The Minimization of the Extraneous Electromagnetic Fields of an Inductive Power Transfer System

James McLean and Robert Sutton
TDK R&D Corp., Cedar Park, Texas, USA
E-mail: jmclean@tdkrf.com

Abstract. The efficiency of inductive wireless power transfer (IPT) systems has been extensively studied. However, the electromagnetic compatibility of such systems is at least as important as the efficiency and has received much less attention. We consider the net magnetic dipole moment of the system as a figure of merit. That is, we seek to minimize the magnitude of the net dipole moment in order to minimize both the near magnetic fields and the radiated power. A 20 kHz, 3.3 kW, IPT system, representative of typical wireless vehicular battery charging systems, is considered and it is seen that one particular value of load impedance minimizes the net dipole moment while another, distinct, value maximizes efficiency. Thus, efficiency must be traded off, at least to some extent, in order to minimize extraneous electromagnetic fields.

1. Introduction
Inductive power transfer (IPT) is the most common approach for high-power wireless power transfer applications, such as the recharging of batteries for electric vehicles [1,2]. In keeping with vehicular power requirements and providing reasonably short recharging times, such systems range in power from approximately 3 to 20 kW for consumer applications and up to 150 kW for commercial vehicles [3]. A representative system is shown in Fig. 1. This configuration employs what has become known as “circular” couplers [4]. Many IPT systems with operating frequencies ranging from 10 kHz to 150 kHz and all with very high efficiency have been successfully demonstrated. Therefore, selection of operating frequency will more likely be motivated by electromagnetic compatibility requirements [5]. From ref. [3] it can be deduced that load powers on the order of 3-20 kW and separation distances of 200 mm will be common in IPT systems existing in consumer environments. This then sets constraints on the minimum extraneous electromagnetic field that can be achieved through careful design.

2. Loosely-Coupled Transformer Model
An inductive power transfer system functions fundamentally as a loosely-coupled transformer. While some electromagnetic radiation necessarily takes place, it causes only a minor perturbation in the primary and secondary currents because of the miniscule electrical size of such a system. A system operating at 150 kHz (λ ≈ 2 km) (probably the highest frequency under consideration for IPT) with a separation of 200 mm and a lateral dimension of 700 mm (comparable to the size of the systems in ref. [4]) still qualifies as quasi-magnetostatic. Thus, the currents can be accurately determined using network theory. Once the primary current \( I_1 \) and secondary
current $I_2$ in Fig. 1 are known, both the near magnetic field and the far radiated electromagnetic field can be determined from the current distribution using electromagnetic field theory. A loosely-coupled transformer will generate an electromagnetic field which in the most general representation is an infinite series of spherical harmonics. The lowest-order terms are three orthogonal magnetic dipoles. Thus, in the lowest order, both the near-field magnetic field and the radiated electromagnetic field are largely proportional to the net dipole moment $\vec{m}_{net}$. This vector phasor quantity is the sum of the dipole moments of the primary and secondary windings, $\vec{m}_1$ and $\vec{m}_2$ respectively. Since in the ideal case, the axes of the couplers are parallel, we consider the scalar phasor quantity $m_{net} = m_1 - m_2$, for the current directions indicated. This quantity, in turn, is proportional to the difference of the currents, $I_1 - I_2$ when the couplers are identical and their directions are defined as in Fig. 1.

For such a pair of coupled inductors connected to a complex load as shown in Fig. 2, the secondary current $I_2$ is related to the primary current $I_1$ as:

$$I_2 = \frac{j\omega M}{j\omega L_2 + R_2 + Z_L} I_1; \quad (1)$$
where \( R_1 \) and \( R_2 \) represent the losses in the primary and secondary windings respectively. Note that in Eqn. 1 the matching networks are absorbed in \( Z'_s \) and \( Z'_L \). For a lossless, tightly-coupled transformer, the primary and secondary fluxes essentially cancel if \(|j\omega L_2| >> |Z'_L|\). For loosely-coupled inductors with unity turns ratio, flux cancelation would still occur if \( j\omega M = j\omega L_2 + R_2 + Z'_L L \). This would require a negative load resistance for perfect cancelation. However, it can be gleaned that the net minimum dipole moment still requires:

\[
jX'_L \approx j\omega (M - L_2).
\]

