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Simulative and Experimental Research on Wireless Power Transmission Technique in Implantable Medical Device

Yue Yu, Hongwei Hao, *Member, IEEE*, Weiming Wang, Luming Li, *Member, IEEE*

***Abstract*—as the development of implantable biomedical devices, the rechargeable battery is applied to improve the life of implantable devices. Inductive transcutaneous power transfer, as a suitable way of charging the implantable rechargeable batteries, is widely used. During charging period, there are several stages based on the charging rule and the load resistance is varying simultaneously. In this paper, a model of inductive transcutaneous power transfer is set up with a compensative capacitor for primary coil in series and another compensative capacitor for secondary coil in parallel to descript the relationship in coupling coefficient, load resistance and conversion efficiency. Simulations were done and experiments were carried out to verify the model, and some suggestions on wireless power transfer design are given.**

I. Introduction

Implantable medical devices, especially the artificial hearts ,pacemakers and nerve stimulators which are playing a more and more significant role in curing many kinds of diseases, have been widely applied for many years. But the devices' lifetime is usually not long enough, essentially because of the limitation of the battery capacity. Traditionally, primary (non-rechargeable) batteries are used in implantable devices with heavier weight, bigger volume and shorter lifetime compared with rechargeable batteries. In the large power consumption device, such as spinal cord stimulation (SCS), rechargeable battery is the only choice to increase the service life and decrease the annual cost. Inductive power transmission on coupling coils is considered as a suitable way of transcutaneous power supplying. Although it has been used in some products such as rechargeable implantable spinal cord stimulators, it is still extensively studied in recent years.

Most of these studies were focused on the optimization of transmission, considering the efficiency and stability of inductive link. E. S. Hochmair exhibited the effect of coupling coefficient k in inductive link and the circuit design to acquire a better efficiency of inductive link in 1987 [1]. As a major method, geometric majorization for the enhancement of the coupling coefficient between two magnetically coupled coils to ameliorate the efficiency of inductive link was studied in [2-5] , and the output changes caused by the different shapes ,number of turns and the relative permeability of the power receiving coils were discussed in [6, 7], from which we can get the design of receiving coils. The circuit of system was also considered, in [8, 9] class-E amplifier was used to evolve the efficiency of inductive link. To get a stable voltage or efficiency, many circuits and systems were presented in [10-12]. For the optimization of inductive link, it is necessary to consider the conversion efficiency η. But the relationship between conversion efficiency and coupling coefficient has not been described exactly in publications up to now.

In this paper, a model is set up with a compensative capacitor in series for primary coil and a compensative capacitor in parallel for secondary coil, to describe the relationship between coupling coefficient and the conversion efficiency. Simulations and experiments were carried out to verify the model. Since there are several stages when charging the implantable battery, such as preparatory charging stage, constant current stage, constant voltage charging stage; the equivalent load resistance is different from each other in different stages, and the conversion efficiency changed with load resistance is studied. At last, some suggestions on wireless power transmission design are given.

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Yue Yu is with School of aerospace, Tsinghua University, Beijing 100084 China.

Hongwei Hao is with School of Aerospace, Tsinghua University, Beijing 100084 China.

Weiming Wang is with School of Aerospace, Tsinghua University, Beijing 100084 China.

corresponding author Luming Li is with School of Aerospace, Tsinghua University, Beijing 100084 China, phone: +86-10-62785716; fax: +86-10-62785716; e-mail: lilm@tsinghua.edu.cn.

II. Proposed Transmission System and Model

A. System Block Diagram

As shown in Figure 1, the basic topology of wireless power transformer consists of three parts: external power amplifier tank circuit, wireless inductive link and implanted receiver. The external part generates a suitable variable frequency signal which is amplified and then added on the primary coil and the coil will generate an alternating magnetic field for inductive link. The receive coil in receiver can gain power from the magnetic field.

Due to the employment of mutual inductance (M in figure 1) in inductive link, there are leakage inductances in both sides. Both the external power amplifier tank circuit and the receiver were added capacitors in series or in parallel with the coil in order to compensate the leakage inductances. To get a higher voltage in the primary coil, a capacitor in series (C_1 in figure 1) is employed in the external circuit. In the receiver, both the series and parallel capacitor were suggested in many articles [13] . In our experiment, a capacitor in parallel (C_2 in figure 1) is employed, and the load get power after rectifier.

