Optimizing Capacitor Placement in EMI-Filter using Back Annotation of 3D Field Coupling Parameters in Circuit Models

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Abstract—To reduce common mode (CM) and differential mode (DM) interference, a DM/CM integrated filter is often required to reduce the level of interference. This paper will show coupling from a Common Mode Choke (CMC) into $C_x$ capacitors can decrease the DM-filtering performance significantly at high frequencies. By retrieving equivalent circuit parameters from a 3D EM field simulation of the components, and include these parameters in the circuit simulator, an optimal capacitor orientation is determined. The optimized placement results in a 15 dB improvement between 5 MHz and 200 MHz.

I. INTRODUCTION

With the increasing trend of miniaturization and modularization in power electronics, Common Mode (CM) and Differential Mode (DM) EMI-filters are being integrated on a single printed circuit board [1], [2]. Passive, active and hybrid solutions are studied extensively in power electronics. With a current trend for implementation in switch-mode power supplies.

Much research exist regarding the performance of EMI filters. The parasitic effects of individual components has been a topic of research over the years, while accurate models were developed [7], [3]. The degradation of EMI filter insertion loss due to these self parasitic effect have been studied extensively. Overviews of the problems in passive EMI filter design are shown in [4] and [5]. Also the different techniques that have been investigated to increase filter performance at high frequencies by regarding component (self)parasitics are mentioned. These techniques usually consist of adding additional components to cancel $ESR$, $ESL$ or $EPC$.

In addition to self-parasitics, mutual parasitics have been known to show an influence on filter performance. In [5], [6] it is shown that a mutual coupling between components have been analyzed in numerous works. For instance in [7]–[10] where coupling between different combinations of passive components were studied.

From this point, 3D simulations are used to identify different stray coupling effects on EMC filter transfer functions. The work of [8] shows a hierarchical importance of different coupling mechanisms and later in [11] the same research group shows a possibility to use stray magnetic couplings to optimize the filters performance by adapting the PCB trace layout. This is done with Partial Equivalent Element Circuit-simulations (PEEC), which are usually used to model tracks or cables. While the optimization techniques of traces are being developed due to the higher hierarchical importance, the study of component placement optimization should not be neglected.

The concept of "A chain is only as strong as its weakest link" was shown in [5]: "that experiments have shown self-parasitics cancellation techniques do not introduce significant improvements if the mutual parasitic effects dominate and they are not sufficiently reduced in advance.". Since the inter-component coupling also has an impact on the EMI filter performance, it should be minimized simultaneously with component-trace coupling.

3D EM-field modeling of EMI filter components and the extraction of mutual coupling impedance based on S-parameters has been done in [12]–[16]. It has been shown that modeling results are in good agreement with measurements and multiple configurations of the "same" filter can be investigated with for instance CST MWS.

Above description of previous work shows a shift towards the extraction and inclusion of field coupling for accurate (passive filter) modeling and design. The focus tends towards 3D EM-field modeling, which often requires much computational power for the more complex and accurate models. The time to optimize the component placement will increase drastically with amount of coupling parameters that are being optimized. To overcome this problem, it is suggested to back annotate the mutual coupling impedance into equivalent circuit simulators and use fast optimization algorithms to discover near optimal solutions.

In this paper the back annotation optimization strategy has been applied to a DM/CM integrated EMI-filter shown in Fig. 1. It is based on the filter topology shown in Fig. 2, which is similar to common EMI-filter topologies described in [4]. The resulting equivalent DM and CM filter circuits are shown respectively in Fig. 3a and Fig. 3b. As is often the case, the design process splits the CM- and DM- filter design. The assumption of DM-components not effecting the performance of CM-components and vice versa is often implicitly assumed.

This paper will follow the design steps as if it were an actual commercially developed product. However for completion, some additional work was done for verification purpose. First
the basic design of the filter will be shown. A quick analytical approximation for coupling will be given, to estimate the possible influence. As the influence was considered to be possibly significant, a 3D simulation for mutual coupling extraction was done. The filters performance was then investigated using back annotation of the mutual inductance parameter into LTSPICE. In conclusion, the simulation results will be compared to measurements. The placement/orientation optimization is done manually in this case, due to the limited amount of configurations. It is applied to the inter component coupling between the DM inductance of the CMC and shunt capacitors. In this particular filter it shows that optimizing the layout, the insertion loss in DM can increase with approx. 15-20dB.

