Coil Inductance Design for Low Power Hybrid Wireless Power Transfer

T A Kurniawan¹*, R B Gumilang¹, G Wibisono¹

¹Department of Electrical Engineering, Faculty of Engineering, Universitas Indonesia
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email: taufiq.alif@ui.ac.id

Abstract. This paper presents a coil inductance design for low power hybrid wireless power transfer (WPT). The proposed coil inductance design of transmitter and receiver circuits of 7.1 µH are designed using handmade copper wire structure. Several coils with the variations of wire diameters, coil loop radius, and numbers of loops are proposed to find optimum structure in the low power hybrid WPT. The optimum coil structure is obtained at wire diameter of 0.5 mm, 2.25-inch coil loop radius and 1 MHz operation frequency. The measured transceiver coil design has exhibited peak power transfer efficiency (PTE) of 33.1% at 1 cm distance between Tx and Rx. Therefore, the proposed coil design is applicable to low power hybrid wireless power transfer circuits.

1. Introduction

Nowadays, the medical implant devices are very promising to conduct therapy in several conditions. Many therapies especially in neurological stimulation for sleep apnea, pain management, Parkinson’s Disease, epilepsy, bladder control, gastrointestinal disorders, numerous autoimmune diseases and psychological disorders can be effectively conducted using implantable circuits [1]. In addition, the retinal prosthesis system using wireless power transfer in [2] for retinal degenerative patients is also interesting solution to reduce the cause of blindness in the world.

One of the successful keys to design wireless power transfer is the optimal wireless power links, especially on the accuracy of the model, i.e., self-inductance and the mutual inductance [3]. Since the two optimum parameters will determine the characteristic power transfer efficiency of the device, many researches have focused on the algorithm design to develop accurate models of wireless power links [4-11]. The most widely approach for designing coil inductors is by using copper wire with a resistivity of 1.68 × 10⁻⁸ Ωm [12] which is designed by optimizing the coil structure. In addition to using a mathematical model, this approach requires a coil model iteration that is measured separately from the whole WPT devices.

This paper is a preliminary research of the hybrid wireless power transfer (H-WPT) design for medical implant devices. The hybrid transceiver coil is designed to facilitate the circuit measurements. In our model, the transmitter block consists of a DC power source, oscillator and transmitter coil. While the receiver block consists of coil receiver, rectifier, and voltage regulator. The transceiver coils are designed in a circular shape with several iterations of copper wire diameter and coil loop radius. To evaluate the reliability of the proposed transceiver coils, we tested the proposed coil in the air with the distance variations between transmitter and receiver i.e., 0 cm, 1 cm, 2 cm and 3 cm.
2. The circuit configuration

The schematic circuit is shown in Figure 1. The signal source is connected directly to the transmission coil \((L_{TX})\), while the receiver coil is connected to the oscilloscope. \(r_{par, TX}\) and \(r_{par, RX}\) are the parasitic resistance in the coil inductor. Its value is determined by the Q-factor value of the coil, following the equation:

\[
Q = \frac{\omega L}{r} \tag{1}
\]

where,

- \(Q\) = Q factor of transceiver coil
- \(\omega = 2\pi f\)
- \(r\) = parasitic resistance (\(\Omega\))

Because the required inductance coil values for the transmitter and the receiver circuits for the proposed WPT circuit are 7.1 \(\mu\)H, the transmitter and receiver coils are designed using copper e-mail wire. The structure design of the coil is shown in Figure 2.

Calculation of the coil inductance is performed by referring to equation [4]:

\[
L = \mu R \left[ \ln \left( \frac{16R}{w} \right) - 2 \right] \tag{2}
\]

where,

- \(\mu\) = the permeability of the medium surrounding the coil (H/m)
- \(w\) = wire diameter (m)
- \(R\) = coil loop radius (m)

3. Measurement Results

Figure 3 illustrates the measurement setup of the proposed circuits. The signal source is Kenwood AG-203 wide Frequency Range Oscillator 10Hz-1MHz. The Oscilloscope GW-instek GDS-1102U 100 MHz is used for the output signal measurement. Several structure coils are designed by handmade using the copper wire of different wire diameters, the coil loop radius, and the numbers of loops. Figure 4 depicts the coil layout design for 7.1 \(\mu\)H modelled by using equation (2). In order to verify the self-inductance value, the LCR meter Dekko L-4070D is used.

