Analysis of Wireless Energy Transmission for Implantable Device Based on Coupled Magnetic Resonance

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Abstract ¡ Medical implant devices for producing therapeutic results in patients are well known. Power supply is one key technique for implantable electrical devices. It is a dream that medical implantable devices have the function of wireless energy transmission in clinical applications. In this paper, structure of wireless power transmission system for implantable devices is designed, theoretical analysis and simulated computation of electromagnetic field energy transmission base on coupled mode theory is performed, the influence of structural parameters on the energy transmission efficiency is investigated.

I. INTRODUCTION

Medical implants are important devices producing therapeutic results in patients, examples of cardiac pacemakers, cardiac defibrillators. Most commercial implantable devices utilize a non-rechargeable battery which stores a sufficient amount of energy to allow the device to operate for several years. Because of the high energy capacity requirement, the battery must be large and heavy. The power supply problem also contributes to the high cost of the implantable devices[1]. A new technology called WiTricity based on the coupled mode theory for wirelessly energy transmission over a fair distance as reported in July of 2007 [2]. This technology provides a new possibility to supply energy for implantable devices utilizing strongly coupled magnetic resonance to transmit power over a distance.

In this paper, design of energy transmission system for implantable devices base on coupled magnetic resonance is performed by computer simulation, the influence of the structural parameters on energy transmission efficiency is also investigated.

II. DESIGN OF WET SYSTEM FOR IMPLANTABLE DEVICE

A. *Structure of Wireless Energy Transmission System*

The WET system structure for implantable device based on the concept of strongly coupled magnetic resonance is designed, which consists of a source, a driving circuit, two resonant coils, a rechargeable circuit and an implantable device, as shown in Fig. 1.

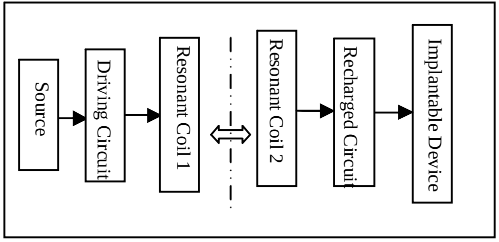


Fig. 1. The scheme of energy transmission system for implantable device.

B. *Theoretical Analysis of Wireless Energy Transmission*

An appropriate theoretical analysis for modeling this resonant power exchange is the well-known coupled mode theory (CMT). According to this theory, the field of the system of two resonant coils 1 and 2 is approximated by $\mathbf{F}(\mathbf{r},t)\approx a_1(t)\mathbf{F}_1(\mathbf{r})+a_2(t)\mathbf{F}_2(\mathbf{r})$, where $\mathbf{F}_{1,2}(\mathbf{r})$ are the eigenmodes of resonant coils 1 and 2 alone, and $a_{1,2}(t)$ are the field amplitudes of two coils. Then the energy exchange between the two resonant coils can be expressed using the following differential equations [2]-[3]

$$\begin{cases}\dfrac{da_1(t)}{dt}=(i\omega_1-\Gamma_1)a_1(t)+ik_{11}a_1(t)+ik_{12}a_2(t)\\ \dfrac{da_2(t)}{dt}=(i\omega_2-\Gamma_2)a_2(t)+ik_{22}a_2(t)+ik_{21}a_1(t)\end{cases}\qquad(1)$$

where $\omega_{1,2}=2\pi f_{1,2}$ are the individual resonant angular frequencies, $\Gamma_{1,2}$ are the individual resonance decay rates due to the intrinsic losses of coils via radiation into free space and absorption inside the material, k_{11} and k_{22} are the coupling coefficients between the resonant coils and non-resonant objects, k_{12} and k_{21} are the coupling coefficients between the resonant coils 1 and 2.

Then the total energy in the system can be calculated by

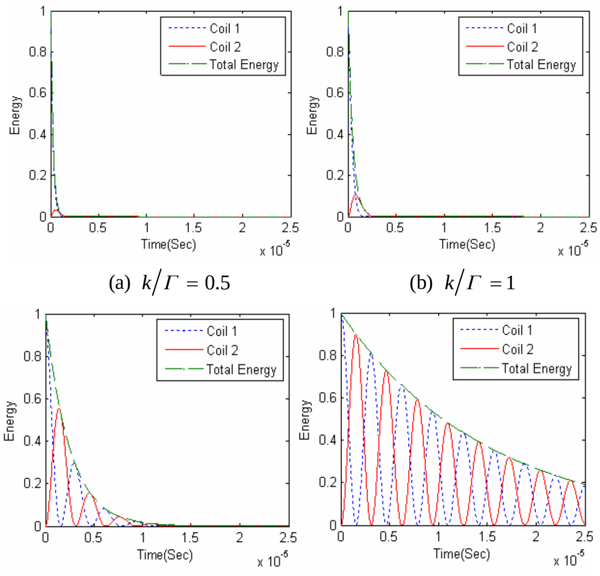
$$p(t)=p_1(t)+p_2(t)=\left|a_1(t)\right|^2+\left|a_2(t)\right|^2=e^{-2\Gamma t}\qquad(2)$$

