Simulation Analysis of Near-Field Magnetic Coupling in Magnetic Elements

Chin-hsiung LEE¹,* and Qin-jun HU²

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

*Corresponding author

Keywords: Magnetic element, Magnetic field coupling, EMI, HFSS simulation.

Abstract. Magnetic components are an important part of power conversion. The placement and wiring of their magnetic elements may affect their suppression of electromagnetic interference noise. Due to the miniaturization and increasingly higher power density, the composition of the power converters become more and more compact, which leads to the near field coupling effects among the components. In this paper, we describe the mechanism of near-field magnetic coupling among the magnetic components. The accuracy of near-field magnetic coupling parameters is further verified by HFSS simulation.

Introduction

Magnetic components, such as inductors, common mode inductors and transformers, are important components of power converters. Due to the miniaturization and increased power density of power converters, the components of the power converters have become very compact, which leads to near field coupling effects among components [1-2]. The near-field coupling could be divided into magnetic field coupling and electric field coupling. The coupling of magnetic elements is mainly composed of magnetic field coupling, which is generally manifested in the mutual inductance between common mode inductors, between common mode inductors and capacitance loops, and between common mode inductors and other magnetic components of the main circuit [3-6].

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.

T-type Near Field Decoupling of Common Mode Inductor and X Capacitor

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. Because the EMI filter is usually a T-type with two common mode inductors and X capacitors, as shown in Fig. 1.

![Figure 1. Near field coupling diagram of T-type filter.](image-url)
Among them, M1 is mutual inductance between L1 and L3, M2 is mutual inductance between L1 and L4, M3 is mutual inductance between L2 and L3, M4 is mutual inductance between L2 and L4. It is assumed that the common mode inductor is positively coupled with the X capacitor parasitic inductance ESL. Similarly, by using the circuit decoupling method, the circuit shown in Fig. 1 can be decoupled into Fig. 2.

![Figure 2. Near field coupling partial decoupling diagram of T-type filter.](image)

Because there are no common nodes between L1 and L4, and between L2 and L3, they cannot be decoupled by simple circuit decoupling method. First, the parameters that have been decoupled in the circuit are ignored, and Fig. 3 is obtained, where I1, I2, I3 and I4 are the currents on the four windings of the common mode inductor.

![Figure 3. Near field coupling model of common mode inductor without common nodes.](image)

The equation can be obtained according to the principle of mutual inductance

\[
\begin{align*}
\begin{cases}
    u_{AB} &= L_1 \frac{di_1}{dt} - M_2 \frac{di_4}{dt} \\
    u_{CB} &= L_2 \frac{di_3}{dt} - M_3 \frac{di_2}{dt} \\
    u_{DE} &= L_3 \frac{di_2}{dt} - M_3 \frac{di_3}{dt} \\
    u_{FE} &= L_4 \frac{di_4}{dt} - M_2 \frac{di_1}{dt}
\end{cases}
\end{align*}
\]

Assume

\[
\begin{align*}
\begin{cases}
    u_1 &= -M_2 \frac{di_4}{dt} \\
    u_2 &= -M_3 \frac{di_3}{dt} \\
    u_3 &= -M_3 \frac{di_2}{dt} \\
    u_4 &= -M_2 \frac{di_1}{dt}
\end{cases}
\end{align*}
\]

The effect of mutual inductance is represented by a controlled source, and Fig. 3 can be transformed to Fig. 4.
Figure 4. Simplified model of near field coupling for common mode inductor without common nodes.

Because of the symmetry of EMI filter, it could be viewed that \( i_1 = i_2, i_3 = i_4 \) and \( M_2 = M_3 \), and the formula would be simplified to:

\[
\begin{align*}
\varepsilon_{AB} &= L_1 \frac{di_1}{dt} - M_2 \frac{di_2}{dt} = L_1 \frac{di_1}{dt} - M_3 \frac{di_3}{dt} = (L_4 - M_3) \frac{di_4}{dt} + M_3 \frac{d(i_1 - i_3)}{dt} \\
\varepsilon_{CB} &= L_3 \frac{di_3}{dt} - M_2 \frac{di_2}{dt} = L_3 \frac{di_3}{dt} - M_2 \frac{di_2}{dt} = (L_5 - M_2) \frac{di_5}{dt} + M_2 \frac{d(i_3 - i_5)}{dt} \\
\varepsilon_{DE} &= L_2 \frac{di_2}{dt} - M_3 \frac{di_3}{dt} = L_2 \frac{di_2}{dt} - M_2 \frac{di_2}{dt} = (L_4 - M_3) \frac{di_4}{dt} + M_2 \frac{d(i_1 - i_5)}{dt} \\
\varepsilon_{FE} &= L_4 \frac{di_4}{dt} + M_2 \frac{di_2}{dt} = L_4 \frac{di_4}{dt} - M_5 \frac{di_5}{dt} = (L_4 - M_5) \frac{di_4}{dt} + M_5 \frac{d(i_1 - i_5)}{dt}
\end{align*}
\]

The decoupling of Fig. 4 can be achieved from Eq. (3), as shown in Fig. 5.

