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Wireless Power Transfer Based on 3-Coil Magnetic Resonance Coupling for Biomedical Implants

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***Abstract*—Electronic biomedical implants rely on wireless power transfer (WPT) systems to remove their dependency on chemical batteries to avoid potential safety issues. As traditional systems based on the inductive link are limited by their transmission distance, the magnetic resonance coupling (MRC) method for WPT has been proposed to increase the delivered power for mid-range applications. In this paper, we design a 3-coil magnetic resonant WPT system with a small power receiver for micro biomedical implants and evaluate its power transfer capability with a pork steak to mimic the attenuation caused by biological tissues. Operating at 180 kHz, the output of the proposed system can supply 56 mW at 3.3 V for an implanted receiver at a distance of 80 mm, which is 1.5 times more efficient than the traditional 2-coil system under the same conditions. Such a result demonstrates the applicability and improvement of the MRC-WPT system for powering up in-body biomedical devices.**

***Index Terms*—Wireless power transfer, magnetic resonance coupling, biomedical implants.**

I. Introduction

To power up in-body biomedical devices, wireless power transfer (WPT) technology is more preferred than the chemical battery because of its risk and inconvenience [1]. One of the most popular methods to realize WPT is to utilize the inductive power transfer (IPT) between the magnetic field created by two coils for high transfer efficiency [2], [3]. However, its efficiency is still limited by the distance and coupling between two coils, which raises a challenge to provide enough power for implantable devices in mid-range (distance larger than the size of the receiver coil) applications.

For higher power delivered to load (PDL), magnetic resonance coupling (MRC) is introduced for IPT systems [4]. Its main characteristic lies in the use of resonance capacitors and resonator coils. The resonance capacitors connected to coils can resonate out the leakage inductance of coils so that the reactive impedance is eliminated to guarantee high efficiency [5]. Besides, the additional resonator coils in multi-coil systems are beneficial for impedance matching to reach a condition of maximum power transfer. It is believed in [5] the total power transfer efficiency (PTE) is sacrificed for PDL. But in the case of long transfer distance, [3] demonstrates a 3-coil WPT system based on MRC can have both high PTE and PDL simultaneously as the 3-coil system requires a much lower load quality factor which is more feasible to achieve. The increased output power from the MRC-WPT system offers room to extend the operation range and reduce the dimension of the receiver coil for implantable devices.

The need for reduced coil size and wide converge range for implantable devices highlights the significance of demonstrating the applicability and superiority of the 3-coil MRC system compared to conventional 2-coil systems. Besides, the implant depth is affected by the power dissipated in tissue, which comes up with another issue. Therefore, in this paper, we design a 3-coil magnetic resonant WPT system with a receiver coil minimized for implantable devices and validate its in-body performance of PDL by placing the power receiver inside a piece of pork. The experiment results indicate that our proposed system provides 1.5 times higher power than the traditional 2-coil system under the same conditions. This system is successfully applied to supply sufficient power to a microcontroller with a Bluetooth Low Energy (BLE) module for implants and will be served as the power supply of an implantable medical device for bone fracture healing in our future project.

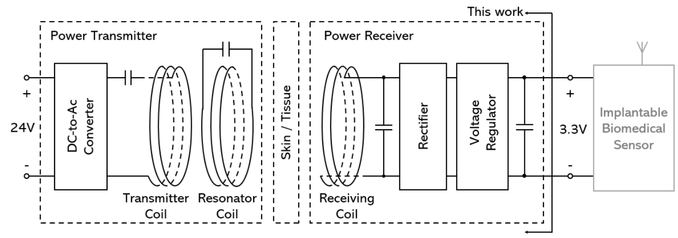

Fig. 1. The overall structure of the 3-coil WPT system based on MRC.

II. 3-Coil Magnetic Resonance Coupling System

The structure of the 3-coil system in this work is illustrated in Fig. 1, including a DC-to-AC converter for AC power source, planar circular coils for inductive MRC, resonance capacitors for PDL enhancement, a rectifier, a voltage regulator and a capacitor for a stable DC output. It is decided to place the resonator coil closed to the transmitter coil to reduce the bulk of the power receiver. In addition, the size of the receiver coil is minimized and smaller than the transmitter coil so that it is suitable for implantable devices.

