Mutual Inductance Measurement and Analysis of Near-Field Magnetic Coupling

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Abstract. Magnetic element is an important component of power converter. It includes inductors, common mode inductors and transformers. Configuration and wiring of their components will affect the ability to suppress 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 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 the simulation through experiments.

Keywords. Near-Field Magnetic Coupling, Transformer, Inductor, EMI.

1. Introduction
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 [1-4]. 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 [5-8].

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. External magnetic field distribution of transformer
Figure 1 is a three-dimensional simulation model of PCB transformer, of which the basic structure is 5 turns on the primary side, 3 turns on the secondary side. The primary side is made of copper foil, and the secondary side is PCB winding. The actual direction of its current work is present in the red line shown in Figure 1(a).
The distribution diagram of the external magnetic field of the transformer is shown in Figure 2. It can be seen that there is still some leakage of magnetic field outside the transformer. The leaking magnetic field will affect the magnetic components around it.

![Three dimensional simulation model diagram of the transformer](image1)

**Figure 1.** Three dimensional simulation model diagram of the transformer.

![Distribution diagram of magnetic field intensity around a transformer](image2)

**Figure 2.** Distribution diagram of magnetic field intensity around a transformer.

The magnetic leakage of the transformer is caused by the equivalent winding of the transformer's primary and secondary windings outside the window, as shown in Figure 1(b). The magnetic equivalent circuit diagram of the transformer is shown in Figure 3. Rg1 and Rg2 are equivalent reluctance from the primary side winding of the transformer to the air loop of the other magnetic components. Rg3 and Rg4 are equivalent reluctance from the secondary side winding of the transformer to the air loop of the other magnetic components. R is the equivalent reluctance of other magnetic elements. It can be seen that the direction of the external magnetic potential generated by the primary and secondary windings of the transformer is superposed. Therefore, the transformer will affect other magnetic elements around it when it works.

![Magnetic equivalent circuit diagram outside the transformer](image3)

**Figure 3.** Magnetic equivalent circuit diagram outside the transformer.
3. The principle of near field coupling

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 4. 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 5 and Figure 6.

![Near field coupling model of inductor and capacitor.](image)

**Figure 4.** Near field coupling model of inductor and capacitor.

![Positive decoupling diagram of inductor.](image)

**Figure 5.** Positive decoupling diagram of inductor.

![Negative decoupling diagram of inductor.](image)

**Figure 6.** Negative decoupling diagram of inductor.

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 formula.

\[
\begin{align*}
U_{AB} &= L_1 \frac{di_1}{dt} \pm M \frac{di_2}{dt} \\
U_{AC} &= L_2 \frac{di_2}{dt} \pm M \frac{di_1}{dt} \\
U_{AB} &= (L_1 \mp M) \frac{di_1}{dt} \pm M \frac{d(i_1 + i_2)}{dt} \\
U_{AC} &= (L_2 \mp M) \frac{di_2}{dt} \pm M \frac{d(i_1 + i_2)}{dt}
\end{align*}
\]
4. 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 Figure 7, the interference and interfered element are connected in series, namely, forward and reverse series in the manner of figure 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 Figure 7(b):

\[ L_{\text{test}1} = L_1 + L_2 + 2M \]  
(3)

When “reverse series”, such as Figure 7(c):

\[ L_{\text{test}2} = L_1 + L_2 - 2M \]  
(4)

The mutual inductance of the interfered body \( L_{\text{test}1} \) and the disturbed body \( L_{\text{test}2} \) is as follows:

\[ M = \frac{L_{\text{test}1} - L_{\text{test}2}}{4} \]  
(5)

As shown in Figure 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 \( M_{13}, M_{23}, M_{14} \) and \( M_{24} \) are very close, it is supposed that \( M_{13} = M_{23} = M_{14} = M_{24} = M \). Subsequently, the circuit diagram of Figure 8 can be coupled to the circuit diagram in Figure 9.
Figure 9. Decoupling circuit diagram for mutual inductance measurement.

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

(6)

\[
L_{dm2} = 2L_{CM2} - 2M_2
\]

(7)

\[
L_{test} = 2L_{CM1} - 2M_1 + 2L_{CM2} - 2M_2 + 8M
\]

(8)

\[
M = \frac{L_{test} - L_{dm1} - L_{dm2}}{8}
\]

(9)

Through impedance analyzer, the Ldm1 is 2.034 µH, Ldm3 is 1.995 µH, Ltest=4.571 µH. According to the formula (9), M is 0.068 µH. The average value of mutual inductance M between the two common mode inductors obtained by simulation is 0.0657 µH, and the error is about 3.4%. The simulation method of HFSS software is available.

5. Conclusion
The leakage of magnetic field and its influence on other magnetic elements are analyzed in this study. From this research and analysis, we can get the mutual influence of common mode inductance on electromagnetic interference. The magnetic field of the differential mode component of common mode inductance is disturbed by the external magnetic field. However, the magnetic field of common mode component has little influence on the outside. There is a loop in the secondary side of the transformer, which also interferes with other magnetic components. 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.

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