Predicting Parasitics and Inductive Coupling in EMI-Filters

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Abstract— **The challenge of EMC is a crucial aspect regarding the reliability of power electronic applications. State-of-the-art in assuring EMC in the radio frequency range are low-pass-filters with passive components. The nowadays filter design is characterized by a trial-and-error-process which is the more efficient the more experienced the designer is. An accurate prediction of EMI-filters' insertion loss requires the correct calculation of mutual coupling between the circuits' components aswell as of the components parasitics. It does need some experience to define crucial points of coupling and it would be best to calculate them by a field solver like the PEEC-method, which has become state-of-the-art in high speed chip design. In this paper it is shown that the prediction of EMI-filter performance can be improved by implementing coupling calculation on the basis of simple formulas, when using a field solver is not wanted.**[1]

I. 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 (EMC) is a crucial aspect regarding the reliability of power electronic applications. State-of-the-art in assuring EMC in the radio frequency range are low-pass-filters with passive components. With extending application of power electronics designing optimum EMI-filters has become a perseverative task of great concern to many system developers and researchers. Although methods of analysis and synthesis of EMC have been developed in the past also for the high frequency range [1, 2] there is still no 3D-CAD-tool to assist the EMI-filter designer. The nowadays filter design is characterized by a trial-and-error-process which is the more efficient the more experienced the designer is. Network simulation in the frequency domain is a powerful tool to analyze filter performance depending on noise source and sink impedances and filter topology. In the last years some work was presented to enable efficient EMI-filters' design using network simulations [3–5] including high frequencies. The presented results prove the possibility to develop a 3D-CAD-tool based on the PEEC-method which takes into account parasitics, inductive and capacitive coupling on a system level. This tool to be developed will be able to take into account electromagnetic interactions between close components which often lead to malfunction and EMC problems. Especially EMI-filters are susceptible to stray fields and coupling has to be taken into account when integrating filters into power devices. As a 3D-CAD-tool is not easy to use and may not become state-of-the-art for everyday's EMI-filter design, this paper presents design rules and easy to use formulas enabling more efficient filter design using a network simulator and the experience gained in the research of system level coupling.

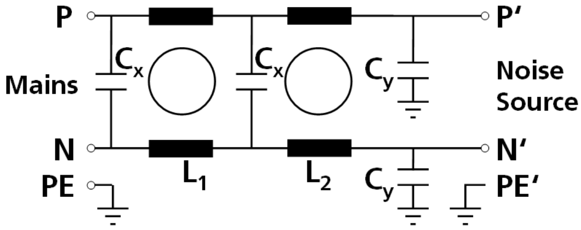

Fig. 1. Investigated filter's topology for single-phase applications.

II. Filter Synthesis - Level 1

In order to design an optimum EMI-filter the filter's topology must put into praxis a maximum mismatch in impedance between the filter and the noise source and sink. As this paper focusses on parasitics and coupling, further investigations are conducted comparing insertion loss in an easy to measure 50Ω environment. A single-phase two-stage filter for seven Amperes is taken as an example to present the developed calculation method.

The filter is designed for a minimum insertion loss of 20dB Differential-Mode (DM) and 30dB Common-Mode(CM) at 150kHz. It consists of two 0.47 μF X-capacitors, two CM-chokes of 2.4 and 3.5 mH and a 10 nF Y-capacitor per line, refer to Figure 1.

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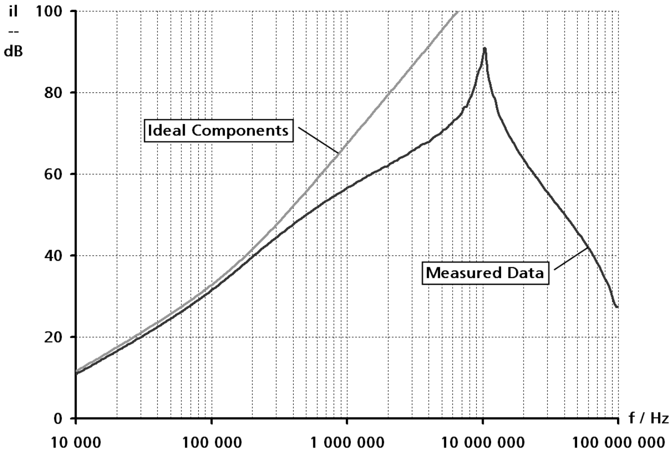

Fig. 2. Comparing insertion loss with measurements.