To explain the contribution of MRC, the equivalent circuit schematic diagram of the proposed 3-coil system is derived and presented in Fig. 2 (a). The capacitors are connected to the coils which are modelled as inductance in the schematic and tuned to work at resonance frequency $\omega = 1/\sqrt{L_1C_1} = 1/\sqrt{L_2C_2} = 1/\sqrt{L_3C_3}$. The inductive coupling between coils is represented by coupling coefficients k_{12} and k_{23} while k_{24} is small and ignored, and the quality factors of each coil are given by $Q_1 = \omega L_1/R_1^{'}$, $Q_2 = \omega L_2/R_2$ and $Q_3 = \omega L_3/R_3$, where $R_1^{'} = R_1 + R_s$.

On the power receiver side, the total resistance at the receiver can be approximated by $R_p = R_{p3}||R_L$, where $R_{p3} =$

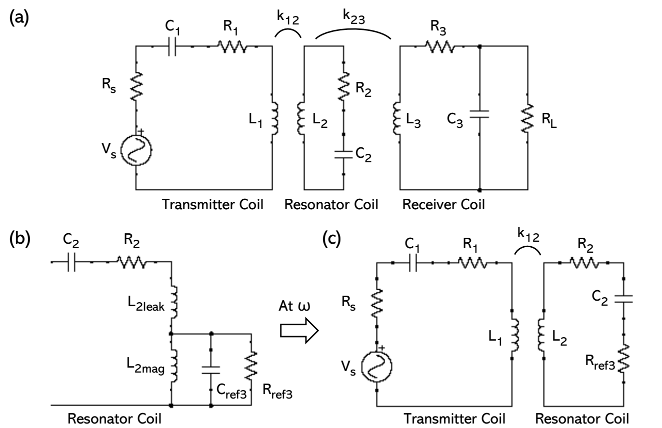

Fig. 2. Equivalent circuit model of the 3-coil WPT system based on MRC.

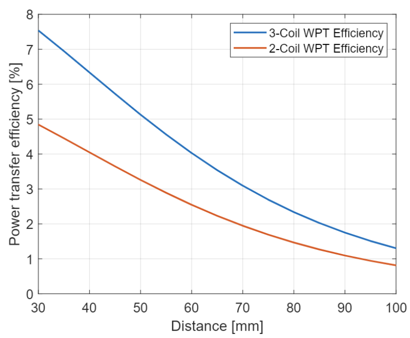

Fig. 3. Calculated PTE of the 3-coil and 2-coil WPT systems.

$Q_3^2 R_3$. Assuming that the distance between the receiver coil and resonator coil is large, and hence they are weakly coupled, the inductance of the resonator coil can be divided into a leakage inductance $L_{2leak} = (1 - k_{23}^2)L_2 \approx L_2(k_{23} \ll 1)$ and a magnetizing inductance $L_{2mag} = k_{23}^2 L_2$. Then, based on the reflected load theory, the load of receiving loop can be reflected in the resonator loop as a transformer according to the turns ratio $n = k_{23}\sqrt{L_2/L_3}$, as shown in Fig. 2 (b), which are given by [2]:

$$R_{ref3} = k_{23}^2(L_2/L_3)R_p = k_{23}^2 \omega L_2 Q_{3L} \tag{1}$$

$$C_{ref3} = (L_3/L_2)(C_3/k_{23}^2) = 1/(\omega L_2 k_{23}^2) \tag{2}$$

where $Q_{3L} = R_p/\omega L_3$ in the parallel RLC circuit. Operating at the resonance frequency, C_{ref3} compensates the inductance $k_{23}^2 L_2$, and thus only the resistance R_{ref3} remains, as shown in Fig. 2 (c). Therefore, the PTE between the resonator coil and receiver coil is defined by the power division between R_2 and R_{ref3} and between R_p and R_L [3]:

$$\eta_{23} = \frac{R_{ref3}}{R_{ref3} + R_2}\frac{R_{p3}}{R_L + R_{p3}} = \frac{k_{23}^2 Q_2 Q_{3L}}{1 + k_{23}^2 Q_2 Q_{3L}} \cdot \frac{Q_{3L}}{Q_L} \tag{3}$$

where the load quality factor $Q_L = R_L/\omega L_3$. Similarly, the coupling between the transmitter coil and the resonator coil in Fig. 2 (c) can be modelled as a contactless transformer [6]. At resonance, the reflected resistance is obtained as:

$$R_{ref2} = \frac{\omega^2 M_{12}^2}{R_2 + R_{ref3}} \tag{4}$$

TABLE I
SPECIFICATIONS OF THE PROPOSED WPT SYSTEM

Parameters	Transmitter Coil	Resonator Coil	Receiver Coil
Inductance (μH)	12.74	12.56	19.14
Capacitor (nF)	60	60	38
Resistance (Ω)	0.81	0.5	0.77
Diameter (mm)	200	200	22
Num. of turns	6	6	36
Frequency (kHz)		180	
DC Input Voltage (V)		24	
Power Consumed by Tx (W)		2.88	
L_1/L_2 Distance (cm)		2	

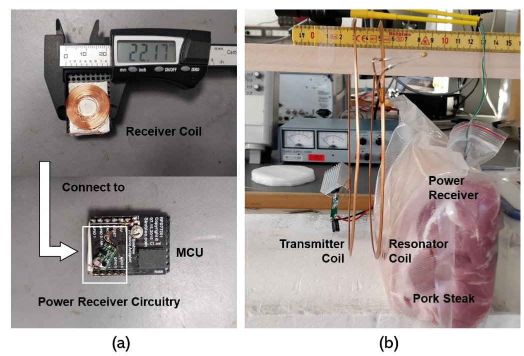

Fig. 4. (a) Power receiver of the system, (b) experiment setup of the WPT system with the pork steak.

where $M_{12} = k_{12}^2 L_1 L_2$ is the mutual inductance. Therefore, the PTE from the transmitter coil to the resonator coil and the overall PTE can be derived as:

$$\eta_{12} = \frac{R_{ref2}}{R_{ref2} + R_1'} = \frac{k_{12}^2 Q_1 Q_2}{1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_{3L}} \tag{5}$$

$$\eta_{3-coil} = \eta_{12}\eta_{23}. \tag{6}$$

By removing the resonator coil from the system, the PTE of a 2-coil system using the transmitter coil and receiver coil only can be written as:

$$\begin{aligned}\eta_{2-coil} &= \frac{R_{ref3}}{R_{ref3} + R_1'}\frac{R_{p3}}{R_L + R_{p3}} \\ &= \frac{k_{13}^2 Q_1 Q_{3L}}{1 + k_{13}^2 Q_1 Q_{3L}} \cdot \frac{Q_{3L}}{Q_L}.\end{aligned} \tag{7}$$

Based on the system design specifications presented in Table 1, the calculated PTE of the 2-coil and 3-coil systems can be drawn in Fig. 3 following the deduced formulas (6) and (7). The PTE is low at around 3% to 7% for mid-range applications because coils are weakly coupled while the proposed 3-coil system contributes to a better performance with 1.5 times higher efficiency at 80 mm. As a result, since increasing the turns of the transmitter coil increases the serial resistance and reduces the quality factor, it is more efficient to introduce an extra resonator coil to improve the efficiency.

III. RESULTS AND EVALUATION

To demonstrate the power delivery performance of the proposed 3-coil system, especially for in-body applications, we test the maximum output power with the receiver placed in a which does not exceed 0.02 W/kg in the experiment and well conforms to the standard of 1.6 W/kg.

Our proposed system is compared to previous related works in Table 2, including conventional 2-coil IPT systems from [3], [7] and [8] and multi-coil WPT systems from [3] and [9], which have similar receiver dimension or system structure. The comparison shows that the strength of our system lies in its high output power with long transmission distance and miniature coil size.