parasitic values, an impedance measurement was done with the Keysight E5061B Enhanced Network Analyzer (ENA). Fig 4 shows the two configuration in which the CMC was measured. The results are shown in Fig. 5. From this the following parasitic values were obtained:

\[ L_{dm} = 112 \mu \text{H}, \quad C_{p,dm} = 10 \text{pF}, \quad R_{p,dm} = 370 \text{k}\Omega \]
\[ L_{cm} = 18 \text{mH}, \quad C_{p,cm} = 45 \text{pF}, \quad R_{p,cm} = 15 \text{k}\Omega \]

The EMI-filter has two stages with two parallel capacitors which are identical and placed as \( C_x \) capacitors. To determine their parasitic ESL and ESR values, an similar impedance measurement was performed using the Keysight E5061B ENA. From this measurement the following values were obtained:

\[ C_x = 4.7 \text{nF}, \quad ESL = 8.2 \text{nH}, \quad ESR = 0.141 \Omega \]

In Fig. 3 four coupling paths are distinguished, while the mutual coupling between capacitors are neglected. This is based on the results of [17]. The mutual inductance between adjacent capacitors is 1.6 nH, which has a relatively small impact on the high frequency behavior of the overall filter. The four coupling paths are split into subcategories. The distinction is made between intra and inter component coupling effects. The coupling between the phases of the CMC is considered intra, while CMC to capacitor coupling is inter-component.

1) Intra-component: In this paper \( M_3 \) and \( M_4 \) are not modeled as separate mutual coupling impedances, as they are intra component coupling paths. By measuring the \( L_{dm} \) and \( L_{cm} \) of CMC as shown in Fig. 4, the coupling is already included. Therefor the "physical" placement in SPICE (Fig. 7) of \( M_3 \) and \( M_4 \) is omitted.

2) Inter-component: \( M_{1-1}, M_{1-2}, M_{2-1} \) and \( M_{2-2} \) are the inductive coupling paths between the CMC and the four shunt capacitors. Their values are approximated by:

\[ M = k \cdot \sqrt{L_1 \cdot L_2} \quad (1) \]
The impedance characteristic of the CMC is shown in Fig. 5. Which shows $L_{DM} = 108 \, \mu H$ and cannot be neglected. From [17] follows that $ESL = 19 \, nH$. Therefore the mutual coupling inductance can be approximated by $M = k \cdot \sqrt{L_1 \cdot L_2} = k \cdot \sqrt{19 \, nH \cdot 112 \, \mu H}$. Even with only 10% of coupling ($k = 0.1$), this would result in approx. $M = 145 \, nH$.

In most cases, this coupling would have been neglected due to the low DM inductance of the CMC. However, based on the findings in [9] it can be seen that the mutual coupling will be additive with the ESL as depicted in Fig. 6. According to [5], the insertion loss characteristic for high frequencies in these filter topologies are dominated by the ESL of the shunt capacitors. As shown in the approximation, the mutual inductance is in the same order of magnitude. To determine the impact on filter performance, the filter is simulated with LTSPICE as shown in Fig. 7.

### III. Simulations

#### A. Circuit Simulations

A distinction is made between the mutual inductances $M_{i-1}$ and $M_{j-2}$ according to the physical distance to the CMC. Based on the approximation, a coupling of 10% is assumed for $M_{j-2}$ and 5% for $M_{i-1}$. This is based on the orientation and placement of the components shown in Fig. 1. For simplicity reasons, only the orientation shown (vertically placed capacitors) is considered. Nevertheless, three coupling configurations are investigated:

- **a)** Parallel, which is the conventional type, where all generated currents are in phase.
- **b)** Cross-symmetric, is an alternative type, where the configuration is I-O, O-I. Therefore is **symmetric** around the CMC.
- **c)** Cross-asymmetric is an alternative type, where the configuration is I-O, I-O. Therefore is **asymmetric** around the CMC.

The distinction is made based on the current being generated in the capacitors either to be in-(I) or out-of phase(O) compared to the first capacitor on the left hand side of the filter.

These are shown in Fig. 8. Crossing the phase and neutral between two parallel capacitors is an idea described in [17]. It assures there is a negative coupling between the capacitors and results in a reduction of the combined $ESL$. In this paper the mutual coupling between CMC and two capacitors should also be reduced. When in parallel, the currents generated in one capacitor add constructively to the currents in the adjacent
one. When using this crossing method, the currents are 180° out of phase.

