

Mitigation of the Magnetic Field Using a Compensation Coil Connected in Parallel to the Source Coil

Silvano Cruciani⁽¹⁾, Wassim Boumerdassi⁽²⁾, Tommaso Campi⁽³⁾, Francesca Maradei⁽³⁾, Mauro Feliziani⁽²⁾

⁽¹⁾ Dept. of Industrial Engineering, Tor Vergata University of Rome, Rome, Italy

⁽²⁾ Dept. of Industrial and Information Engineering, University of L'Aquila, L'Aquila, Italy

⁽³⁾ Dept. of Industrial and Information Engineering, Sapienza University of Rome, Rome, Italy

Compensation coils are used to mitigate magnetic fields as they are simple, efficient and generally low-cost. They produce a magnetic field that opposes the incident one. They are classified into passive coils, when there is no excitation, and active coils when there is independent excitation. Here we propose a new compensation coil configuration that combines the advantages of passive coils (no excitation) with those of the active coil (high performance) using a parallel connection of the shielding coil with the primary source coil.

Index terms — Compensation coil, Magnetic field, Field mitigation, EMC, Electromagnetic field safety, Shielding, WPT.

I. INTRODUCTION

Compensation coils are devices used to reduce the intensity of unwanted magnetic fields in the environment that can produce electromagnetic field (EMF) safety and electromagnetic compatibility (EMC) issues. Passive compensation coils operate by natural electromagnetic principles, without the need for external energy, while active compensation coils require power supply and electronic control.

Passive coils rely on the principle of electromagnetic induction. They consist of loops of conductive wire arranged in specific configurations [1]-[3]. When an incident magnetic field links the coil, it induces a current in it that generates a reaction magnetic field that counteracts the incident one and, therefore, the resulting magnetic field is mitigated. Since they do not require an electrical power supply or electronic components, they are simple in construction and operation, highly reliable, cost-effective, and require minimal maintenance.

However, passive compensation coils have limitations as the field mitigation may be unsatisfactory. For this purpose, active compensation coils are much more efficient in terms of shielding performance [4]-[5], even if they require independent excitation, generally regulated with electronic control based on magnetic field sensing. Clearly this type of compensation coil is much more complex and therefore less robust, as well as much more expensive, so it is used sparingly.

In this work, a new type of compensation coil is proposed which combines the advantages of the passive coil (no independent excitation and robustness) and of the active coil (high shielding performance). The new idea presented here is to create a compensation coil powered by the same source coil via a parallel connection, therefore without an independent excitation system.

II. METHODS

The geometry and positioning of the compensation coil are critical for effective magnetic field cancellation. They essentially depend on the magnetic field distribution of the source coil and the desired cancellation zone. In this study the

magnetic field source is modelled as a planar circular coil, while the compensation coil is modeled as a circular coil, as shown in Fig.1, where r_{in} and r_{out} are the inner and outer radii of the planar source coil carrying a current I , r_{SH} is the radius of the circular compensation coil with current I_{SH} .

With the source coil geometry and current I held constant, we first determine the optimal values for I_{SH} and the radius r_{SH} to achieve maximum magnetic field mitigation. After determining the value of I_{SH} , the challenge lies in implementing an electrical configuration to generate this current effectively. Here, the idea is to generate this current by adopting a parallel connection with some turns of the source coil as shown in Fig.2, where the source coil is modeled by the inductor $L = L_1 + L_2$ and the compensation coil by L_3 , which is inductively coupled with L_1 and L_2 . In the figure the resistances and mutual inductances are not represented for simplicity, even if they are physically present. In the parallel connection I_{SH} is different from I in magnitude and phase. The latter can be varied using an additional series capacitor C_{SH} .