Figure 5 shows the measurement of power transfer efficiency (PTE) at a wire diameter of 0.5 mm and the distance between Tx and Rx is 1 cm. It is illustrated that the highest PTE of 31.44% is obtained at the highest operating frequency and the largest coil loop radius. Increasing the coil loop radius and the frequency are directly proportional to the improvement of the PTE.

Figure 6 illustrates the PTE measurement on a 2.25-inch coil loop radius and 1 cm Tx-Rx distance. It is seen that the variations of the wire diameter influence the PTE, with the highest value at a wire...
diameter of 0.5 mm. Figure 7 shows the PTE measurement on a 2.25-inch coil loop radius and 1 MHz operation frequency. It shown that coil distance variations from 0 to 3 cm decrease the PTE from about 70% to 10%.

4. Conclusion
A 7.1-µH coil inductance design has been demonstrated using handmade copper wire structure. The proposed transceiver coil inductance has 33.1% PTE at a 1 cm distance between transmitter and receiver. Based on the various wire diameters, the coil loop radius, and the numbers of loops, the optimum coil structure is obtained at a 0.5 mm wire diameter and a 2.25-inch coil loop radius. In order to improve the PTE, increasing operation frequency until several MHz is possible. However, the WPT applications in biomedical implant device is restricted about 20 MHz. Therefore, the proposed coil inductance is applicable to low power hybrid wireless power transfer systems.
Figure 7. Measurement results of the PTE over 2.25-inch coil loop radius and 1 MHz frequency

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References
[1] I. A. Mashahadi, M. Pahlevani, S. Hor, H. Pahlevani, E. Adib, “A New Wireless Power Transfer Circuit for Retina Prosthesis”, IEEE Transactions on Power Electronics, vol. 34, no. 7, pp. 6425-6439, July 2019.
[2] J. McDonald, “Integrated Circuits for Implantable Medical Devices”, White paper on Freescale, Journal Title, electronic file available at: https://cache.freescale.com/files/32bit/doc/white_paper/ICIMDOVWP.pdf, August 2019.
[3] S. I. Babic and C. Akyel, “Calculating mutual inductance between circular coils with inclined axes in air,” IEEE Trans. Magn., vol. 44, no. 7, pp. 1743–1750, Jul. 2008.
[4] Sadeque Reza Khan, Sumanth Kumar Pavuluri, and Marc P. Y. Desmulliez, “Accurate Modeling of Coil Inductance for Near-Field Wireless Power Transfer”, IEEE Transaction on Microwave Theory and Technique, vol. 66, no. 9, pp. 4158-4169, Sept 2019.
[5] A. K. RamRakhyani, S. Mirabbasi, and M. Chiao, “Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants,” IEEE Trans. Biomed. Circuits Syst., vol. 5, no. 1, pp. 48–63, Feb. 2011.
[6] C. M. Zierhofer and E. S. Hochmair, “Geometric approach for coupling enhancement of magnetically coupled coils,” IEEE Trans. Biomed. Eng., vol. 43, no. 7, pp. 708–714, Jul. 1996.
[7] S. Atluri and M. Ghovanloo, “Design of a wideband power-efficient inductive wireless link for implantable biomedical devices using multiple carriers,” in Proc. 2nd Int. IEEE EMBS Conf. Neural Eng., Mar. 2005, pp. 533–537.
[8] X. Li et al., “A wireless magnetic resonance energy transfer system for micro implantable medical sensors,” Sensor, vol. 12, no. 8, pp. 10292–10308, Aug. 2012.
[9] Y. Yi, U. Buttner, Y. Fan, and I. G. Foulds, “Design and optimization of a 3-coil resonance-based wireless power transfer system for biomedical implants,” Int. J. Circuit Theory Appl., vol. 43, no. 10, pp. 1379–1390, 2015.
[10] T. P. Duong and J.-W. Lee, “A dynamically adaptable impedance matching system for midrange wireless power transfer with misalignment,” Energies, vol. 8, no. 8, pp. 7593–7617, 2015.
[11] D.-H. Kim, J. Kim, and Y.-J. Park, “Optimization and design of small circular coils in a magnetically coupled wireless power transfer system in the megahertz frequency,” IEEE Trans. Microw. Theory Techn., vol. 64, no. 8, pp. 2652–2663, Aug. 2016.
[12] I. Giancoli, Douglas C., Physics, 4th Ed, Prentice Hall, (1995).