Simulation Analysis of Wireless Power Transmission System for Biomedical Applications

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Abstract. In recent years, more and more implantable medical devices have been used in the medical field. Some of these devices, such as brain pacemakers, require long-term power support. The WPT (wireless power transmission) technology which is more convenient and economical than replacing the battery by surgery, has become the first choice of many patients. In this paper, we design a WPT system that can be used in implantable medical devices, simulate the transmission efficiency of the system in the air and in the head model, and simulate the SAR value when the system working in the head model. The results show that when implantation depth of the secondary coil is 3 mm, the efficiency of the system can reach 45%, and the maximum average SAR value is 2.19 W/kg, slightly higher than the standard of IEEE.

1. Introduction

In 2007, researchers at the Massachusetts Institute of Technology light a 60-watt bulb at a distance of 2 meters \cite{1}, opening a new history of researching WPT technology. The team used two copper coils with a diameter of 50 cm in the experiment, realized the radio energy transmission by resonance, and lighted the bulb. Khan\cite{2,3} presented a magnetically coupled planar four coil printed spiral resonator-based wireless power transmission system and analyzed the effect of square structure and circular structure on system efficiency. The experiment results showed: Square resonators could produce higher measured power-transfer efficiency than circular resonators at a 10 mm distance for biomedical applications at a resonant frequency of 13.56 MHz. What’s more, circular coils could get higher power than the square coils under the same medium properties. Tang\cite{4} developed a larger coil (24×30 cm²) designed to be embedded in the back of a vest to power dc pumps for artificial hearts. They measured an output power of 48.2 W and a corresponding energy efficiency higher than 80% at a 7.7 cm distance. Liu\cite{5} presented a design approach to achieve the optimal efficiency in a magnetic resonant WPT system. Experimental validations were demonstrated by both simulation and measurement results of a 6.78 MHz WPT system prototype with the maximum efficiency of 76.1% at a distance of 50 mm. Yi\cite{6,7} presented a 3-coil resonance-based WPT system using a single layer of inductor coil windings. Theoretical analysis and experimental measurements in terms of quality factor Q and power transfer efficiency were done. Their 3-coil scheme can achieve experimental transfer efficiency was over 85% when the distance was 5 mm, and about 50% PTE at a distance of 20 mm. Xu’s design\cite{8} was specifically applied to transcutaneous power medical implants within free-moving laboratory animals and they also described a novel power receiver coil design of the same shape as the exterior of the implant. Li \cite{9} presented a novel implantable magnetic coupling resonate WPT system for biological applications and the measured results showed that 15.7dB coupling enhancement can be
obtained by integrating with the MNG metasurface. There are other researchers [10,11] have studied WPT system for biomedical applications.

In this paper, the key parameters of WPT system are analyzed theoretically, and a WPT system based on PCB coils for biomedical applications is designed. What’s more, we simulate the transmission efficiency of the system in the air and in the head model. Finally, the SAR value of the head is simulated when the system is working.

2. Efficiency Calculation of WPT System

There are many methods to calculate the self-inductance of a planar coil. For planar circular coils, the self-inductance can be calculated by:

$$L = \frac{\mu N^2 D_{\text{avg}}}{2} \left[ \ln\left(\frac{2.46}{\varphi}\right) + 0.2 \varphi^2 \right]$$  \hspace{1cm} (1)

In this equation, \(N\) is the number of turns, \(D_{\text{avg}}\) is the average diameter and \(\varphi\) is the occupancy ratio:

$$\varphi = \frac{D_o - D_i}{D_o + D_i}$$  \hspace{1cm} (2)

Where \(D_o\) is the external diameter and \(D_i\) the internal diameter as illustrated in Fig. 1.

In order to find the total parasitic resistance of the planar circular coil, we must know the length of the conductive trace \(l_c\), resistivity of the conductive material \(\rho_c\), and its thickness \(t\):

$$l_c = 4nD_o - 4nw - (2n + 1)(s + w)$$  \hspace{1cm} (3)

$$R_{dc} = \rho_c \frac{l_c}{w \cdot t}$$  \hspace{1cm} (4)

Where \(w\) and \(s\) are the line width and spacing, respectively.

Each coil has its own quality factor, we use \(Q_1\), \(Q_2\), \(Q_{2L}\) to represent the quality factor of primary, quality factor of secondary without load, and quality factor of secondary with load, respectively and they are calculated from the following equations:

$$Q_1 = \frac{L_1\omega}{R_{S1}}$$  \hspace{1cm} (5)

$$Q_2 = \frac{L_2\omega}{R_{S2}}$$ \hspace{1cm} (Quality factor without load)\hspace{1cm} (6)

$$Q_{2L} = \frac{R_L}{L_2\omega} \times \frac{1}{1/Q^2} + 1 \approx \frac{R_L}{L_2\omega}$$ \hspace{1cm} (7)
\[
Q_1 = \frac{Q_2}{Q_2 + Q_L} \quad \text{(Quality factor with load)}
\]  \tag{8}

Where \( L_1, L_2 \) are self-inductance of the primary and secondary coil, respectively. \( R_1, R_2 \) are parasitic resistance of the primary and secondary coil, respectively. \( R_L \) is resistance of the load. \( \omega \) is the angular frequency and there is \( \omega = 2\pi f \).

