# Influence of Mutual Coupling on Parasitic Capacitance in Common Mode Chokes

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*Abstract*—**In the search for a physics based model for a Common Mode Choke (CMC), the high frequency behavior of a multitude of chokes is studied. The high frequency behavior (above self-resonance) is often regarded as purely capacitive, while actually/obviously it has an inductive origin as well. The goal of this paper is to highlight and characterize this behavior and to warn for a common misconception.**

## I. Introduction

Filter design is a research area of importance for Electromagnetic Compatibility (EMC) as these are commonly used for Electromagnetic Interference (EMI) mitigation in a wide range of applications, while their usage is especially relevant in power systems. With the increasing trend of miniaturization, modularization and higher switching speeds in power electronics, a need for accurate high frequency component models arises due to unexpected high frequency behavior [1]. The investigation of parasitic effects of individual components has lead to simplistic models where physical origins were derived from [2]. In case of a non-ideal capacitor, the frequency dependent impedance can be modeled with an equivalent circuit consisting of a series connection between three ideal RLC-components. Where the inductance and resistance are considered to be a parasitic effect and named equivalent series inductor (ESL) and equivalent series resistor (ESR) respectively. In case of a non-ideal inductor, they are parallel connected as shown in Fig. 1a, with the capacitance and resistance to be parasitic and named equivalent parallel capacitor (EPC) and equivalent parallel resistor (EPR) respectively. The origin of ESL is often explained through the leads of the capacitors, while ESR is the conductivity of the materials. EPC is often thought to be the sum of several capacitances, while EPR is the considered to be a turn to turn field effect. Their values can be determined via impedance measurements.

The parasitic effects can be extended to higher complexity by incorporating mutual coupling effects between components, traces or even between component-parts. For relatively simple passive components like capacitors or inductors, inter-component coupling effects can be incorporated (based on curve-fitting) to increase simulation accuracy [3], [4]. The physical basis of these simplified models are explained in [5]. For instance, the leads of a capacitor form a AC-current loop with produces a magnetic flux that is picked up by any other loop and can be considered an inductive coupling.

For more complex components, such as the CMC, the self parasitics are already a challenge to address [6], [7]. Not only a mutual coupling exists within the component itself, but its dependent on the type of current (Common Mode (CM)/Differential Mode (DM)). Also non-linear behavior of the magnetic core material contributes to the complexity of modeling the component accurately [8].

Many models exist for describing a choke's behavior [6]–[10]. Many models show similarities with the equivalent impedance of a non-ideal inductor shown in Fig 1a. Sometimes the characteristics of the core are taken into account, but often only by including the mutual inductive coupling. Based on the equivalent circuit for three parallel and (magnetically) coupled inductors (Fig. 1b) one should be able to predict the approximate CM impedance based on a measurement of a single phase.

In [9], [10] it is assumed that the inductive coupling has negligible, to no, effect on the capacitive behavior of the CMC. Based on the explanation of the physical origin and analytical calculation of the capacitive behavior from [6] and [11], this assumption seems to be a valid one. In the calculation, it is assumed the capacitance is an infinite sum of small contributing capacitances. Integrating them all (or most of them at least) the surface integral will result in approximately the total capacitance. Their results show good agreement between measurements and calculations.

Equivalent circuit modeling based on curve fitting is a useful tool for describing a component or systems behavior in terms of circuit elements. In many cases it has been shown, that the resulting equivalent circuit has a physical origin and can thus be explained by physical parameters. This paper focuses on the modeling of the equivalent parasitic capacitance of a CMC and its physical origin.

In section II it is shown that the curve fitting method is not suited as a basis for deriving a physics based model. Section III-A increases the contribution of turn-to-turn capacitance ($C_{tt}$). In section III-B the effect of coupling through the magnetic core is investigated by measurements, which shows a need for incorporating inductive behavior in modeling a CMC at higher frequencies.