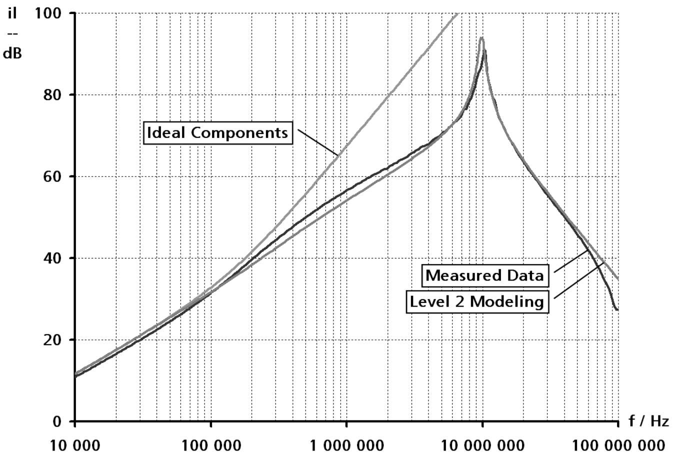

Fig. 3. Level 2 modeling takes into account the components' parasitic elements. In case of Common-Mode, level 2 modeling is very accurate.

A. Common-Mode Synthesis

As Y-capacitors may not be too big due to leakage current, the required CM-attenuation is to be reached mainly by chokes. A 30dB insertion loss in a 50Ω environment requires a 5 mH inductance which is built on two cores with A_l ≈10000nH. Applying 15 and 19 turns provide 5.9mH with a tolerance of ±25%. The 10nF Y-capacitors provide additional attenuation at higher frequencies.

To investigate filter performance the insertion loss between load and mains connectors of the filter is measured using a Gain-Phase-Analyzer HP4194A. Please notice that CM-attenuation is measured both lines in parallel with respect to ground.

As expected the attenuation measured at 150kHz is close to the ideal components' value. The slight difference even in the range of low frequencies is due to tolerances of the ferrite core material. Already at 500kHz there is a noticeable difference of more than 6dB due to parasitics.

B. Differential-Mode Synthesis

DM-attenuation is mainly achieved by X-capacitors because one is not limited in capacitance value between lines. DM-chokes are not very common because they have to withstand the high currents at low frequencies in terms of saturation. Nevertheless in CM-chokes design one does not minimize stray inductance [6] but optimizes it, because stray inductance is useful for attenuating DM. Thus, stray inductance should be as large as possible but small enough to prevent core saturation.

After level 1 design for the necessary insertion loss at 150kHz, todays practical EMI-filter design starts a trial-and-error process in order to achieve compatibility also at higher frequencies. It will now be shown that it is straight forward to take into account the high frequency behaviour of EMI-filters in advance using a network simulator.

III. FILTER SYNTHESIS - LEVEL 2

The international standard IEC 61800 regarding power drive systems with adjustable speed defines a range of intensional low frequency signals below 9kHz and the interfering high frequency signals above 9kHz. Therefore every component and effect of electrical characteristics between 9kHz and at least 10MHz has to be taken into account for efficient simulative filter design in the entire EMI frequency range.

Taking into account parasitics of lines and components can be done in several ways. The most accurate method is to measure these values for every part of the circuit. When executing these measurements utmost attention lies on the same working conditions than in the final circuit. The backdraw of this method for EMI-filters design is, that every component must be known at the time when one maybe wants to use different components. Therefore it is helpful to be able to calculate parasitics for every considerable component in advance. Calculating resistance of the circuit's lines is straightforward. The inductive parasitics of lines and components are calculated applying the "Concept of Partial Inductance" [7]. Every straight piece of conducting material has got its easy to calculate resistance and a partial self-inductance. Every filter component's high frequency behaviour is described by equivalent circuits with partial inductances. All loop inductances are then calculated correctly where all partial inductances are mutually coupled. Details to the calculation of ESL of capacitors can be found in [3]. Calculating winding capacitances in advance has been presented in [4].