If \( R_2 = 0 \), a purely reactive load \( jX'_L = j\omega (M - L_2) \) can make the primary current \( I_1 \) and secondary current \( I_2 \) equal and hence the dipole moments of the primary and secondary equal in magnitude and opposite in phase thereby completely canceling the net dipole moment. This is equivalent to connecting the two windings in series-opposing fashion, a similar arrangement to an MRI z-gradient coil. This situation is the extreme case of no transferred power and no power dissipated in the secondary winding. On the other hand, in the absence of losses, the denominator in Eqn. 1 could be forced to zero with \( j\omega L_2 = j\omega M \), although this results in an infinite primary-side input impedance. Yet another value of reactance, \( jX'_L = -j\omega (L_2 + M) \) would cause \( I_1 = -I_3 \) and thus providing direct addition of the dipole moments. It provides the same magnetic field as would be obtained connecting the two coils in series-aiding fashion in a similar arrangement to a Helmholtz coil.

However, it is clear from the above equation that the net dipole moment cannot be zero as long as a resistive component of the load exists, even if the secondary winding is lossless. When finite power is transferred to the load, the dipole moments cannot cancel completely, but rather a finite minimum net dipole moment exists. Thus, if we set the load power, \( P_L = |I_2|^2 \Re (Z'_L) \), we can choose \( I_2 = \sqrt{\frac{P_L}{\Re (Z'_L)}} \), setting the phase of \( I_2 \) to zero. Thus, we consider the quantity:

\[
\sqrt{\frac{P_L}{\Re (Z'_L)}} \frac{I_1}{I_2} - 1 = \sqrt{\frac{P_L}{\Re (Z'_L)}} \frac{j\omega L_2 + R_2 + Z'_L}{j\omega M} - 1 \propto m_1 - m_2. \tag{2}
\]

This has a minimum value of \( \frac{2\sqrt{R_L}}{\omega M} \sqrt{P_L} \) when \( Z'_L = j\omega M - j\omega L_2 + R_2 \). Thus, we consider:

\[
\frac{1}{\sqrt{P_L}} \frac{1}{2\sqrt{R_L}} \frac{1}{\omega M} \left| \frac{j\omega L_2 + R_2 + Z'_L}{j\omega M} - 1 \right|.
\]

This gives the magnitude of the net dipole moment relative to the minimum value that can be obtained with fixed power delivered to the load.

### 3. Maximum Efficiency versus Net Dipole Moment

The following circuit parameters are representative of a 3.3 kW IPT system for vehicular battery charging: \( f = 20 \text{ kHz}, L_1 = L_2 = 540 \text{ μH}, M = 275 \text{ μH}, k = .501, R_1 = R_2 = R_s = 271 \text{ mΩ} \). For these values, the efficiency of the system, \( \eta = \frac{P_{\text{load}}}{P_{\text{in}}} \) is plotted as a function of the real and imaginary components of the load impedance in Fig. 3. The net dipole moment is plotted in Fig. 4. The maximum efficiency is obtained with \( Z'_L = \sqrt{R_s^2 + \omega^2 M^2 - j\omega L_2} \) while the minimum dipole moment is obtained with \( Z'_L = j\omega M - j\omega L_2 + R_s \). The efficiency when the load is fixed for minimum dipole moment is 31.3 %. On the other hand, the magnitude of the net dipole moment at the maximum efficiency load it about 8 times that of its minimum value.

### 4. Conclusions

It is not possible to simultaneously minimize the net dipole moment while maximizing efficiency in an IPT system. Thus, a compromise between these two goals must be sought.
Figure 3. Efficiency plotted as a function of the real and imaginary components of the load. The value of $Z'_L$ for maximum efficiency is: $Z'_L = 34.55 - j6.7 \ \Omega$. The efficiency is 98.44% at this point.

Figure 4. Net dipole moment plotted as a function of the real and imaginary components of the load. The value of $Z'_L$ for minimum dipole moment is: $Z'_L = .271 - j3.3 \ \Omega$. The contour plot is normalized to the dipole moment at this value of effective load impedance.

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