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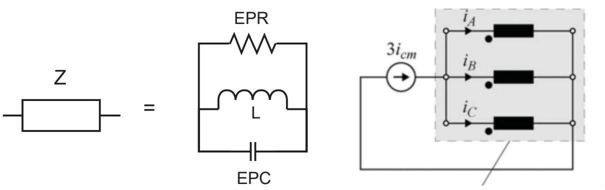



(a) non-ideal inductor (b) CMC

Fig. 1: Equivalent circuits of a inductor and a three phased CMC

## II. CM-Impedance modeling by curve fitting a single phase measurement

In Fig. 1a a possible equivalent circuit for a single inductor was introduced and Fig. 1b shows by placing three magnetically coupled impedances in parallel the CMC could be modeled. From the impedance measurement of a single phase ($Z_{phase}$), the RLC-values of the non-ideal inductor circuit can be extracted. Putting three of these circuits in parallel, with the addition of the mutual coupling, should result in the CM-impedance ($Z_{cm}$). Using the following equations, one could derive the appropriate values of the RLC-circuit and model the $Z_{phase}$ and $Z_{cm}$. The coupling coefficient k is often considered to be equal to 1.

$$L = \frac{|Z_{cmc}|}{2\pi f} \tag{1}$$

$$EPC = \frac{1}{2\pi f \cdot |Z_{cmc}|} \tag{2}$$

$$EPR = \max(Z_{cmc}) \quad \text{at} \quad f_{L=EPC} \tag{3}$$

$$M = k \cdot \sqrt{L_1 L_2} \tag{4}$$

The resulting fitted line, which represents the ($Z_{phase}$), is then plotted against the CM impedance measurement. Since this shows a good agreement, one would assume the modeling has been done correctly in this case and physical origins for the equivalent circuit components are sought. This paper focuses on the parasitic capacitance and the physical phenomena linked to it.

In [11], [12] a combination of numerous of capacitive effects results in the total EPC. Amongst others $C_{tt}, C_{tc}$ and $C_{ta}$. These respectively represent Turn-to-Turn, Turn-to-Core and Turn-to-Ambient capacitance. The simplest models only incorporate the $C_{tt}$. The measured EPC of a single phase should therefor be twice as small as the measured parasitic capacitance from the CMC. Due to the mere fact, that only half the amount of windings are being measured and that they are placed in parallel. It was demonstrated for a single CMC, that the derived capacitance of a single phase is equal to the measured capacitance of two parallel phases.

In the following section, an investigation on the parasitic capacitance is performed. Another approach is proposed to address the physical origin of the equivalent 'capacitive' behavior of CMC's and inductors in general.

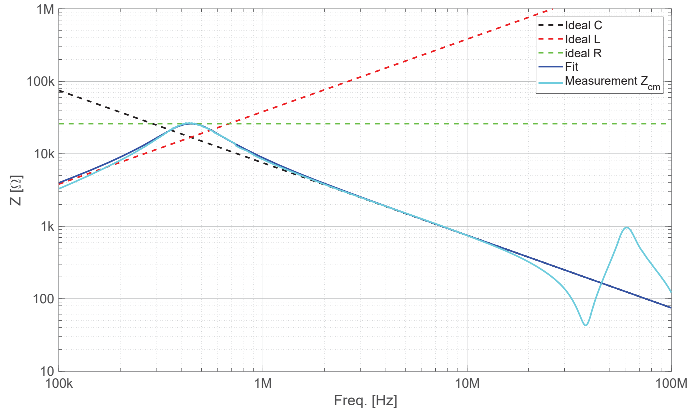
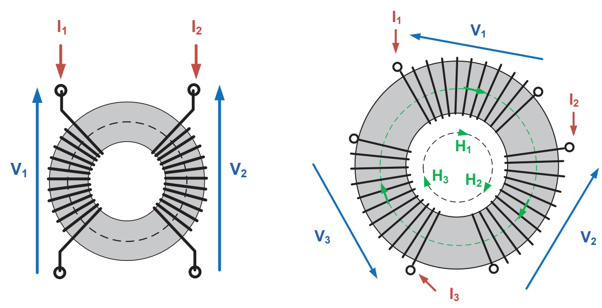



Fig. 2: Equivalent circuit (Fig. 1a) fitting based on the $Z_{phase}$ measurement with N = 26 compared to a $Z_{cm}$ measurement. $Z_{cm} \neq Z_{phase}$ is expected.

## III. Towards a physics based approach

Several two phased (Fig. 3a) and three phased (Fig. 3b) common mode chokes have been measured. A choke can be considered as two (or three) inductors on the same core, that introduces a mutual coupling effect through magnetic flux. The modeling of their non-ideal behavior has been addressed in section II and shown in Fig. 1a. The investigated EPC is considered to arise from a combination of multiple physical phenomena. The most obvious ones have been addressed in numerous publications, which are mostly capacitive in origin. $C_{tt}, C_{tc}$ and $C_{ta}$ are considered to be the dominant effects in most cases. In case the combined contribution of these capacitances are relatively small compared to some other unknown one, the assumption that they are dominant might be inaccurate. This section is divided into two subsections. Section III-A shows the phase and CM measurements of three different chokes. By increasing the windings it is assumed the EPC increases and the summed capacitive phenomena becomes the dominant effect. In section III-B the effect of mutual (inductive) coupling is investigated, by removing and introducing coupling in several measurement setups.




