Impedance Matching in Magnetic-Coupling-Resonance Wireless Power Transfer for Small Implantable Devices

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***Abstract*—In this paper, we present an impedance matching technique in magnetic-coupling-resonance wireless power transfer system for small implantable medical devices. By developing an equivalent circuit model of the WPT system, we show that impedance matching can be realized. Electromagnetic field simulations demonstrated that our proposed technique has capability of achieving maximum input power and available efficiency without using impedance matching circuits.**

Keywords - Impedance matching, Magnetic coupling resonance, Wireless power transfer

I. Introduction

Wireless power transfer (WPT) systems for small implantable medical devices have attracted attention because they can provide electrical power without the use of conductive wires and cables [1]. Although small primary and rechargeable batteries can be used as an energy source, they have a problem due to their size, mass, potentially chemical composition, and finite lifecycle and lifetime. Their design methodology, however, is still in the early stage of development and thus robust and compact design for WPT systems are strongly required.

Figure 1 shows a conventional WPT system consisting of a magnetic-coupling-resonance WPT block and impedance matching circuits. In order to realize maximum available efficiency, we must use the impedance matching circuits. However, both the volume and cost increase because the matching circuits require additional inductors and capacitors.

In this paper, we propose an impedance matching technique in magnetic-coupled-resonant WPT system for small implantable medical devices without matching circuits. By developing an equivalent circuit model of the WPT system, we show that impedance matching can be realized. The proposed impedance matching technique has capability of achieving maximum input power and available efficiency without matching circuits. Note that, in this paper, we set resonant frequency of the resonators to 144 MHz for implantable biomedical applications [2]. This paper is organized as follows: Section II describes design approach of our proposed impedance matching technique. Sections III shows the simulation results using SPICE and electromagnetic field simulator. Section IV concludes the paper.

II. Proposed impedance matching

Figure 2 shows a simplified schematic of the WPT system, where E and R_{s} are the voltage and resistance of the input

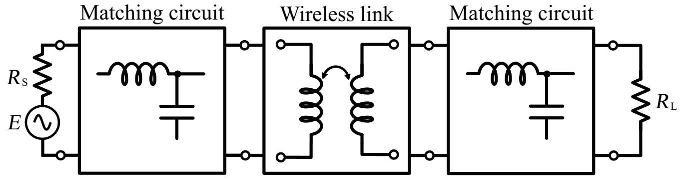

Fig. 1. Conventional WPT system. Input and output impedance matching circuits are used to achieve high power transfer efficiency.

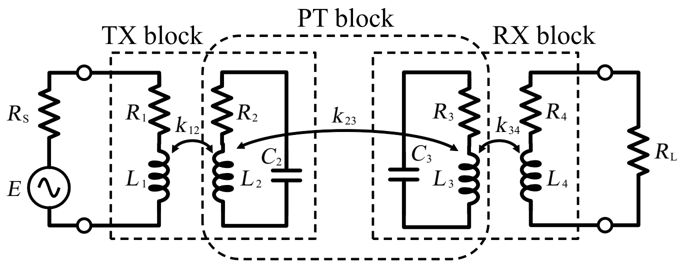

Fig. 2. Simplified schematic of the WPT system. Impedance matching circuits are not used.

power source, L_1–L_4 are the inductance, k_{12}–k_{34} are the coupling coefficients, C_2–C_3 are the capacitance, R_1–R_4 are the parasitic resistance, and R_{L} is the load resistance. The system can be divided into three blocks: transmitter (TX), receiver (RX), and power transfer (PT) blocks. A coil and resonator in each TX and RX blocks are coupled by magnetic induction, while resonators between TX and RX are coupled by magnetic resonance. Without impedance matching circuits, the power transfer efficiency of the system degrades significantly.

To address this issue, we develop an impedance matching technique by using an equivalent circuit model. Figure 3 (a) shows a schematic of the proposed equivalent circuit model. In our proposed model, we introduce virtual inductors in TX and RX blocks to analyze each block separately. The output load power P_{LOAD} can be given by

$$P_{\mathrm{LOAD}} = \eta_{\mathrm{TX}} \cdot \eta_{\mathrm{PT}} \cdot \eta_{\mathrm{RX}} \cdot P_{\mathrm{IN}}, \quad (1)$$

where η_{TX}, η_{PT}, and η_{RX} are power transfer efficiency of the TX, PT, and RX blocks, respectively, and P_{IN} is the input power. Therefore, we have to increase each η and P_{IN} to maximize P_{LOAD}. The procedure of the proposed impedance matching are as follows.

step.1) First, we define the physical size of the RX resonator and the distance between TX and RX resonators.