A. Common-Mode Synthesis

The crucial parasitic parameter with CM insertion loss is the winding capacitance, because attenuation is mainly achieved by the CM-chokes. In the example chosen, a single layered CM-choke with 2.4mH - built of a R26 core and copper wire with 0.9mm diameter excluding the insulation - measured a winding capacitance of 1.1pF. The value calculated in advance is 1.5pF which is a very good accuracy. A second CM-choke with one and a half layers of that same wire built 3.7pF. The calculation in advance

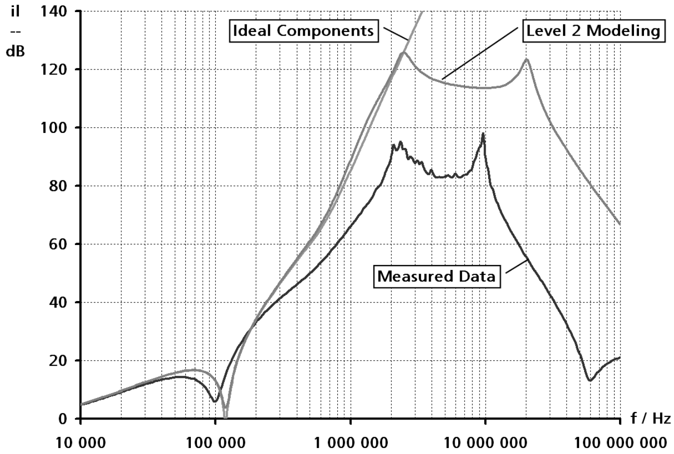

Fig. 4. Level 2 modeling takes into account the components' parasitic elements. In case of DM, level 2 modeling is still not very accurate.

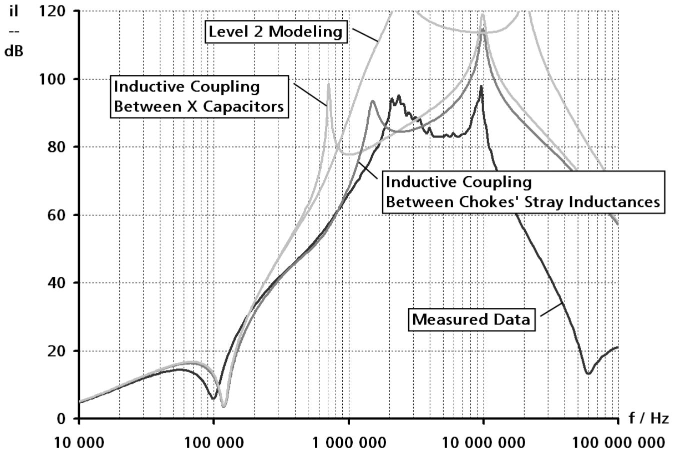

Fig. 5. DM-insertion loss taking into account mutual magnetic coupling between X-capacitors and between stray inductances of CM-chokes.

provides a value of 2.2pF which still is a good accuracy regarding the geometry tolerances with hand-made chokes and the simplifications necessary for efficient calculation [4].

Besides the winding capacitances of the CM-chokes the parasitic inductance of the Y-capacitors' path to reference potential is easily calculated using partial inductances. Comparing the calculated insertion loss with the measurement in Figure 3 shows that for the chosen example, level 2 modeling is sufficient to predict correct CM-performance in the entire range of conducted EMI up to 30MHz.

B. Differential-Mode Synthesis

As DM-attenuation is mainly achieved by X-capacitors, parasitic inductance of these is supposed to be most important for high frequency behaviour. DM-inductance of the CM-chokes is a little higher than the commonly expected 1% of CM-inductance because potted cores have been used. With potted cores DM-inductance is increased and parasitic capacitance using the core as an electrode is strongly reduced.

Calculating insertion loss while taking into account the components' parasitics provides the values shown in Figure 4. Please note that the Y-capacitors with their parasitic inductance show responsible for the second resonance at 20MHz. Although the prediction becomes better at frequencies higher than 2MHz, in case of DM, level 2 modeling is still not very accurate even at low frequencies such as 500kHz. Over all, calculated insertion loss is much too high. This divergence is mainly due to mutual inductive coupling between components and lines of the circuit. In the following it will be shown that crucial couplings may be taken into account on the basis of simple formulas.

IV. Filter Synthesis - Level 3

An accurate prediction of EMI-filters' insertion loss requires the correct calculation of mutual coupling between the circuits' components aswell as of the components parasitics. It does need some experience to define crucial points of coupling and it would be best to calculate them by a field solver like the PEEC-method, which has become state-of-the-art in high speed chip design [8]. However, lets see what can be done without such field calculations.

In general, capacitive coupling between parts of the circuit on a system level is observed at higher frequencies only, whereas mutual magnetic coupling is decisive even in the range of kHz. As DM-attenuation is mainly achieved by X-capacitors partial mutual magnetic coupling between those is firstly calculated to 1.2nH using the well known formulas for coupling between parallel current filaments located in the center of the capacitor's film roll.