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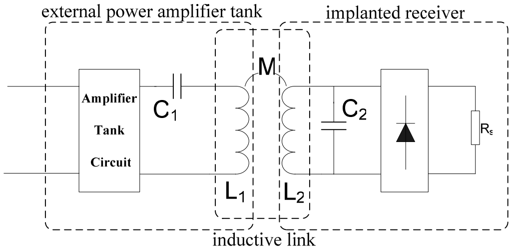

Figure 1 Block diagram of the wireless power transmission system

B. Model of System

Figure 2a is the T equivalent circuit of the inductive link, which can be applied in the system to analyze the circuit, especially the conversion efficiency η. L_1-M is the leakage inductance of external coil inductance, L_2-M is the leakage inductance of implanted coil inductance and M is the mutual inductance. Figure 2b displays the equivalent circuit of the circuit in figure 1.

R_1 is parasitical resistance of external circuit, which is made up of parasitical resistance in amplifier circuit such as on-resistance of MOSFET or transistor, resistance of coil L_1, and equivalent series resistance of capacitor C_1. R_2 is parasitical resistance of implanted circuit, which is made up of parasitical resistance such as resistance of coil L_2, equivalent series resistance of capacitor C_2 and resistance of diodes. R_S is the load resistance.

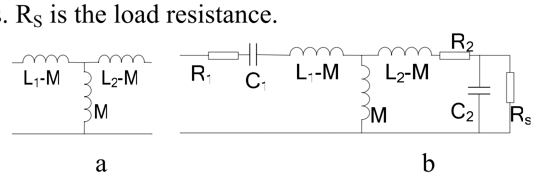

Figure 2: a. T equivalent circuit of the inductive link; b. the equivalent circuit of system

The mutual inductance M could be expressed by the coupling coefficient k as follow:

$$M = k\sqrt{L_1 \bullet L_2} \tag{1}$$

As the distance Z between primary and secondary coil is far larger than the diameter of secondary coil r_2 (in figure 3), typically, Z is bigger than 4 $\times r_2$; the coupling coefficient k is small (k<0.1); and the inductance L_1 is similar to L_2. The compensative capacitor could be

$C_1 = \frac{1}{\omega^2 L_1}$, $C_2 = \frac{1}{\omega^2 L_2}$ as a simply choice.

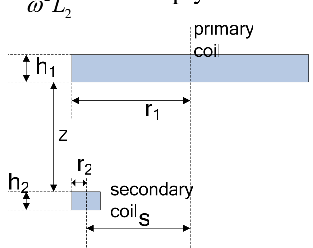

Figure 3 relative locating between primary coil and secondary coil, and geometric parameters of two coils.

C. Model Calculation

To optimize the circuit and the inductive link, it is necessary to consider following functions: Conversion efficiency $\eta = P_{rs} / P_1$; P_{rs} is the power on load R_s; P_1 is the total power consumption. U_{rs} is the voltage on R_s. These functions are calculated with the model in figure 2 as follow:

$$R = \left\{ \left[(R_s // \frac{1}{j\omega C_2}) + R_2 + j\omega(L_2 - M) \right] // j\omega M \right\} + R_1 + j\omega(L_1 - M) + \frac{1}{j\omega C_1} \tag{2}$$

R is the equivalent impedance from power input with the voltage U_1 on it. The current on R_1 is $I_1 = U_1/R$; and the total power consumption $P_1 = |U_1 \times I_1|$.