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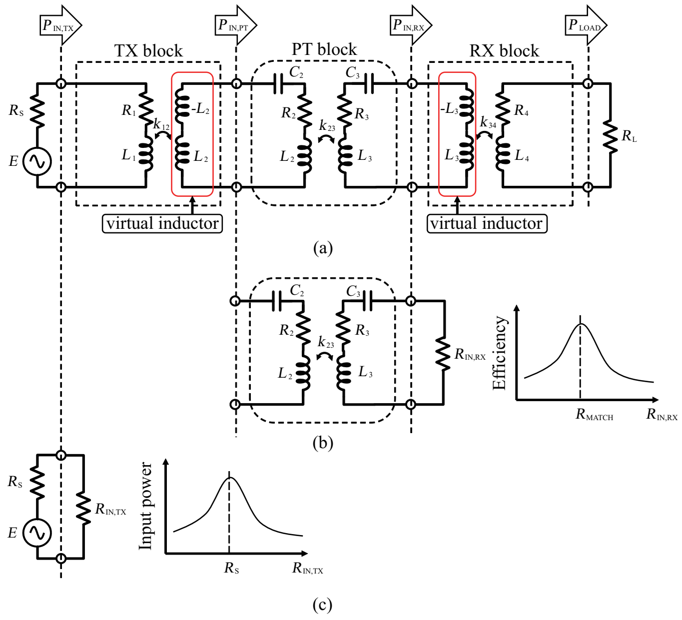

Fig. 3. (a) Converted equivalent circuit, (b) design approach of PT block and RX block and (c) design approach of TX block.

Because inductance of L_3 mainly depends on the size, L_3 and R_3 are determined so that quality factor becomes maximum [3]. After that, C_3 is determined from the resonant frequency.

step.2) Next, we analyze the PT block. Figure 3 (b) shows a simplified model of the PT block, where $R_{\mathrm{IN,RX}}$ is the input impedance of the RX block. As discussed later, we analyze the model so that power transfer efficiency of the PT block η_{PT} becomes as high as possible. L_2, C_2, and R_2 are determined through the analysis.

step.3) Next, we analyze the RX block. From the analysis in step.2, we obtain input impedance of the RX block $R_{\mathrm{IN,RX}}$ that gives maximum η_{PT}. Therefore, we can determine L_4 and R_4 using the results.

step.4) Finally, we analyze the TX block. Figure 3 (c) shows a simplified model, where $R_{\mathrm{IN,TX}}$ is the input impedance of the TX block. $P_{\mathrm{IN,TX}}$ becomes maximum when $R_{\mathrm{IN,TX}}$ is equal to R_{s}. Therefore, we can determine L_1 and R_1.

Details of the analysis are described as follows.

A. Power transfer efficiency of the PT block

The power transfer efficiency of the PT block η_{PT} (=$P_{\mathrm{IN,RX}}/P_{\mathrm{IN,PT}}$) is given by

$$\eta_{\mathrm{PT}} = \frac{1}{\left(1+\frac{R_3}{R_{\mathrm{IN,RX}}}\right)\left\{1+\frac{1}{k_{23}^2 Q_2 Q_3}\left(1+\frac{R_{\mathrm{IN,RX}}}{R_3}\right)\right\}}, \quad (2)$$

where Q_2 and Q_3 are the quality factors of TX and RX resonators. From Eq. (2), η_{PT} can be maximized when

$$R_{\mathrm{IN,RX}} = R_{\mathrm{MATCH}} = R_3\sqrt{1+k_{23}^2 Q_2 Q_3}. \quad (3)$$

With the condition, the maximum $\eta_{\mathrm{PT,MAX}}$ can be given by

$$\eta_{\mathrm{PT,MAX}} = \frac{k_{23}^2 Q_2 Q_3}{\left\{1+\sqrt{1+k_{23}^2 Q_2 Q_3}\right\}^2}. \quad (4)$$

Therefore, the higher $k_{23}^2 Q_2 Q_3$, the higher the $\eta_{\mathrm{PT,MAX}}$.

The $\eta_{\mathrm{PT,MAX}}$ increases as $k_{23}^2 Q_2 Q_3$ increases. To realize high-k_{23} TX resonator, we have to choose optimal coil diameter as discussed in [4]. L_2 and R_2 are designed so that k_{23} becomes maximum. After that, C_2 is determined from the resonant frequency.

