Simulation and Analysis of Conductive Electromagnetic Interference in Near-Field Magnetic Coupling

Chin-Hsiung Lee¹,* and Qinjun Hu²

¹Sino-Euro Aviation College, Fuzhou Polytechnic, China
²State Grid Zhangzhou Power Supply Co., China

*Corresponding author

Abstract. Inductors, common-mode inductors, transformers and other magnetic components are important components of power converters. Their layout and wiring may affect the ability to suppress EMI noise. As a result of miniaturization and higher power density, the composition of power converter becomes more and more compact, which leads to the near-field coupling effect between components. In our study, the mechanism of near-field magnetic coupling between magnetic elements is analyzed, and the accuracy of the parameters of near-field magnetic coupling is further verified by experiments.

Keywords: near-field magnetic coupling; simulation analysis; EMI; conducted EMI.

1. Background

Due to miniaturization and increased power density, the composition of the power converters have become considerably compact, which leads to near field coupling effects among the components [1-2]. Near-field coupling could be divided into magnetic field coupling and electric field coupling. The coupling among the magnetic components of power converters is mainly magnetic field coupling. It is reflected in the common-mode inductance, the parasitic inductance between the common-mode inductance and the capacitance loop, and between the common-mode inductor and other magnetic elements in the main circuit. [3-6]

2. Analysis of the External Magnetic Field of Magnetic Elements

The linkage of the magnetic field leakage from magnetic components is the main source of the near magnetic field coupling among the components. In this paper, a three-dimensional electromagnetic simulation software HFSS is used to analyze the spatial distribution of the magnetic fields from the magnetic components of the common mode inductors and transformers and their influences on other magnetic components.

2.1. Magnetic Field Distribution of Common Mode Inductor in Common Mode

Figure 1(b) is a HFSS three-dimensional simulation model, which is based on the size of a real common mode inductor (as shown in Figure 1(a)). The yellow part is windings, and the grey part is ferrite magnetic ring. The magnetic field distribution around the common mode inductor is obtained by setting the same current excitation on the inductor and conducting simulations. The result, the amplitude of the magnetic field around the common mode inductor, is shown in Figure 2.

Figure. 3 is a magnetic equivalent circuit diagram of common mode inductor and other magnetic components, where Rcm1 and Rcm2 are the equivalent reluctance in the two sides of the common mode inductor magnetic ring. Rg1 and Rg2 are the equivalent reluctance of the air loop, and R is the equivalent reluctance of the ferrite magnetic ring.
reluctance of other magnetic elements. Since the common mode inductors are excited by common mode currents in the same amplitude and phase, it is possible that the magnetic potentials produced by these two common mode current excitations would be opposite to the magnetic flux reversal produced by other magnetic components, and would thus be offset. Therefore, the magnetic field produced by the common mode inductor does not affect the magnetic elements around it.

![Physical diagram](image1.png)  ![3-D simulation model](image2.png)

**Figure 1.** Common mode inductor.

![Distribution diagram](image3.png)

**Figure 2.** Distribution diagram of magnetic field intensity around common mode inductors.

![External magnetic equivalent circuit diagram](image4.png)

**Figure 3.** External magnetic equivalent circuit diagram of common mode inductor.

### 2.2. Magnetic Field Distribution of Common Mode Inductor in Differential Mode

The model in Figure 4 is the same as Figure 1, but the direction of the current excitation is different. In Figure 4, current excitation with opposite direction was set to simulate the magnetic field distribution under differential mode current. The obtained distribution of the differential mode magnetic field around the common mode inductor is shown in Figure 5.

The differential mode magnetic equivalent circuit diagram of the common mode inductor is shown in Figure 6, where Rd1 and Rd2 are the equivalent reluctance in the two sides of the common mode inductor magnetic ring, Rg is the equivalent reluctance of the air in the magnetic ring, Rg1 and Rg2 are the equivalent reluctance of the air loop from the magnetic ring to other magnetic components outside the magnetic ring, and R is the equivalent reluctance of other magnetic elements. Common mode inductors are excited by differential mode current in the same amplitude but inverse phase. According to the superposition theorem, the magnetic flux generated by two differential mode currents excited by the common mode inductor is the same as the flux produced by other magnetic components. It's a
superimposed relationship. Therefore, the magnetic field generated by the differential mode of the common mode inductor will affect the magnetic components around it.

Figure 4. Three dimensional simulation model of common mode inductor.

(a) XY plane  (b) YZ plane  (c) XZ plane

Figure 5. Distribution diagram of magnetic field intensity around common mode inductors.

Figure 6. Magnetic equivalent circuit diagram.

3. Near Field Coupling and Decoupling of Magnetic Elements

The magnetic field coupling model can be expressed by the mutual inductance M. Therefore, in the near field coupling model of the inductor and capacitor of the EMI filter, it is a form of controlled voltage source, as shown in Figure 7. The current I in the figure is the current flowing through the interference source.

Because the EMI filter has many magnetic components and capacitor elements, the coupling relationship between them is more complex, which is not conducive to the analysis of their mutual influence. According to the principle of the circuit, we can decouple the components of the coupling relationship, and then analyze the coupling effect of the near field, just as the decoupling method of the basic circuit principle shown in Figure 8 and Figure 9.

(a) Near field coupling model of inductor.  (b) Near field coupling model of capacitor.