Figure 5 shows an insertion loss reduction of more than 20dB by coupling between the filters X-capacitors in the first and the second stage. Another interesting point of coupling are stray fields of the CM-chokes. For further investigations the coupling between the two CM-chokes with DM-currents is measured depending on the distance between them and their orientation in 3D-space.

Figure 7 shows the result for the used chokes. As expected coupling decreases with the components' distance. For the example single-phase two-stage filters choke a mutual magnetic coupling of k=0.07 is determined. From the view of coupling between the chokes the commonly used orientation is worst. The stray field of one choke is directed to and on one level with the other choke. Some orientations might be avoided because they would result in a slightly unsymmetric filter build up. Regarding only coupling between the chokes and maintaining symmetry, the orientation with one choke rotated 90° out of the filter-PCB's level would provide lowest coupling.

Figure 8 shows three voltage gains of the EMI-filter with rotated magnetic axes of the CM-chokes' stray fields. This experiment shows that coupling with the chokes clearly affects filter performance in the entire frequency range. Due to the coupling of the chokes' stray field to the other surrounding components, none of the tried choke configura-

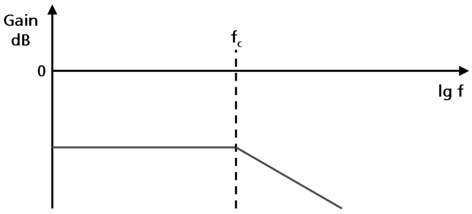

Fig. 6. Voltage gain between two similar CM-chokes in principle.

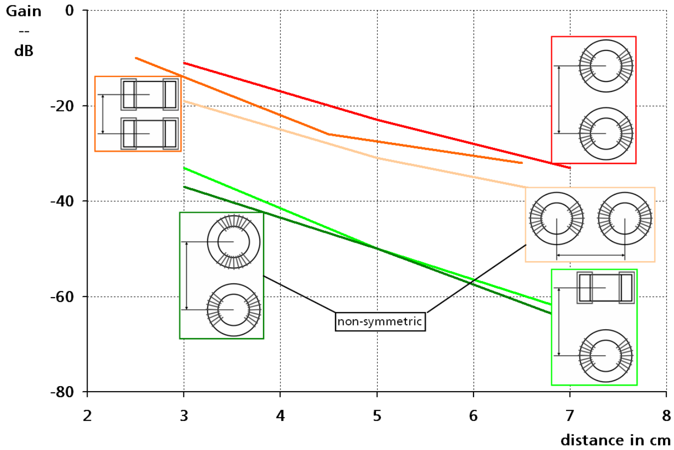

Fig. 7. Measured voltage gain at frequencies lower than f_C between two CM-chokes depending on distance and orientation of the components.

tions can said to be optimum. Thus, the complexity of coupling's impact on filter performance is also made clear. Referring again to Figure 5, which shows a good accordance of predicted and measured values up to 5MHz, it can be said, that the prediction of EMI-filter performance can be improved prominently by calculating the most important system level mutual magnetic couplings.

V. CONCLUSION

An accurate prediction of EMI-filters' insertion loss requires the correct calculation of mutual coupling between the circuits' components aswell as of the components parasitics. It does need some experience to define crucial points of coupling and it would be best to calculate them by a field solver like the PEEC-method, which has become state-of-the-art in high speed chip design. In this paper it is shown that the prediction of EMI-filter performance can be improved by implementing coupling calculation on the basis of simple formulas.

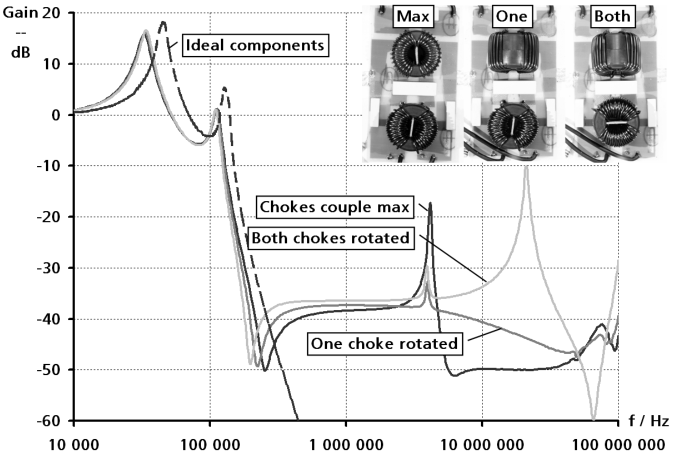

Fig. 8. Comparison of voltage gain with magnetic axes of CM-chokes rotated.

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