(a) 2-phase (b) 3-phase

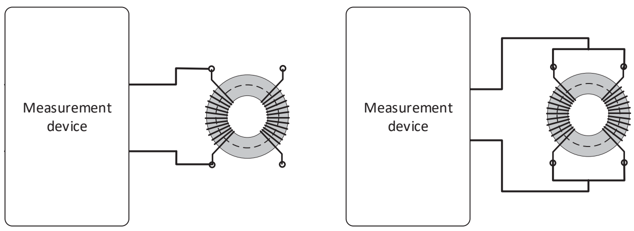
Fig. 3: sketch of CMC

## A. Dominant Capacitance

The investigation has been performed for three sectionally wound CMC's (Fig. 4), with increasing number of windings. They have been measured in two configurations shown in Fig. 5. Their measured common mode impedance $Z_{cm}$ and phase impedance $Z_{phase}$ are shown in Fig. 6a. As expected, their inductance value increases with increased amount of turns. This is also confirmed by the physical derivation of the inductance value of toroidal inductor given by [13].

$$L = \frac{\mu N^2 A}{l} = \frac{\mu N^2 h \ln \frac{d_o}{d_i}}{\pi} \text{ (toroid)}$$


Fig. 4: The measured chokes with data-sheet values: 5 mH, 10 mH and 20 mH and their amount of turns from left to right. The core material is MnZn.




(a) Phase impedance (b) Common Mode impedance

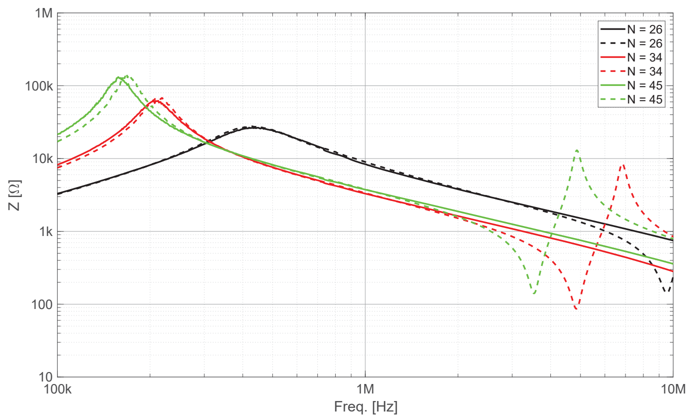
Fig. 5: Impedance measurement

Fig. 6a and Table I show that the EPC of the choke with N=45 is lower than in the case of N=34. Which is contradictory to the assumption: "the amount of windings is directly related to the total $EPC$". To investigate the capacitive behavior and compare the different chokes, the measured ratios between CM-EPC and Phase-EPC are displayed in Fig. 6b according to:

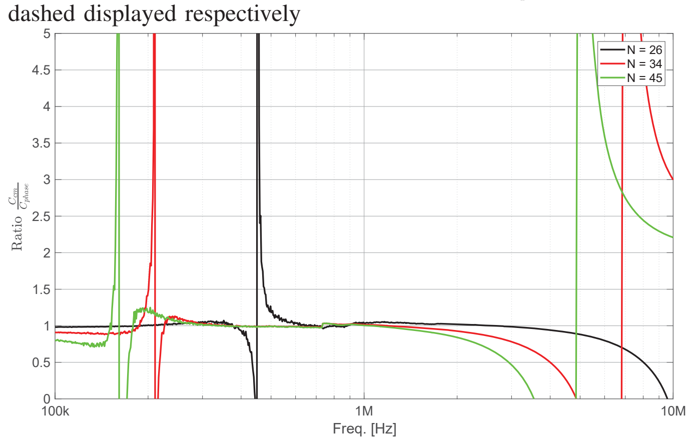
$$Ratio = \frac{EPC_{cm}}{EPC_{phase}}$$

In the previous section it was already mentioned, that a ratio of 2 is expected. As a CMC consists of two inductively coupled inductors in parallel. In the high frequency domain the inductors act as capacitors, and therefore should add up in the parallel case.