Figure 7. Near field coupling model of inductor and capacitor.
The two inductors L1 and L2 have mutual inductance M, which are positive coupling and negative coupling, respectively. The decoupling of the circuit can be realized through the equation.

\[
\begin{align*}
U_{AB} &= L_1 \frac{di_1}{dt} \pm M \frac{di_2}{dt} \\
U_{AC} &= L_2 \frac{di_2}{dt} \pm M \frac{di_1}{dt}
\end{align*}
\]

(1)

\[
\begin{align*}
U_{AB} &= (L_1 \mp M) \frac{di_1}{dt} \pm M \frac{d(i_1 + i_2)}{dt} \\
U_{AC} &= (L_2 \mp M) \frac{di_2}{dt} \pm M \frac{d(i_1 + i_2)}{dt}
\end{align*}
\]

(2)

4. Simulation Method for Extracting Near Field Coupling Parameters of Common Mode Inductors

HFSS is a powerful electromagnetic field simulation software, which is widely used in various engineering electromagnetic fields. Based on the Maxwell differential equation and using the finite element method, the calculation of the engineering electromagnetic field is transformed into a matrix solution. In this way, the three-dimensional model of HFSS is used to simulate the near field coupling of two common mode inductors.

The structure of the EMI filter of the prototype is shown in Figure 10(a). According to the placement of EMI filter, the 3D model is built in HFSS software, as shown in Figure 10(b). In order to facilitate the modeling and accurate simulation of the actual inductance, the winding of the common mode inductor model is made of a single turn, and the result is multiplied by the number of turns when calculating the mutual inductance.

Figure 10. A schematic diagram of the experimental filter and 3D model.
The magnetic coupling parameters of the simulated EMI filter must be excited by the common mode inductor, and the direction of the corresponding current is set in the HFSS simulation model, as shown in the red arrows of Figure 11.

![Figure 11. Current direction of common mode inductor model.](image)

**Figure 12.** The schematic diagram of the coupled two devices in HFSS simulation.

As the results of simulation with HFSS software are S, Y and Z parameters, the mutual inductance between the two devices can be calculated based on the Z parameters obtained by simulation. This is because the two devices with near field coupling can be regarded as a two port network, as shown in Figure 12. This two port network satisfies the Equations (5) and (6), where

\[ U_1 = Z_{11} \cdot I_1 + Z_{12} \cdot I_2 \]  
\[ U_2 = Z_{21} \cdot I_1 + Z_{22} \cdot I_2 \]  
\[ Z_{21} = Z_{12} = \frac{U_1}{I_2} \bigg|_{I_1=0} = j\omega \cdot M \]

Therefore,

\[ M = \frac{Z_{12}}{j\omega} \]  

| Table 1. Simulation parameters of mutual inductance (Unit: nH) |
|-----------------|-----------------|-----------------|-----------------|
| M1 | M2 | M3 | M4 |
| 65.57 | 65.75 | 65.44 | 65.99 |

The simulated Z parameters between the common mode inductor CM1 and the CM2, as shown in Figure 13, are brought into the Equation (6) to get the near field coupling parameters between the two common mode inductors, as shown in Table 1.
According to the simulation results in Table 1, we can see that the values of M1, M2, M3 and M4 are almost the same. Based on the decoupling model of T filter near field coupling, the parasitic inductance of the X capacitor in the two common mode inductor is 0.263 µH. The resonant frequency of the X capacitor in the two common mode inductor decreases, and the suppression ability of the EMI filter to the differential mode is reduced. At the same time, the mutual inductance parameter of the common mode inductor is far less than that of the differential mode component, so it can be neglected.

5. Conclusion
Firstly, the leakage of magnetic field and its influence on other magnetic components are analyzed. It can be seen from the analysis that the magnetic field of the differential mode component of the common mode inductor is disturbed by the external magnetic field as the common mode inductor works. Secondly, the near-field magnetic coupling mechanism between magnetic elements is analyzed, and the X capacitor is decoupled through the circuit decoupling principle. After decoupling, a mutual inductance on the X capacitor is superimposed with the ESL of the X capacitor itself. Finally, the magnetic coupling parameters of the common mode inductor are simulated by the three-dimensional electromagnetic field simulation software HFSS, and the accuracy of the simulation is verified by experiments.

Acknowledgments
This work was supported by Scientific Research Startup Foundation of Fuzhou Polytechnic under project RCQD201802.

References
[1] Li Longtao 2012. Modeling and effectiveness evaluation of switching power transmission EMI. Dissertation, Harbin Institute of Technology.
[2] Zhang Yu, Chen Qingbin, Chen Wei 2013. Study on EMI simulation of switched power supply. Proceedings of the Twentieth Annual Conference of China Power Society, pp 1205-1209.
[3] Ma Yinfei 2012. Research on the prediction of switched power transmission EMI. Dissertation, Hebei University of Technology.
[4] Chen Qingbin, Chen Wei 2012. Evaluation method for common mode conducted noise suppression capability of transformer in switching mode power supply. Chinese Journal of Electrical Engineering, 18, pp 73-79.
[5] Xu Ke 2012. Analysis and suppression technology of common mode electromagnetic interference in power electronic devices. Dissertation, Chongqing University.
[6] Chen Qingbin 2012. Research and application of magnetic field conduction EMI characteristics and filter near-field coupling characteristics of switching power supply. Dissertation, Fuzhou University.