B. Power transfer efficiency of the RX block

The power transfer efficiency of the RX block η_{RX} is given by

$$\eta_{\mathrm{RX}} = \frac{P_{\mathrm{LOAD}}}{P_{\mathrm{IN,RX}}} = \frac{R_{\mathrm{L}}}{R_{\mathrm{L}}+R_4}. \quad (5)$$

The η_{RX} becomes 1 because R_{L} is much larger than R_4.

From Fig. 3 (a), the input impedance of $R_{\mathrm{IN,RX}}$ can be calculated as

$$R_{\mathrm{IN,RX}} = \frac{\omega^2 k_{34}^2 L_3 L_4 R_{\mathrm{L}}}{R_{\mathrm{L}}^2+(\omega L_4)^2}. \quad (6)$$

Therefore, L_4 is determined by using Eqs. (3) and (6) (i.e., $R_{\mathrm{IN,RX}} = R_{\mathrm{MATCH}}$).

C. Power transfer efficiency of the TX block

In the following, we discuss the power transfer efficiency on the assumption that $R_{\mathrm{IN,RX}}$ is equal to R_{MATCH}. The power transfer efficiency of the TX block η_{TX} is given by

$$\eta_{\mathrm{TX}} = \frac{P_{\mathrm{IN,PT}}}{P_{\mathrm{IN,TX}}} = \frac{1}{1+\frac{1}{k_{12}^2 Q_1 Q_2}\left\{1+\frac{k_{23}^2 Q_2 Q_3}{1+\sqrt{1+k_{23}^2 Q_2 Q_3}}\right\}}. \quad (7)$$

The η_{TX} becomes 1 because $k_{12}^2 Q_1 Q_2$ is much larger than 1.

From Fig. 3 (a), $R_{\mathrm{IN,TX}}$ can be calculated as

$$R_{\mathrm{IN,TX}} = R_1\left(1+\frac{k_{12}^2 Q_1 Q_2}{1+\frac{k_{23}^2 Q_2 Q_3}{1+\sqrt{1+k_{23}^2 Q_2 Q_3}}}\right). \quad (8)$$

The maximum input power $P_{\mathrm{IN,TX,MAX}}$ can be given by

$$P_{\mathrm{IN,TX,MAX}} = \frac{E^2}{8R_{\mathrm{S}}}, \quad (9)$$

when $R_{\mathrm{IN,TX}}$ is equal to R_{s}. Therefore, L_1 is determined from $R_{\mathrm{IN,TX}} = R_{\mathrm{s}}$.

III. Results

In order to evaluate our proposed model, we performed SPICE and electromagnetic field simulation. Figure 4 shows the WPT system we used. The diameter of RX resonator was set to 4 mm [5] and that of TX resonator was set to 30 mm. Table I summarizes design parameters, which were calculated from the electromagnetic field simulator. The E, R_{S}, R_{L}, operating frequency, and distance between resonators were set to 2.0 V, 50 Ω, 200 Ω, 144 MHz, and 10 mm, respectively.

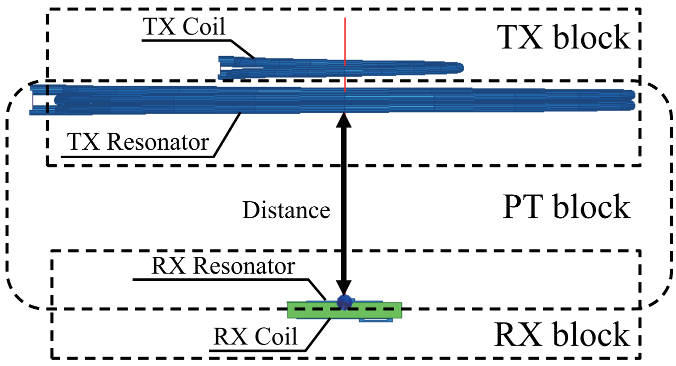

Fig. 4. WPT system.