where, $p(t)$ is the total energy of system, $p_1(t),p_2(t)$ are the energy in coils l and 2 respectively.

III. SIMULATION RESULTS IN DIFFERENT COUPLED MODES

The decreasing rate of the total energy transferred in the system is directly affected by resonant decay rate Γ , and that the coupling coefficient k reflects the transmission rate of energy between the two resonant coils. Therefore, k/Γ is the distance-dependent figure-of-merit for the resonant energy transfer system. To illustrate, we plot three curves representing the energy variation in each resonant coil and the total energy of the system under the different condition of

k/Γ as shown in Fig. 2.



(a) $k/\Gamma = 0.5$ (b) $k/\Gamma = 1$

(c) $k/\Gamma = 5$ (d) $k/\Gamma = 15$

Fig.2. Energy transmission situations in different coupled modes

IV. OPTIMAL DESIGN OF SYSTEM STRUCTURE PARAMETERS

To reduce the individual resonance decay rates $\Gamma_{1,2}$ and form an efficient energy exchange channel, each resonant coil should have a high quality factor Q. We can obtain the frequency values of resonant coils with different parameters when Q reaches $Q_{\max}$ as shown in Table 1. we find that the resonant frequency deceases with the growth of coil radius, turns or wire¡s radius when Q reaches $Q_{\max}$, i.e., each of the three parameters influences f. Due to the size limit of implantable devices, resonant coil 2 in the energy transmission system should be small in radius, which gives rise to the growth of the intrinsic frequency f of resonant coil 2.

TABLE I

PARAMETERS OF COILS

Coils	N	r (mm)	a (mm)	$Q_{\max}$	f (MHz)
1	2	15	0.5	1507	237.0
2	2	30	0.5	1342	150.7
3	2	300	2	2002	14.0
4	2	300	5	3601	10.8
5	10	15	0.5	5985	172.3
6	15	250	1	7397	11.3

Symbols- N: nubmer of turns; r : radius of coil, a : radius of wire

Since the two resonant coils usually have different parameters, an average resonant decay rate is defined by by $\Gamma_{12} = \sqrt{\Gamma_1 \Gamma_2}$. By adjusting the capacitance, the optimal configuration of the strongly coupled mode of the energy transfer system for an implantable device can be achieved. As seen in Table 1, with No.4 coil as the receiving coil and No.1 coil as the transmitting coil, k/Γ_{12} reaches the highest value of 8.6 when the resonant frequency of two coils is 15 MHz (Fig. 6).

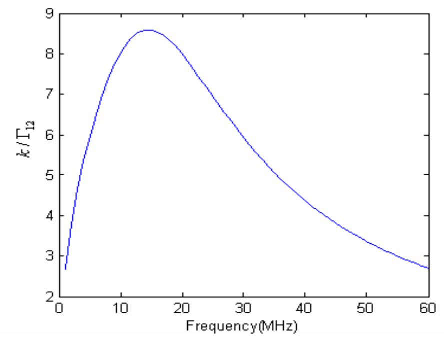


Fig. 6 Frequency matching of coils with different parameters.

V. CONCLUSION AND DISCUSSION

In this paper, we have elaborated both the structure and theory of wireless energy transmission system for implantable devices base on coupled mode theory. We have also presented our results of simulation on several coupled modes in the energy transfer system. Based on our analysis, we have gained more insights into k/Γ as the distance-dependent figure-of-merit in the resonant energy transfer system for implantable devices..

Furthermore, we have investigated the optimal design of system parameters. Because the limit of space, the receiving resonant coil within implantable device must be small in size. Challenges still remain in the energy transmission system for implantable device, such as how to reduce the size of the resonant coil significantly with the least loss of efficiency and how to ensure electromagnetic safety while transmitting a reasonably large amount of energy. These problems will be our next steps of investigation.

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