk} \\ with\ L_{DM} &= 1\%\ L_{CM} \end{aligned}$$

An empirically approved approximation for L_{DM} is 1% of the CM-inductance. The 1% approximation is a worst case value in terms of core saturation. As the power carrying nominal current is a DM signal the leakage inductance is an important parameter and may not be too big to prevent core saturation. On the other hand it is a useful parasitic element to attenuate DM signals at higher frequencies. For a good filter design the leakage inductance is optimized so it is as big as possible, but small enough to prevent core saturation [6]. For example, if leakage inductance can be higher, one can use a core with lower permeability, with more windings needed there is more leakage inductance. Nave developed a calculation method for leakage inductance of two phase chokes which takes the geometry into account.

For this study CM- and DM-impedances of eleven choke types are measured. Figure 4 shows mea-

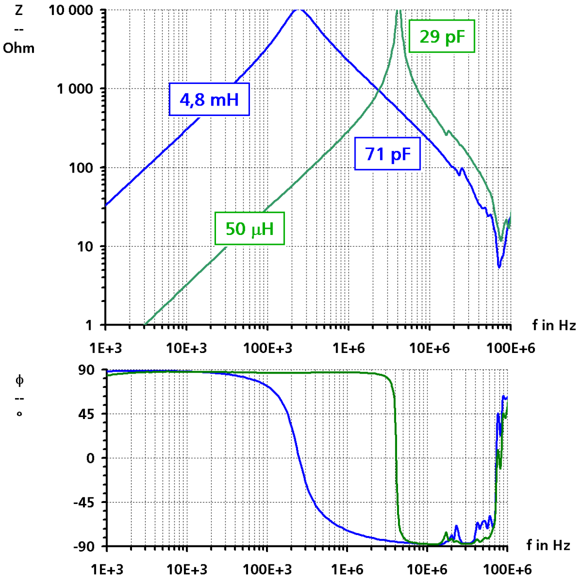

Fig. 4: Measurement of CM- and DM-impedance.

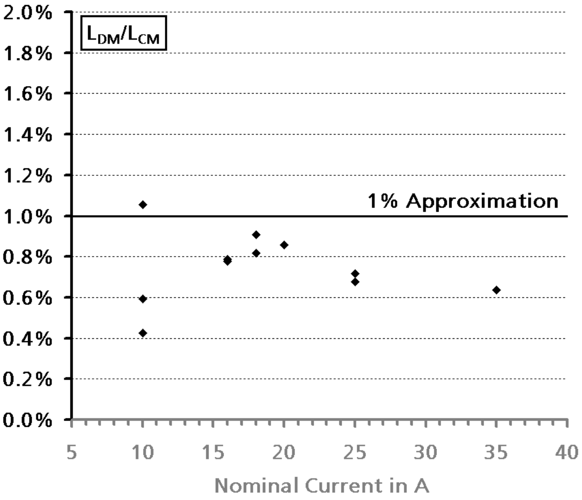

Fig. 5: DM-inductance as a percentage of the CM-inductance verifying the 1%-rule.

surement results. Parameters of equivalent circuits are determined at certain frequencies. CM- and DM-inductance are determined at 10kHz. The CM-capacitance is determined where the impedance is clearly capacitive with a phase of minus 90°. The DM-capacitance is determined at the resonance frequency in the range of MHz.

Figure 5 shows the measured DM-inductances as a percentage of the rated CM-inductance of all choke types. The DM-inductance follows no trend according to nominal current or absolute value of the nominal inductance but the measured values confirm the 1%-rule very well.

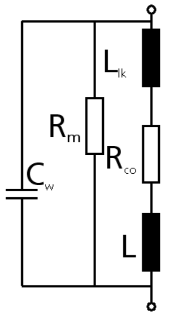

Fig. 6: Parasitics of single phase ferrite chokes.

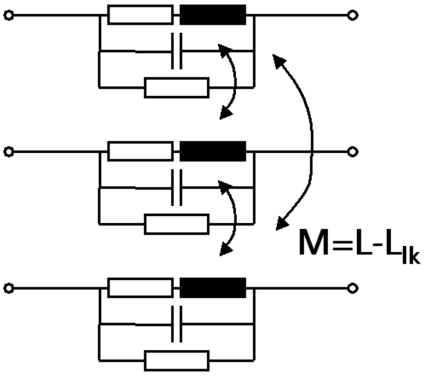

Fig. 7: Parasitics of three phase ferrite chokes.