TABLE I. DESIGN PARAMETERS

	TX coil	TX resonator	RX resonator	RX coil
Shape	helical		spiral	
Thickness(μm)	-		70	
Width(mm)	0.5		0.254	
Pitch(mm)	0.2		0.2	
Diameter(mm)	12	30	4	5
Turns	1	2	3	3
Frequency(MHz)	-	144	144	-
R (Ω)	0.0875	0.523	0.330	0.407
L (nH)	23.9	274	31.7	46.2
C (pF)	-	4.46	38.5	-
Q	257	474	86.9	103
k_{12}	0.115		-	-
k_{23}	-	0.0124		-
k_{34}	-	-	0.366	
k_{13}	0.0079			
k_{14}	0.0087			
k_{24}	0.0154			
R_{MATCH} (Ω)	0.894			
$R_{\mathrm{IN,RX}}$ (Ω)	0.824			
$R_{\mathrm{IN,TX}}$ (Ω)	50.2			

From Eqs. (4) and (9), theoretical maximum input power and efficiency are calculated as 10 mW and 46%, respectively.

Figures 5, 6, and 7 show the input power and efficiency as a function of frequency, load resistance R_{L}, and distance between resonators, respectively. Results using the proposed model showed good agreement with those using EM model.

At resonant frequency of 144 MHz, the input power and efficiency became maximum. The input power and efficiency of the proposed model were 10 mW and 46%, respectively, as shown in Fig. 5. Thus, we confirmed that the efficiency in TX and RX blocks become almost 100% and $R_{\mathrm{IN,TX}}$ and $R_{\mathrm{IN,RX}}$ become optimal value.

Input power and power transfer efficiency decreased outside of $R_{\mathrm{L}} = 200\ \Omega$ as shown in Fig. 6. This is because $R_{\mathrm{IN,TX}}$ and $R_{\mathrm{IN,RX}}$ changed with R_{L} and then was not able to maintain $R_{\mathrm{IN,TX}} = R_{\mathrm{S}}$ and $R_{\mathrm{IN,RX}} = R_{\mathrm{MATCH}}$.

Input power also decreased outside of distance = 10 mm as shown in Fig. 7 (a). This is because $R_{\mathrm{IN,TX}}$ changed with distance and then was not able to maintain $R_{\mathrm{IN,TX}} = R_{\mathrm{S}}$.

IV. Conclusion

In this paper, an impedance matching technique in magnetic-coupling-resonance wireless power transfer system for small implantable medical devices was presented. We can obtained the theoretical maximum input power and efficiency without using impedance matching circuit. Electromagnetic simulations demonstrated that our proposed method has capability of achieving maximum available input power, 10 mW, and efficiency, 46%.

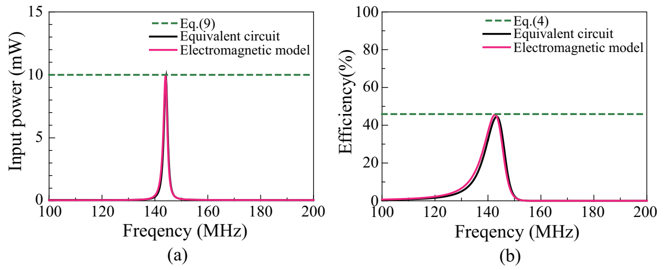

Fig. 5. Simulated (a) input power and (b) efficiency as a function of frequency.

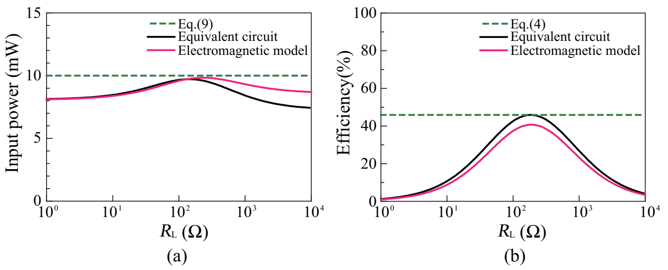

Fig. 6. Simulated (a) input power and (b) efficiency as a function of load resistance.

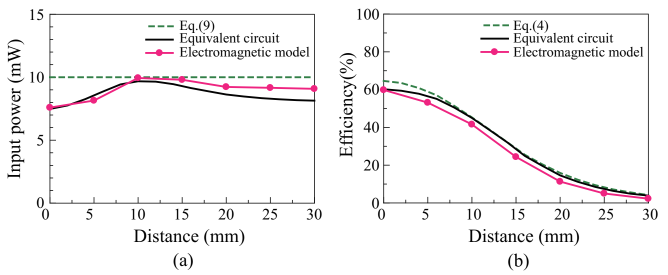

Fig. 7. Simulated (a) input power and (b) efficiency as a function of distance.

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