The PCB coil shown in fig. 1 can be considered a set of concentric single-turn coils with shrinking diameters, connected in series. Therefore, we can find the mutual inductance between a pair of single-turn coils in parallel planes and estimate the mutual inductance values between two coils having \( N_1 \) and \( N_2 \) turns, which are separated by distance \( d \) and have average radius \( a \) and \( b \):

\[
M_{1,2} = N_1^2 N_2^2 \frac{\mu_0 a b}{2} \int_0^{2\pi} \frac{\cos \phi}{\sqrt{a^2 + b^2 + d^2 - 2ab \cos \phi}} d\phi
\]  \tag{9}

Where \( \mu_0 \) is the permeability of vacuum.

With the above parameters of a WPT system, we can calculate the efficiency of the system by:

\[
\eta = \frac{k^2 Q_1 Q_{2L}}{1 + k^2 Q_1 Q_{2L}} \times \frac{Q_2}{Q_2 + Q_L}
\]  \tag{10}

Where \( k \) is the coupling coefficient between two transmission coils, there is \( k = \frac{M}{\sqrt{L_1 \cdot L_2}} \).

3. Simulation Analysis of WPT System

The parameters of primary coil and secondary coil we used are shown in Table 1:

| Tab.1 detailed parameters of the coil |
|-------------------------------------|
| primary coil | secondary coil |
| Number of layers | 1 | 2 |
| The number of turns per layer | 22 | 8 |
| Outer diameter, \( D_0 \)(mm) | 45 | 23 |
| Inner diameter, \( D_i \)(mm) | 10 | 7 |
| Conductor material | copper | copper |
| Conductor width, \( w \)(mm) | 0.254 | 0.254 |
| Conductor spacing, \( s \)(mm) | 0.546 | 0.746 |
| Conductor thickness, \( t \)(mm) | 0.02 | 0.02 |
| Substrate material | FR4 | FR4 |
| Substrate thickness, \( h \)(mm) | 1 | 1 |

The coil is tuned to 13.56 MHz by series and shunt capacitance in the system. Firstly, we simulate the efficiency of the system at different transmission distances in the air and then migrate the secondary coil to a three-layer human head model (skin, bone, brain stem), as shown in figure 2(a). The system efficiency when secondary coils is implanted at different depths in the head is simulated again. The magnetic field distribution when the system is working is shown in figure 2(b).
The efficiency of the system in the air and in the head model is shown in Figure 3(a). As we can see, in the air, as the transmission distance increases, the efficiency of the system gradually decreases, because increasing the distance reduces the coupling coefficient between the coils. When the system works in the head model, the overall efficiency tends to decrease with implantation depth of the secondary coil increasing (but increasing at the distance of 5 mm - 7 mm). Then we simulated the average SAR value of the head at the implantation depth of 3 mm. As shown in Figure 3(b), the results showed that the average SAR value is 2.19 W / kg, slightly larger than the standard of IEEE, 2.0 W/kg [12].

4. Conclusion
In this paper, the key parameters of WPT system (self-inductance, impedance, quality factor and mutual inductance) are theoretically analyzed with the help of the previous empirical formula, and a specific WPT system that can be implanted into the human head is simulated. The transmission efficiency of the system in air and in the head model is compared. Finally, the SAR value of the head model when the system is working is simulated. The results show that the average SAR value is 2.19W / kg, which is slightly larger than the IEEE standard. This article also has some shortcomings. When the implantation depth of secondary coil is within 7mm, the efficiency of the system first decreases and then increases. This phenomenon has not been explained reasonably, which will be the focus of our next work.

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References
[1] Kurs, A, et al. "Wireless power transfer via strongly coupled magnetic resonances." Science 317.5834(2007):83.
[2] Khan, Sadeque Reza, and G. S. Choi. "Analysis and Optimization of Four-Coil Planar Magnetically Coupled Printed Spiral Resonators." Sensors 16.8(2016):1219.
[3] Khan, Sadeque Reza, and G. S. Choi. "Optimization of planar strongly coupled wireless power transfer system for biomedical applications." Microwave & Optical Technology Letters 58.8(2016):1861–1866.
[4] Tang, Sai Chun, et al. "Intermediate Range Wireless Power Transfer with Segmented Coil Transmitters for Implantable Heart Pumps." IEEE Transactions on Power Electronics PP.99(2016):1-1.
[5] Liu, Zhongtao, Z. Zhong, and Y. X. Guo. "Rapid design approach of optimal efficiency magnetic resonant wireless power transfer system." Electronics Letters 52.4(2016):314-315.
[6] Yi, Ying, et al. 3-Coil resonance-based wireless power transfer system for implantable electronic. 2013.
[7] Yi, Ying, et al. "Design and optimization of a 3-coil resonance-based wireless power transfer system for biomedical implants." International Journal of Circuit Theory & Applications 43.10(2015):1379-1390.
[8] Xu, Qi, et al. "A Novel Mat-Based System for Position-Varying Wireless Power Transfer to Biomedical Implants." IEEE Transactions on Magnetics 49.8(2013):4774-4779.
[9] Li, Long, et al. "Efficient Wireless Power Transfer System Integrating With Metasurface for Biological Applications." IEEE Transactions on Industrial Electronics PP.99:1-1.
[10] Bilicz, Sándor, et al. "Modeling of Resonant Wireless Power Transfer With Integral Formulations in Heterogeneous Media." IEEE Transactions on Magnetics 52.3(2016):1-4.
[11] Wu, Rongxiang, et al. "Design and Characterization of Wireless Power Links for Brain–Machine Interface Applications." IEEE Transactions on Power Electronics 29.10(2014):5462-5471.
[12] Engineers, Electrical Electronics, and I. S. Board. "IEEE Standard for Safety Levels With Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz." IEEE Std C IEEE, 2002:1.