4 Parasitic Capacitances

The high frequency behaviour of inductors is described by the equivalent circuit shown in Figure 6. Besides the leakage inductance L_{lk}, parasitics of chokes are resistors accounting for copper and magnetizing loss and the winding capacitance C_w.
Presupposed the three phase choke with three coils on the same core is just a combination of three single phase chokes, the equivalent circuit of a CM-choke including parasitics looks like Figure 7.
How do parasitics affect CM- and DM-impedance? With the impedance definition in Figure 3 the equivalent circuits in Figure 8 provide a CM-capacitance of three times the winding capacitance. The DM-capacitance is supposed to be two thirds of the winding capacitance. Therefore the ratio of DM- to CM-capacitance is $\frac{2}{9}$ or 22%.

Figure 9 shows the measured values of eleven choke types. DM values range from 4 to 19pF. Regarding the corresponding CM values from 13 up to 68pF the measured ratio is higher than the expected 22% due to additional parasitic capacitances between the three phases of the CM-choke. Measured ratios of parasitic capacitances of choke types with nominal currents from 10 to 35 Ampère

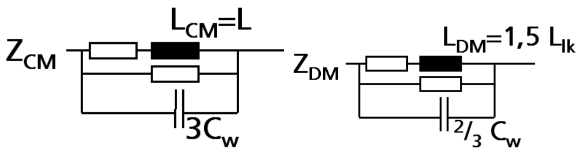

Fig. 8: CM- and DM-impedance of three phase CM-chokes including parasitics.

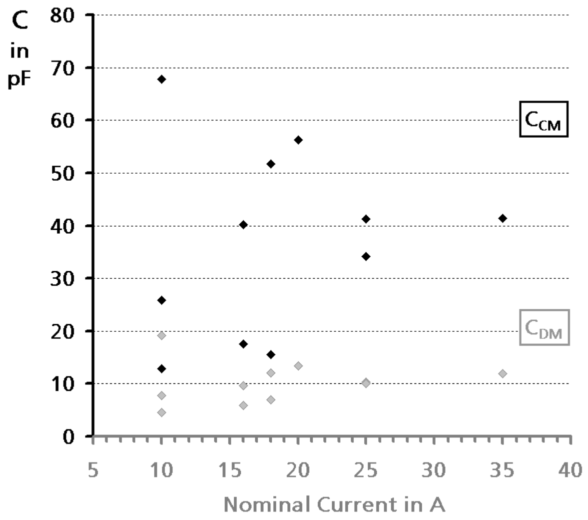

Fig. 9: Measured parasitic capacitances of eleven choke types with nominal currents from 10 to 35 Ampère

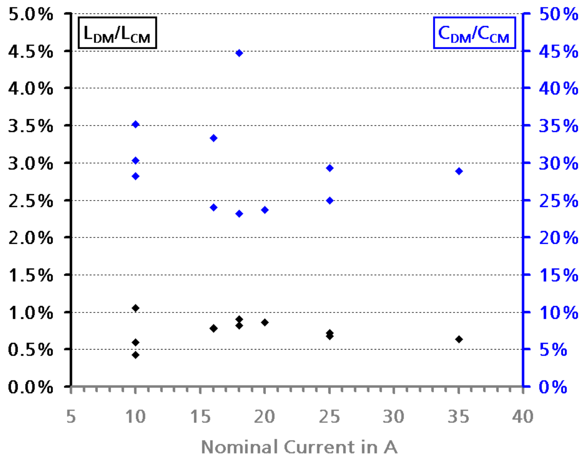

Fig. 10: Measured ratios of parasitics of eleven choke types with nominal currents from 10 to 35 Ampère

range from 23 up to 45% with a mean value of 30%. Hence the equivalent circuit in Figure 7 with a single lumped parameter for each coil is only an approximate physical model of a three phase choke.

5 Variation of Samples' Parameters

Variation of samples' parameters measured in this work is up to 25% with both, inductive and capacitive parameters due to tolerances of the core material on one hand and due to the variation of the assembly of samples windings on the other hand. Reproducable machine wound samples dont have any measureable variation in parasitic capacitance. The parasitic capacitance's variation of hand wound power components with few but large windings can be very high.