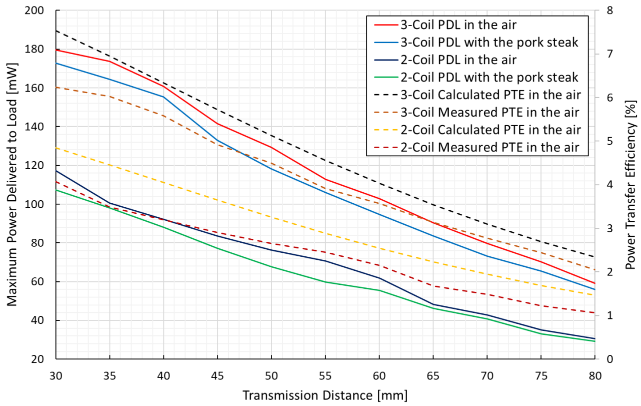

Fig. 5. The measured PDL, measured and calculated PTE versus transmission distance of the 2-coil and 3-coil systems with and without the pork steak.

TABLE II
COMPARISON WITH PREVIOUS WORKS

Reference	Num. of Coils	Output Power (mW)	Distance (mm)	Receiver Size (mm)
[3]	2	170	120	$d = 400$
[3]	3	260	120	$d = 400$
[3]	3	43.4	10	$d = 10$
[7]	2	57	50	20×30
[8]	2	29.8	20	d = 20
[9]	4	18	10	d = 10
This Work	**3**	**56**	**80**	d **= 22**

d denotes the outer diameter of the coil.

500g pork steak. The use of real tissue can imitate the situation when a WPT system delivers power to an implantable device in the human body, and hence the power loss due to absorption in this process can be observed. By measuring the highest output current the receiver can supply at the desired output voltage, the maximum output power at a certain transmission distance is obtained. The size of the receiver can be seen in Fig. 4 (a) and the measurement setup is shown in Fig. 4 (b).

In vitro experiment results are plotted in Fig. 5. It is obvious that the 3-coil WPT system largely increases the PDL. At a distance of 80 mm, the 3-coil system can transfer 56 mW to the load through real tissue from the transmitter DC input power of 2.88 W, which is improved by 1.5 times compared to the conventional 2-coil method. The measured PTE of free space show close agreement with the calculated values in Fig. 5, and the results in measurement are slightly smaller due to the efficiency loss in DC/AC power conversion. With a wider coverage at the same amount of output, the 3-coil system can supply the implantable device to operate about 20 mm further away from the transmitter than a 2-coil system. In addition, considering in-body applications, passing through the pork would attenuate a part of the power as shown in results with and without pork, and this phenomenon is caused by the lower magnetic permeability of the tissue. But the amount of loss is nearly 6% at 80 mm, which is acceptable because the system is still able to provide as high as 17 mA current with 3.3 V for the operation of implantable devices. As for a safe consideration of the radiation damage, the specific absorption rate (SAR) can be roughly estimated from the transmitted power loss,

IV. CONCLUSION

In this paper, we present a 3-coil WPT system based on MRC. From the experiment, it is demonstrated that through the biological tissue, the receiver of our proposed system that uses a coil with a diameter of 22 mm can obtain 56 mW from the transmitter at a distance of 80 mm when it consumes 2.88 W DC input power. Such a result shows our 3-coil system based on MRC can offer a high value of PDL, the size of the receiver is suitable for implantable devices, and its mid-range application is promising for deep biomedical implants, despite the power dissipation in tissue. Although the overall PTE is low, it is because the receiver coil is minimized for biomedical implants and applied in a long transmission distance resulting in weak coupling while its PDL is sufficient for normal microchip systems. By connecting the output of the power receiver to a microcontroller, we verify that our WPT system can power up a temperature sensor as a biomedical implant remotely, which senses and sends the data to a laptop through BLE. This pilot validation on the WPT system and its achievements make a preparation for our in vivo animal test and pave the path for our further research on bone fracture monitoring using an implantable medical device.

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