Fig. 9: The theoretical improvement gained by using a crossover of phase and neutral between capacitors in individual stages of the filter

Fig. 9 shows a theoretical improvement of 15−20 dB. Note however this is assuming the coupling factor to be 5-10%. To confirm the approximation a 3D simulation was created in CST MWS. This is explained in the following section.

B. Field simulation

The 3D EM-field simulation have been carried out on the simplified inductor model shown in [11] and the simplified capacitor model described in [15]. The models are sketched in Fig. 11. Since the focus of this paper is on back annotation, only the resulting mutual inductance will be presented here. Which was derived from eq. 1 in [13].

\[
M = \left| \frac{2 \cdot Z_0 \cdot S_{21}}{(1 - S_{22} + S_{22} S_{11} - S_{11} - S_{21})} \right| \left( \frac{1}{(2 \cdot \pi \cdot f)} \right) \approx 90 \text{nH}
\]  

This shows the coupling to be in the order of magnitude of ESL and therefore a limiting factor to the filter performance. Next the multiple configurations are measured and compared to the SPICE simulations.

1) Verification of Simulation: Measurements were done to verify the results from the 3D EM-field simulation. The S-parameters were measured between the actual used capacitor and CMC using the Keysight ENA. Fig. 10 shows the setup used. The capacitor was positioned at a similar distance as it is going to be implemented. The Mutual inductance is then calculated through equation 2 and results in:

\[
M_{ij-1} = 90.3 \text{nH} \quad M_{j-2} = 56.1 \text{nH}
\]

C. Back Annotation

To back annotate the 3D EM-field parameter of mutual inductance in the used circuit simulator, the coupling factor needs to be determined. By rearranging equation 1, the coupling factor can be determined based on the self inductances of the components and the mutual inductance between them.

\[
k = \frac{M}{\sqrt{L_1 \cdot L_2}}
\]

By implementing the found value for the coupling factor \( k \), the circuit simulation (shown in Fig. 7) can now be enhanced. This can then be used for choosing an appropriate component orientation based on the filter requirements.

IV. FILTER MEASUREMENTS

To determine the coupling factors value the following equation is used:

\[
k_1 \approx 0.1 \quad k_2 \approx 0.06
\]

The coupling factors that were determined from the 3D EM-field simulation are similar to the approximation that was made. Therefore the theoretical improvement shown in Fig 9 holds. Thus the back annotation of DM driven CMC to capacitor coupling suggests it is possible to increase the high frequency attenuation (by 15-20 dB) of a common EMI filter topology by choosing an "optimized" orientation of components. This is a noticeable achievement for two reasons. Firstly, the \( L_{dm} \) is often neglected, not to mention the coupling from this DM inductance to other components. Secondly, the optimized orientation was found using equivalent circuit simulations.

To verify the simulations, the multiple configurations of the EMI-filter were created and measured using a VNA. The configurations were all implemented on the same PCB. This was done in a similar manner as was shown in [17]. The PCB consists of four electrically separated conducting planes in which the topside (shown in Fig. 1) is used as neutral and bottomside as phase. The two planes on either side of the board are only connected through the CMC (and VNA). The capacitors are then alternately connected as shown in Fig. 12.
V. RESULTS

The measurements are shown in Fig. 13. As was predicted, the coupling between CMC and capacitors severely degrades the high frequency performance of the EMI filter. However an optimal placement of components found via back annotating the 3D EM-field coupling parameters increases the performance with approximately 15dB from 5 MHz to 200 MHz, which is an interesting application range from an EMC point of view.

![Fig. 12: 3D Model used to determine mutual coupling](image1)

![Fig. 13: DM - Measurement of filter](image2)

VI. CONCLUSION

Based on a simple approximation of the inductive coupling between components it was suggested that through optimized component placement an improvement of 15dB or more could be achieved for frequencies between 5 MHz and 200 MHz for this specific passive filter. The approximation was verified by 3D EM-field simulations and the mutual inductance parameter was back annotated into circuit simulations. It showed possibilities for high frequency performance improvement. Measuring multiple component orientations of the same implemented filter verified the expectations based on the simulations.

It has been shown that mutual coupling between components are also a limiting factor in high quality passive filters. Therefore the understanding of these coupling mechanisms and their modeling should be encouraged, even though coupling between components is of less hierarchical importance as was suggested. The paper has also shown that placement optimization can be done with back annotation of EM-fields into equivalent circuit simulators.

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