6 Calculation of Winding Capacitance

Single-layered cylindrical coils without any core have a winding capacitance depending only on the radius R of the cylinder [14].

$$C = 48\,R\,pF \tag{1}$$

Equation 1 shows, the winding capacitance of single layered coils in air is very small. The diameter of the coil had to be more than 40mm for C to become more than 1pF. The ferrite core acts as a perfect conducting electrode though the conductivity of ferrite is much smaller than that of copper [8]. Thus, capacitive coupling to the core raises the winding capacitance of single layer coils significantly. The distributed capacitance of a single-layered winding is calculated via the electrical energy $W_e = \frac{1}{2}\,C\,U^2$. As the part of the energy in the space between the windings is negligible the resulting winding capacitance C is one third of the capacitance between the winding and the core [5]. With cylindrical windings the surface of a cylinder is used to calculate the equivalent parallel plate capacitor [11]. This method is adapted to toroid windings with toroid surfaces.

$$C_w = \frac{C_k}{3} \quad with\ C_k = \varepsilon_r\,\varepsilon_0\,\frac{area}{distance} \tag{2}$$

Where *area* is the part of the toroid surface covered by the winding. ε_r depends on insulation material and air enclosures. The main parameter to determine the capacitance of single layer CM-chokes is

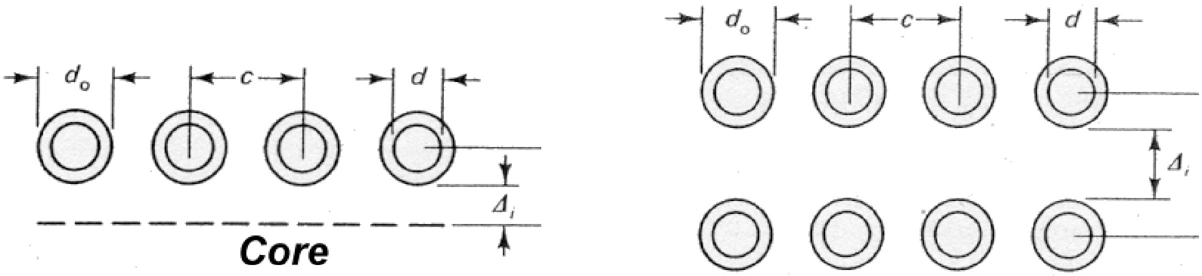

Fig. 11: Calculating the effective distance to the core and between two layers.

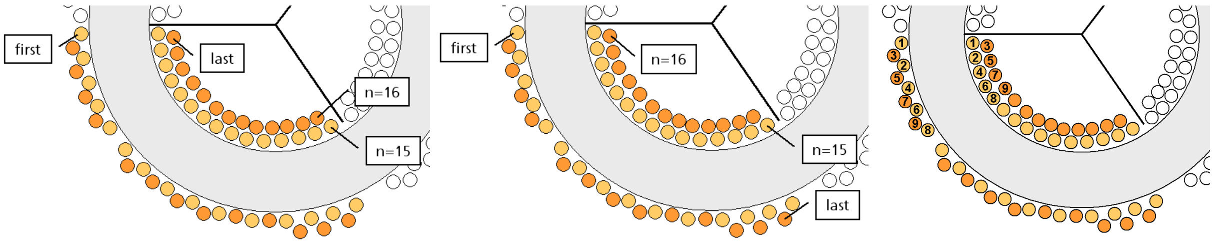

Fig. 12: Winding schematics for two-layer windings on toroids. The ongoing wound second layer on the left and the equally directed in the middle. The banked winding on the right has the lowest capacitance

the equivalent *distance* between windings and the core.

The effective distance for the calculation of the capacitance between layer and core is calculated easily if the assembly is well defined. Referring to [14] with the identifiers of Figure 11 the equivalent distance becomes:

$$distance = \Delta_i + \frac{1}{2}\left(d_0 - 1.15d + 0.26c\right) \qquad (3)$$

The distance Δ_i between windings and core may be difficult to determine especially of cores with rectangular cross-section. The insulation diameter d_0 equals approximately d with varnished wires. The distance c between windings is not constant along the windings. Inside the core c usually equals d_0. Its variation depends on the shape of the core and thus, there is to be determined the mean value.