The primary coil, TX, with N turns is divided into 2 parts: TX,1 and TX,2. The part TX,2 of n turns is connected in parallel with the shielding coil. Then, the circuit can be modeled by three different coils and analyzed by the following equations:

$$\begin{bmatrix} V_{TX,1} \\ V_{TX,2} \\ V_{SH} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{12} & Z_{22} & Z_{23} \\ Z_{13} & Z_{23} & Z_{33} \end{bmatrix} \begin{bmatrix} I_{TX,1} \\ I_{TX,2} \\ I_{SH} \end{bmatrix} \quad (1)$$

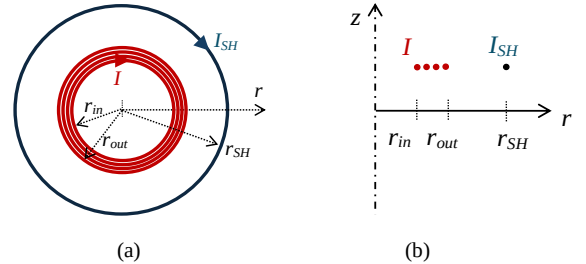


Fig.1. Planar source coil (in red) with a circular compensation coil (in blue). (a) Top view; (b) Axially symmetrical representation.

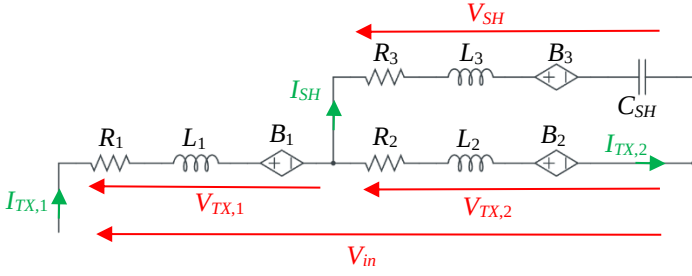


Fig. 2. Equivalent circuit of the system (B1, B2 and B3 are current-controlled voltage sources modeling the inductive coupling between coils).

where $z_{ij} = \pm j\omega k_{ij} \sqrt{L_i L_j}$ is the mutual coupling between the coils i and j when $i \neq j$ being k_{ij} the coupling coefficient, while $z_{ii} = R_i + j\omega L_i$ is the self-impedance of the i th coil, being R_i the coil resistance and L_i the self-inductance when $i, j = 1, 2, 3$.

The electrical conditions of the circuit connections are:

$$V_{in} = V_{TX,1} + V_{TX,2} \quad (2)$$

$$V_{TX,2} = V_{SH} \quad (3)$$

$$I_{TX,1} = I_{TX,2} + I_{SH} \quad (4)$$

where $V_{TX,1}$ is the voltage across N - n turns and $V_{TX,2}$ is the voltage across the remaining n turns. The shielding coil is connected in parallel with the n turns. From (1)-(4) it yields:

$$\begin{bmatrix} V_{in} \\ 0 \end{bmatrix} = \begin{bmatrix} z_{11} + 2z_{12} + z_{22} & z_{13} + z_{23} - z_{12} - z_{22} \\ z_{13} + z_{23} - z_{12} - z_{22} & z_{22} + z_{33} - 2z_{23} \end{bmatrix} \begin{bmatrix} I_{TX,1} \\ I_{SH} \end{bmatrix} \quad (5)$$

By considering the terminations, the analysis can be simplified by modeling the source as a voltage source V_s in series with a source resistance R_s . This yields:

$$\begin{bmatrix} V_s \\ 0 \end{bmatrix} = \begin{bmatrix} z_{11} + 2z_{12} + z_{22} + R_s - j\frac{1}{\omega C_{TX}} & z_{13} - z_{12} + z_{23} - z_{22} \\ z_{13} - z_{12} + z_{23} - z_{22} & z_{22} + z_{33} - 2z_{23} - j\frac{1}{\omega C_{SH}} \end{bmatrix} \begin{bmatrix} I_{TX,1} \\ I_{SH} \end{bmatrix} \quad (6)$$

where C_{TX} represents a series compensation capacitor (not shown in Fig.2), if present. The series capacitor C_{SH} is used to minimize the phase difference between the currents $I_{TX,1}$ and $I_{TX,2}$, or to enhance the shielding effectiveness (SE).