In Fig. 6b, the resonant peak of the $Z_{cmc}$ curve can be seen as the first asymptote. In each of the cases, the EPC ratio is equal to 1, up to a certain higher frequency. Even though the assumption of more turns is higher capacitance doesn't hold, the ratio between phase and CMC EPC is constant within a certain bandwidth. As the parasitic capacitance exhibits a more complex behavior than a mere physical capacitance would suggest, further investigation is required. In the next section mutual coupling through the core-material is investigated.




(a) Common mode $Z_{cm}$ and phase impedance $Z_{phase}$, solid and dashed displayed respectively




(b) Measurement of $EPC$ with impedance analyzer

Fig. 6: Impedance measurement

TABLE I: Measured values for the three investigated chokes with amount of turns N

| Chokes | L [mH] @100 kHz | EPC [pF] @1 MHz | EPR [kΩ] | Ratio EPC |
|---|---|---|---|---|
| N=26 | 5.2 | 17.7 | 27.71 | 1 |
| N=34 | 11.9 | 47.4 | 68.37 | 1 |
| N=45 | 27.2 | 42.2 | 143.81 | 1 |

## B. Mutual Coupling Effect

A relative simple model of a CMC consists of two parallel placed and inductively coupled inductors. In section II it has been shown by using equations 1 to 4, to calculate the values of the equivalent circuits displayed in Fig. 1, one is able to model a CMC's impedance. However, based on the assumption that the total parasitic capacitance increases by placing two identical inductors in parallel, the high frequency behavior of the CMC should not be equal to that of a single inductor.

In this subsection two identical three phased CMC's were used to investigate the mutual coupling between phases and its effect on the impedances. The measurements have been done for 2 and 3 phases. For simplicity, only the measurements of 2 phases are shown. In case of common mode currents the (non-ideal) inductors are connected parallel wise as shown in Fig. 1b and Fig. 3b. They have near perfect inductive coupling for low-frequencies. In this case, we define low-frequencies as those that are below the first resonant frequency of the choke. The ferromagnetic or nano-crystaline core provides an inductive coupling that influences a choke's behavior differently for DM and CM currents. The mutual induction between two inductances has been defined with equation 4.

Assuming near perfect coupling ($k \approx 1$) and identical winding $L_1 \approx L_2 = L$, one can calculate the resulting impedance. A CM measured CMC (Fig 5b) would have an inductance equal to L.

$$\frac{(L_1 + M) \cdot (L_2 + M)}{(L_1 + M) + (L_2 + M)} = \frac{(L + M)}{2} = L$$

while DM measured (Fig 7d) it would become approximately zero:

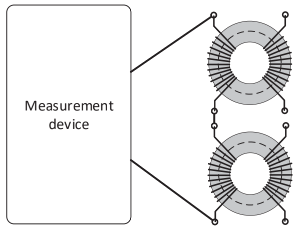
$$\frac{(L_1 - M) \cdot (L_2 - M)}{(L_1 - M) + (L_2 - M)} = \frac{(L - M)}{2} \approx 0$$

A vector network analyzer (VNA) with impedance analyses feature has been used to measure the chokes in multiple configurations. As explained only two out of three phases are shown, however the measurements have also been performed with a third identical choke. This resulted in similar results, however scaled to the amount of used phases. The ratio's have again been calculated with respect to a single phase measurement (Fig 5a). The following configurations were used in the measurement setup:

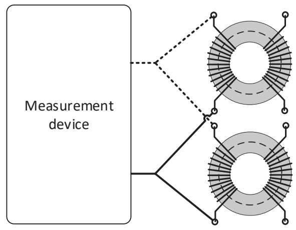
1) series-decoupled (Fig 7a)
2) parallel-decoupled (Fig 7b)
3) series-coupled (Fig 7c)
4) parallel-coupled (Fig 5b)

Which considers the phases as single inductors, that can be connected in series or in parallel. Either on the same core (coupled, $M = L$) or on different cores (decoupled, $M = 0$). Note however that in case of the coupled series connection the flux of the phases are additive in nature, as opposed to a DM measured CMC. As the coupling is primarily inductive in nature, it is expected that it has no influence on the EPC. Based on these assumptions Table II summarizes the expected values for each configuration. The DM results have been omitted in the graphs and table to reduce display complexity.