Multilayer windings' capacitance is calculated from the layer-to-layer capacitances C_l. The global maximum of parasitic capacitance is with the two-layer winding because more layer-to-layer capacitances are connected in series. Regarding a two-layer winding with the second layer wound in the same direction than the first one, its capacitance becomes:

$$C_{equally\ directed} = \frac{C_k}{12} + \frac{C_l}{4} \qquad (4)$$

Only the twelvth part of the capacitance between the first layer and the core adds to the two-layer winding's capacitance. The layer-to-layer capacitance is dominant when C_k is not huge. There is a big influence of winding technology on C_l. With the second layer wound inversely directed C_l adds $\frac{4}{3}$ times more to the overall capacitance:

$$C_{inverse} = \frac{C_k}{12} + \frac{C_l}{3} \qquad (5)$$

C_l is calculated with the toroid surface between the layers and the equivalent distance according to Figure 11.

7 Minimization of Multilayer Winding's Capacitance

Generally the capacitance increases linearly with the dimensions of the regarded assembly. Nevertheless the parasitic capacitances does not increase linearly with the nominal current respectively the wire diameter because the choke types are also different in terms of core shape, number of turns and type of wire. As it was shown all these parameters do have an influence on the parasitic capacitance. Hence it is very difficult to calculate in advance if the geometry is not well defined.

The capacitance of single layered windings is small compared to multi-layer winding's capacitances. If these are not to avoid careful design of the winding can reduce parasitic capacitance significantly. The

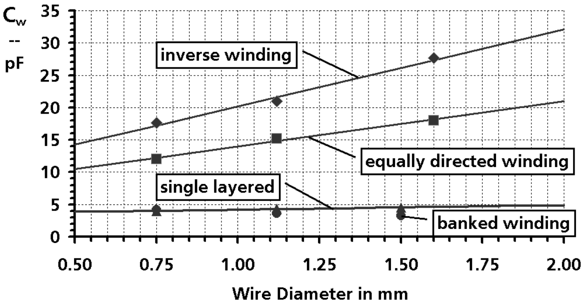

Fig. 13: Parasitic capacitance of windings on a ferrite core of approximately 32 turns.

maximum capacitance has the two layered winding with the beginning and the end of the winding in close proximity [7]. But even if two layers are necessary the parasitic capacitance can be reduced by clever winding techniques shown in Figure 12.

Zuhrt calculates from energy considerations [14] that the capacitance of the inverse two-layer winding is 133% of the winding wound in the same direction like the first layer. Figure 13 shows measurements with different wires on the same core and confirms both, the winding schematic reduces the parasitic capacitance by 33% and it increases linearly with the wire dimensions. Compared to the single-layer capacitance of a winding with the same number of turns, the two-layer capacitance may become very high. Therefore it is worthwhile to use low-capacitive winding techniques like banked winding for multi-layer windings. The measured values in Figure 13 show capacitances of banked windings in the range of single-layer capacitances. For high-end power chokes banked winding is the winding technology to choose.

8 Conclusion

In this paper the parasitic behaviour of CM-chokes with three phases is discussed in a frequency range up to 30 MHz. Therefore CM- and DM-impedances of three exemplars of eleven choke types are measured. The DM-inductance is 0.5 to 1% of the CM-inductance. Leakage inductance of one phase is $\frac{3}{2} L_{DM}$. Parasitic winding capacitances are in the range of 4 to 23 pF. The DM-capacitance is about 30% of the CM value.

It is possible to calculate the parasitic capacitance of cylindrical chokes if the assembly is well defined. Winding capacitances of CM-chokes on toroid cores are calculated analog to calculations of cylindrical chokes. Because of the great influence of parameters like distance to the core and relative position between windings, which is not constant along each winding, the calculations in advance are not exact. Nevertheless a good benefit is gained when taking into account realistic values. Furthermore empirical found values for winding capacitances on toroids support EMI-filters' design due to the linear relationship between capacitance and dimensions. Knowing parasitics enables new optimization approaches in designing EMI of power electronic systems.

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