The voltage on inductance M is U_2:

$$U_2 = I_1 \bullet \left\{ \left[(R_s // \frac{1}{j\omega C_2}) + R_2 + j\omega(L_2 - M) \right] // j\omega M \right\} \tag{3}$$

The current on R_2 is I_2:

$$I_2 = U_2 / \left[(R_s // \frac{1}{j\omega C_2}) + R_2 + j\omega(L_2 - M) \right] \tag{4}$$

The voltage on load R_s is U_{rs}:

$$U_{rs} = I_2 \bullet (R_s // \frac{1}{j\omega C_2}) \tag{5}$$

Power on load R_s is P_{rs}:

$$P_{rs} = \frac{|U_{rs}|^2}{R_S} \tag{6}$$

III. The Coupling Coefficient and Load

A. System Analyze

Mutual inductance M of two coils is given by [1].

$$M = \pi \mu n_1 n_2 \bullet \sqrt{r_1 \bullet r_2} \bullet I$$

$$I = \int_0^\infty J_1\left(x\sqrt{\frac{r_1}{r_2}}\right) J_1\left(x\sqrt{\frac{r_2}{r_1}}\right) J_0\left(x\frac{s}{\sqrt{r_1 \bullet r_2}}\right) \bullet \frac{\sinh\left(x(h1/r1)\sqrt{r_1/r_2}\right)}{x(h1/r1) \bullet \sqrt{r_1/r_2}} \bullet \frac{\sinh\left(x(h2/r2)\sqrt{r_2/r_1}\right)}{x(h2/r2) \bullet \sqrt{r_2/r_1}} \bullet \exp\left(-x\frac{z}{\sqrt{r_1 \bullet r_2}}\right) dx \tag{7}$$

μ=4π nH/cm and other parameters depend on the geometry of coils and their location. In transcutaneous power transmission, the distance between primary and secondary coil (Z in figure 3) is not constant; the alignment (s in figure 3) is changing; so coupling coefficient will changes. Also, the design of coil, especially the geometric (i.e. $h_1, h_2, r_1, r_2, n_1, n_2$) will affect coupling coefficient. In many articles [2-5], the methods of enhance coupling coefficient were presented to increase the efficiency. We will get the relationship between coupling coefficient and conversion efficiency from the model in figure 2b.

On the other side, the load could also affect the energy gotten from the magnetic field. There are several stages when charging the implanted battery: preparatory charging stage with a low current to battery, constant current stage charging with a constant current which is larger than the current in preparatory charging stage; constant voltage charging stage with constant voltage while the current to battery is varying. As the status is changing, the load resistance is changing which will lead to the varying of conversion efficiency and the voltage on the load.

B. Model Simulation

Calculating the model in figure 2b, using formulas (2-6). The conversion efficiency could be calculated as:

$$
\begin{aligned}
\eta &= \frac{P_{rs}}{P_1} = \frac{|U_{rs}|^2 \bullet R}{|U_1|^2 \bullet R_S} = \frac{R}{R_S} \bullet \frac{\left| I_2 \bullet \left(R_s // \frac{1}{j\omega C_2} \right) \right|^2}{|U_1|^2} \\
&= \frac{R\left(R_s // \frac{1}{j\omega C_2} \right)^2}{R_S \left(\left(R_s // \frac{1}{j\omega C_2} \right) + R_2 + j\omega (L_2 - M) \right)^2} \bullet \frac{|U_2|^2}{|U_1|^2} \\
&= \frac{R\left(R_s // \frac{1}{j\omega C_2} \right)^2 \left\{ \left[\left(R_s // \frac{1}{j\omega C_2} \right) + R_2 + j\omega (L_2 - M) \right] // j\omega M \right\}^2}{R_S \left(\left(R_s // \frac{1}{j\omega C_2} \right) + R_2 + j\omega (L_2 - M) \right)^2} \bullet \frac{|I_1|^2}{|U_1|^2} \\
&= \frac{R\left(R_s // \frac{1}{j\omega C_2} \right)^2 \left\{ \left[\left(R_s // \frac{1}{j\omega C_2} \right) + R_2 + j\omega (L_2 - M) \right] // j\omega M \right\}^2}{R_S \left(\left(R_s // \frac{1}{j\omega C_2} \right) + R_2 + j\omega (L_2 - M) \right)^2} \bullet \frac{|I_1|^2}{|U_1|^2} \\
&= \frac{\left(R_s // \frac{1}{j\omega C_2} \right)^2 \left\{ \left[\left(R_s // \frac{1}{j\omega C_2} \right) + R_2 + j\omega (L_2 - M) \right] // j\omega M \right\}^2}{R_s R \left(\left(R_s // \frac{1}{j\omega C_2} \right) + R_2 + j\omega (L_2 - M) \right)^2} \qquad (8)
\end{aligned}
$$