Figure 5. Near field decoupling model for common mode inductor without common nodes.

Through the above method, the complete decoupling of T-type circuit can be realized, as shown in Fig. 6. At the same time, the near field coupling inductance of each branch can be obtained.

Figure 6. Near field coupling complete decoupling model for T-type filter.

**Mutual Inductance Measurement**

If the two magnetic elements are close to each other and the coupling coefficient is large, mutual coupling method can be used to measure the coupling coefficient between them. As shown in Fig. 7, the interference and interfered element are connected in series, namely, forward and reverse series in the manner of Fig. 7(b), (c), and the inductors of two cases are measured respectively. The coupled inductor M is obtained by a certain process of calculation.
When "forward series", such as Fig. 7(b):

\[ L_{\text{ser1}} = L_1 + L_2 + 2M \]

When "reverse series", such as Fig. 7(c):

\[ L_{\text{ser2}} = L_1 + L_2 - 2M \]

The mutual inductance of the interfered body and the disturbed body is as follows:

\[ M = \frac{L_{\text{ser1}} - L_{\text{ser2}}}{4} \]

As shown in Fig. 8, the two common mode inductors in the prototype are very close. Therefore, the mutual inductance measurement method can be used to obtain the near field coupling parameter M of the two common mode inductors. Since simulation shows that the values of M13, M23, M14 and M24 are very close, it is supposed that M13=M23=M14=M24=M. Subsequently, the circuit diagram of Fig. 8 can be coupled to the circuit diagram in Fig. 9.

\[ L_{\text{dm1}} = 2L_{\text{CM1}} - 2M_1 \]  

\[ L_{\text{dm2}} = 2L_{\text{CM2}} - 2M_2 \]
\[ L_{\text{test}} = 2L_{\text{CM1}} - 2M_1 + 2L_{\text{CM2}} - 2M_2 + 8M \] (9)

\[ M = \frac{L_{\text{test}} - L_{\text{dm1}} - L_{\text{dm2}}}{8} \] (10)

Through impedance analyzer, the \( L_{\text{dm1}} \) is 2.034 \( \mu \)H, \( L_{\text{dm3}} \) is 1.995 \( \mu \)H, \( L_{\text{test}} \)=4.571 \( \mu \)H. According to the Eq. (10), \( M \) is 0.068 \( \mu \)H. The average value of mutual inductance \( M \) between the two common mode inductors obtained by simulation is 0.0657 \( \mu \)H, and the error is about 3.4%. The simulation method of HFSS software is available.

**Conclusion**

In this paper, we present the leakage of magnetic field of common mode inductor and transformer in operation and its influence on other magnetic elements are analyzed. Through analysis and simulation, it can be concluded that the magnetic field of the differential mode component of common mode inductance has greater magnetic interference to the outside. The magnetic field of common mode component has less influence on the outside. The near-field magnetic coupling mechanism among magnetic elements is analyzed, and the T type near-field coupling of the common mode inductor 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, which makes the high frequency filtering performance of the filter worse. 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.

**Acknowledgement**

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

**References**

[1] Zhang Yu, Chen Qingbin, Chen Wei, Study on EMI simulation of switched power supply. Proceedings of the Twentieth Annual Conference of China Power Society, pp 1205-1209. (2013)

[2] Li Longtao, Modeling and effectiveness evaluation of switching power transmission EMI. Dissertation, Harbin Institute of Technology. (2012)

[3] Ma Yinfei, Research on the prediction of switched power transmission EMI. Dissertation, Hebei University of Technology. (2012)

[4] Chen Qingbin, Chen Wei, 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. (2012)

[5] Chen Qingbin, Research and application of magnetic field conduction EMI characteristics and filter near-field coupling characteristics of switching power supply. Dissertation, Fuzhou University. (2012)

[6] Xu Ke, Analysis and suppression technology of common mode electromagnetic interference in power electronic devices. Dissertation, Chongqing University. (2012)