III. RESULTS

The considered electro-geometrical configuration of Fig.1 was simulated with the following parameters: $r_{in} = 200$ mm, $r_{out} = 227$ mm, $r_{SH} = 300$ mm, $z = 0$, $f = 85$ kHz, $V_s = 10$ V, $R_s = 100$ m Ω , $C_{TX} = 37.94$ nF, $N = 10$, $n = 1$, $R_1 = 295$ m Ω , $L_1 = 76.1$ μ H, $R_2 = 27.5$ m Ω , $L_2 = 1.54$ μ H, $R_3 = 25.4$ m Ω , $L_3 = 2.2$ μ H, $k_{12} = 0.68$, $k_{13} = 0.259$, $k_{23} = 0.24$. The coil currents obtained by the circuit analysis are shown in Fig. 3 for different values of C_{SH} . It can be observed that $I_{TX,1}$ and $I_{TX,2}$ are approximately in phase when $C_{SH} < 1$ μ F.

The magnetic shielding effectiveness is defined as $SE = 20\log_{10}(B/B_{SH})$, where B is the magnetic flux density without the shielding coil and B_{SH} is the magnetic flux density with the shielding coil. It is calculated vs. C_{SH} at different points $r > r_{SH}$

assuming $z = 0$, and the results are shown in Fig.4. As observed, SE is always larger than 35 dB, representing a significant value of magnetic shielding at this intermediate frequency.

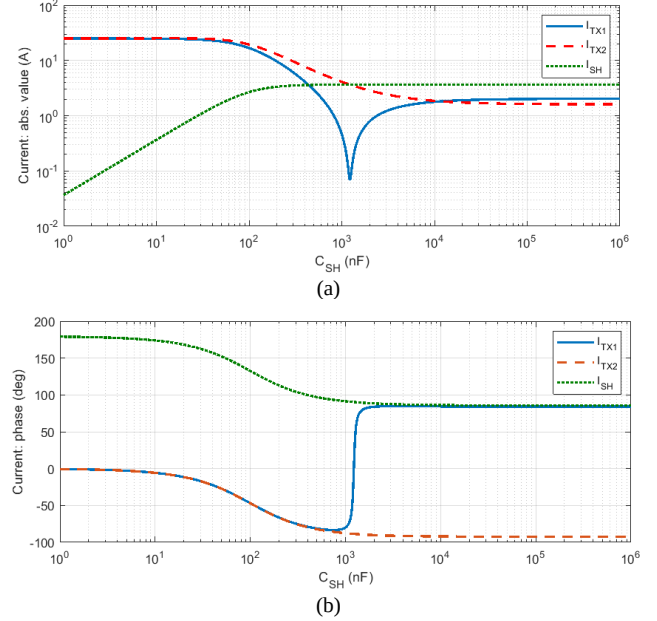


Fig. 3. Coil currents vs. series capacitance C_{SH} . (a) magnitude; (b) phase.

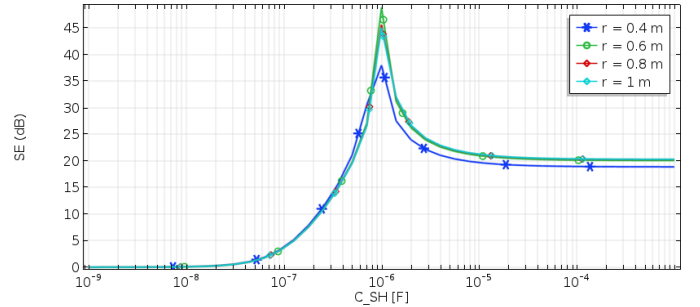


Fig. 4. Calculated SE vs. C_{SH} at different points $r > r_{SH}$ and $z = 0$.

IV. CONCLUSIONS

The proposed method of powering the shielding coil represents a significant and highly promising innovation, especially for Wireless Power Transfer (WPT) applications, as it combines the benefits of both passive and active coils.

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