Using Matlab to calculate formula 8, figure 4 illustrates the conversion efficiency through wireless power transmission, with the changes of mutual inductance *M* and load resistance *Rs* both of have boundary:

$M \in \left[0, \sqrt{L_1 \bullet L_2}\right]$ or $k \in [0,1]$

$R_s \in [0, +\infty]$

As shown in figure 4, the conversion efficiency is a monotone increasing function of *M*. Transcutaneous power transmission is a kind of weak magnetic couple, k<0.1 This suggests the design should have a bigger *M*.

With a constant *M*, there exists an optimized *Rs*, which could get a maximum efficiency and the optimized *Rs* changes with the variation of *M*. So to different load resistance *Rs*, we should choose different system with different *M*.

IV. Experiments and Results

A. Experiment Design

To verify the model and its result, an experiment was designed and carried out. The efficiency and the voltage on load were measured. The parameter of the transmitter coil and receiver coil used in the experiments are shown in Table. 1. To reduce the parasitic resistance of inductance, especially L_1, multi-wires was used to enhance the wire area. Mn-Zn ferrites were used in both coils to enhance the coupling between them. The ferrite PC95 made by Panasonic is used.

In the experiment, the frequency was 25.5 kHz; input a sinusoidal AC voltage with peak-peak voltage 6V. The load resistance varied from 1.82Ω to 3.57kΩ. In the experiment, the efficiency was changing with the variation of load resistance. As the geometry of coils was constant, the location of coils was changed to modify *M*, i.e.: Distance: 10mm, 20mm; Misalignment: 10mm.The value of M is measured experimentally. The total energy consumption and the energy gotten on load were measured by power analyzer PM1000+, made by Voltech.

B. Result Analysis

Figure 5 shows the relationship between efficiency and load resistance and relationship between load resistance and voltage on it, in which the line shows the simulation result which is closed to the points of experiment results, with distance of 20mm and 10mm, and misalignment of 10mm respectively.

From the results of experiment and simulation, a higher mutual inductance or coupling coefficient should be applied for a higher conversion efficiency, in transcutaneous power transmission with weak coupling (k<0.1). As energy efficiency largely depends on the load resistance, it should be concerned that the variation of load and optimization of it. The resistance converter would be employed for a higher efficiency.

Focusing on consumption of energy, table 2 illuminates that most of consumption is consumed on parasitical resistance of external circuit, major on primary coil's parasitical resistance. So, the most useful and straight method for increasing energy efficiency is to reduce parasitical resistance of external circuit.

TABLE I

PARAMETER OF COILS

parameter	Transmitter coil	Receiver coil
Wire diameter	0.31mm	0.15mm
Number of wires	4	1
Parasitic resistance	1.443Ω	1.435Ω
Turns	85	100
Core size	Φ31×37mm	Φ6×5mm
Inductance	879.9μH	223.3μH

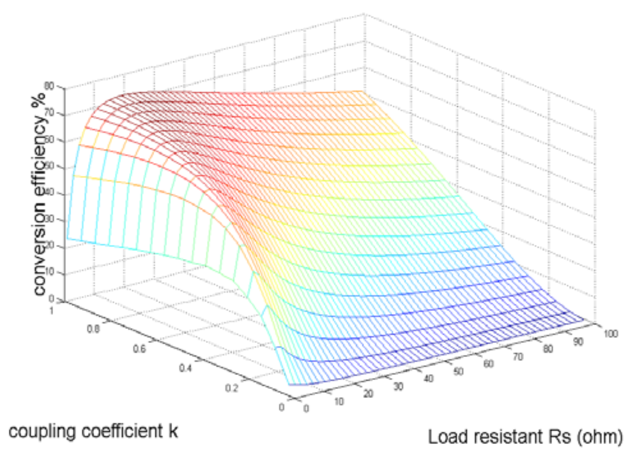

Figure 4 simulation results about the conversion efficiency η varying as the load resistance *Rs* and coupling coefficient *k* changes.