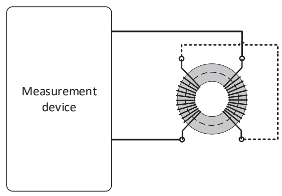
By comparing the results from Fig 8, which are summarized in Table II, one can see the expected inductances agree. In contrast to the expected EPC values. In case of two decoupled parallel phases the equivalent parasitic capacitance is additive and the ratio becomes $\approx 2$, while in the coupled case the ratio becomes 1 again. It appears the EPC is influenced by an inductive coupling. Therefore we can conclude the simplistic model as described in section II holds for low frequencies only. Also the assumption that the capacitive behavior of a CMC is



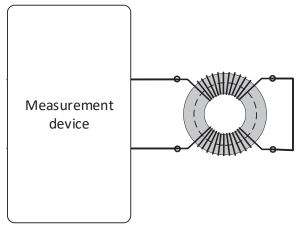

(a) Decoupled series impedance




(b) Decoupled parallel impedance

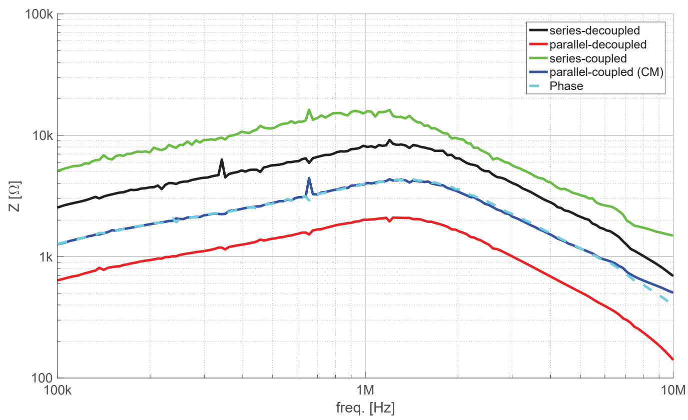



(c) Coupled (constructive) series impedance

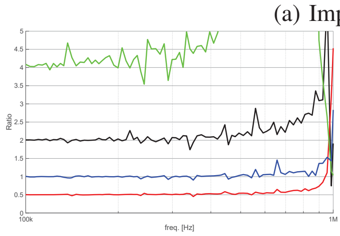



(d) DM i.e. Coupled (deconstructive) series impedance

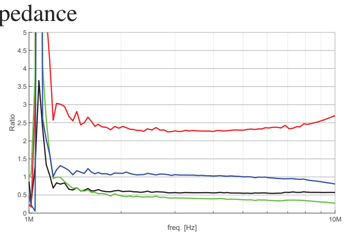
Fig. 7: Impedance measurement




(a) Impedance



(b) Inductance ratios



(c) Capacitance ratios

Fig. 8: Impedance measurements with the extracted inductance and capacitance values

TABLE II: Expected values for two phases and their approximated measured values from Fig 8

| | Expected L | Measured L | Expected EPC | Measured EPC |
|---|---|---|---|---|
| series-decoupled (Fig 7a) | $L + L = 2L$ | $\approx 2L$ | $\frac{1}{\frac{1}{C}+\frac{1}{C}} = 0.5C$ | $\approx 0.52C$ |
| parallel-decoupled (Fig 7b) | $\frac{L \cdot L}{L+L} = 0.5L$ | $\approx 0.5L$ | $C + C = 2C$ | $\approx 2.3C$ |
| series-coupled (Fig 7c) | $(L + M) + (L + M) = 4L$ | $\approx 4.1L$ | $\frac{1}{\frac{1}{C}+\frac{1}{C}} = 0.5C$ | $\approx 0.48C$ |
| parallel-coupled (Fig 5b) | $\frac{(L+M)\cdot(L+M)}{(L+M)+(L+M)} = L$ | $\approx L$ | $C + C = 2C$ | $\approx C$ |

merely a sum of physical capacitances seem to be a common misconception. For high frequency behavior modeling the inductive influence of the core at high frequencies cannot be neglected. However, as was mentioned, the core's capacitive influence is often incorporated.

## IV. Conclusion

This paper has shown that curve fitting can be an accurate method for creating an equivalent circuit describing the measured impedance closely. However applying it to physical modeling, one could be lead to false conclusions on effects involved. As the impedance above resonance looks like a capacitance, it does not mean it is a mere physical one. This paper has showed that the capacitive behavior of a CMC is influenced by the mutual coupling through the core material. Fig. 8c and Table II both have shown the measured EPC is not a mere super position of the corresponding capacitances of the individual chokes. The case of super position has been shown by the decoupled measurements, as the possible influence of inductive coupling has been removed. Therefor it was proved, in this case, modeling only physical capacitances cannot explain the behavior of a CMC. Further research is needed to produce a high frequency model of a CMC that incorporates physical inductive effects at these frequencies.

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