TABLE II

ENERGY CONSUMPTION

R_S	P_1	P_{RS}	P_{RL1}	η_1	η_2
1.82 Ω	1.37 W	0.008 W	1.28 W	0.61%	9.22%
23.90 Ω	1.32 W	0.089 W	1.16 W	6.70%	55.35%
74.73 Ω	1.26 W	0.148 W	1.05 W	11.70%	69.37%
100.06 Ω	1.25 W	0.146 W	1.03 W	11.69%	67.56%
224.69 Ω	1.22 W	0.104 W	1.02 W	11.38%	66.55%
909.86 Ω	1.22 W	0.033 W	1.09 W	2.70%	25.04%

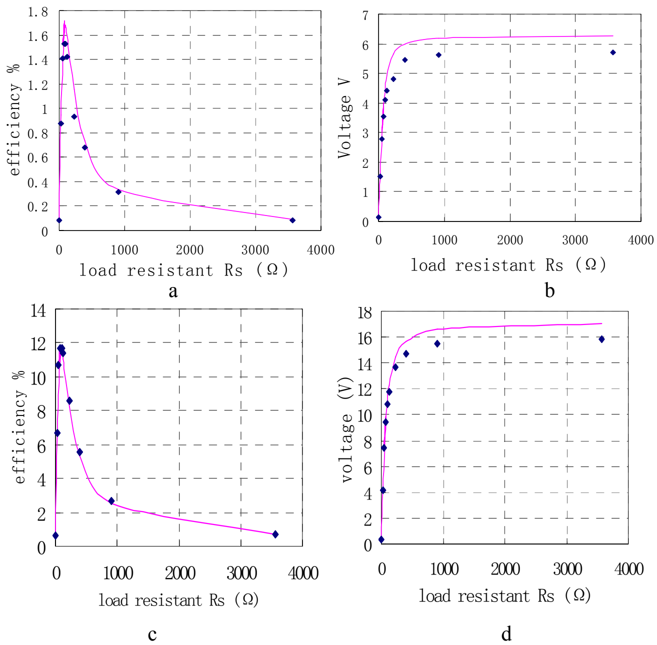

Figure 5 a relationship between efficiency and load resistance with distance 20mm and misalignment 10mm;
b relationship between load resistance and voltage on it with distance 20mm and misalignment 10mm;
c relationship between efficiency and load resistance with distance 10mm and misalignment 10mm;
d relationship between load resistance and voltage on it with distance 10mm and misalignment 10mm.

P_1 is the total energy consumption; P_{RS} is the energy gotten on load; P_{RL1} is the energy consumed on parasitical resistance of external circuit; $\eta_1 = P_{RS} / P_1$; $\eta_2 = P_{RS} / (P_1 - P_{RL1})$;

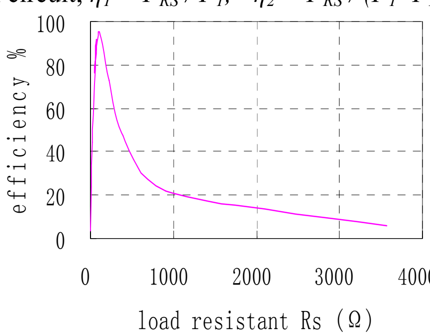

Figure 6 the relationship between coupling coefficient *k* and conversion efficiency η. As R_{L1}=0 Ω,

Figure 6 is a simulation with R_1=0Ω. There are many other parasitical resistances on external circuit, so the calculation in table 2 is not closed to the line in figure 6. But, a lower R_1 is significant to increase energy efficiency.

V. CONCLUSION

This paper illustrates and analyzes a model of wireless power transmission. The simulative and experimental verification are finished. Three recommendations are given.

1) Higher mutual inductance M is suggested while designing the coils, because the transfer efficiency is a monotone increasing function of M in this situation.
2) Energy efficiency largely depends on the load resistance, it should be concerned that the variation of load and how to optimize it. The transformer or others would be employed for a higher efficiency if possible to convert the load resistance.
3) One useful and straight method of increasing energy efficiency is reducing parasitical resistance of external circuit.

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