

Simulation analysis on miniature wireless power transfer system

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Abstract. In recent years, the research on implantable medical devices has become a hot scientific topic, and the power supply of these devices are especially concerned. Generally, these devices are usually powered by disposable batteries. However, for some of the long-term human implant devices, such as pacemakers, once the battery has been exhausted after several years, the patient has to replace the battery by surgery, which increases the patient's economic burden and pain. Wireless power transfer technology, using non-contact way for power transfer, can be a good solution to this problem. In this paper, a micro induction coil was designed, and the transfer efficiency in the air and human tissue model of two-layers were simulated by Ansoft HFSS. The results showed that the system could achieve the energy transfer in both cases, meanwhile, it indicated that the transfer efficiency was lower in a relative larger permittivity of transmission medium.

1. Introduction

In 2007, Kurs from Massachusetts Institute of Technology lighted a 60W bulb using wireless power transfer(WPT) technology at a distance of 2 meters [1]. Since then, the studies on WPT technology have attracted more attention and a series of researchers have been conducted in this area. Fu invented a general WPT system with one-transmitter and multiple-receiver at 13.56MHz, which exhibited the whole efficiency of 80% under the optimal loading conditions [2]. Zhang designed a high efficient WPT system via strongly coupled magnetic resonances. The experiments and simulations demonstrated that the transmitter, designed as a cube-shaped structure and composed by four pairs of inductive coils, could be applied to mobile electronic devices [3]. Khan proposed a high-quality factor resonator and compared the transfer efficiency of the square and round resonators in different conditions, finally he used the three layers of human tissues to simulate the system efficiency [4]. Ahn designed and optimized a four-coil WPT system by coupling the first and fourth coils. The system efficiency and transfer power achieved 65.2% and 17.2W respectively [5]. Kim designed a metal cover of mobile phone using WPT system, with the highest efficiency reached 65% at 6.78 MHz [6]. Ha-Van added a metamaterial slab between the two transfer coils, as a result, the transfer efficiency of the system was enhanced by 8.2% [7]. Tang designed a WPT system for pacemakers, with transfer efficiency and power reached 80% and 48.2W respectively [8]. In addition, some other WPT technical schemes also achieved good results [9-13].

2. LOSS COUPLED-MODE THEORY

The circuit energy loss existed in the actual power transfer system. For the WPT system, the loss mainly existed in the coil's own resistance and electromagnetic radiation. Assuming the electromagnetic radiation is a radiation resistor, then we can simplify the system circuit model by



combining these two resistors into a loss resistor. Fig 1 shows a circuit schematic diagram of WPT system with transmitter and receiver.

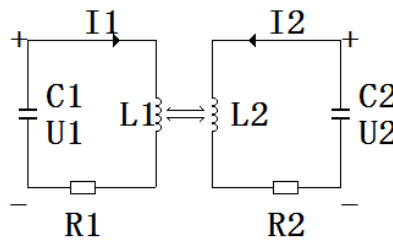


Fig 1. Circuit model of the wireless power transfer system

According to the above system, the basic coupled-mode equation is written as:

$$\begin{cases} \frac{da_1}{dt} = -(j\omega_1 + \Gamma_1)a_1 + jk_{12}a_2 \\ \frac{da_2}{dt} = -(j\omega_2 + \Gamma_2)a_2 + jk_{21}a_1 \end{cases} \quad (1)$$

Where a_1 and a_2 represent the coupled-mode amplitude of the transmitter and the receiver respectively; ω_1 and ω_2 represent the angular frequency of the transmitter and the receiver, and $\omega = 2\pi f$; Γ_1 and Γ_2 represent the loss coefficient (consisting of the resistance loss and the electromagnetic radiation loss and so on); k_{12} and k_{21} represent the coupling coefficient between transmitter and receiver. Assuming the two devices are the same, so $k_{12} = k_{21} = k$.

Substituting $k_{12} = k_{21} = k$ into equation (1), and setting up the initial conditions: $a_1(0) = 1$, $a_2(0) = 0$, the following formula can be obtained:

$$\begin{cases} a_1(t) = e^{-Bt} \left[\cos\left(\frac{1}{2}At\right) + \frac{2B}{A} \sin\left(\frac{1}{2}At\right) \right] \\ a_2(t) = je^{-Bt} \left[\frac{2B}{A} \sin\left(\frac{1}{2}At\right) \right] \end{cases} \quad (2)$$

Where $A = \sqrt{4k^2 - j(\Gamma_2 - \Gamma_1)^2 - (\omega_2 - \omega_1)^2}$, $B = \frac{(\Gamma_2 + \Gamma_1)^2 - j(\omega_2 + \omega_1)}{2}$.

Assuming two resonators are the same, then $\Gamma_2 = \Gamma_1 = \Gamma$, thereby, the energy in each resonator is expressed as:

$$\begin{cases} |a_1(t)|^2 = e^{-2\Gamma t} \cos^2(kt) = e^{-2\Gamma t} \frac{1 + \cos(2kt)}{2} \\ |a_2(t)|^2 = e^{-2\Gamma t} \sin^2(kt) = e^{-2\Gamma t} \frac{1 - \cos(2kt)}{2} \end{cases} \quad (3)$$

So in the WPT system, the total energy in the transmitter and the receiver is the sum of both:

$$W(t) = |a_1(t)|^2 + |a_2(t)|^2 = e^{-2\Gamma t}. \quad (4)$$

It can be seen from the equation (2) and (3), as for the loss oscillation system, the energy in each resonator is decided by loss coefficient Γ and coupling coefficient k . However, the total energy in the system only interrelates with Γ , the total energy will decay with time. The larger the Γ , the faster the energy decays in the system.

Coupling coefficient k is a physical quantity to reflect the coupling strength between transmitter and receiver. To some extent, k incarnates the ability of energy transfer, and loss coefficient Γ presents energy loss rate of WPT system. Considering k and Γ play vital roles in the transfer efficiency, a new concept of coupling strength is defined:

$$\gamma = \frac{k}{\sqrt{\Gamma_1 \Gamma_2}} = \frac{k}{\Gamma}. \quad (5)$$

γ is an important parameter in the magnetic resonant coupling WPT system. As shown in Fig 2, putting $\gamma = 0.1, 1, 10, 100$, we get the energy transfer in different conditions. The black solid line in the fig 2 indicates the total energy in the system, and the red dotted line and the blue dashed line represent the energy in two resonators respectively.

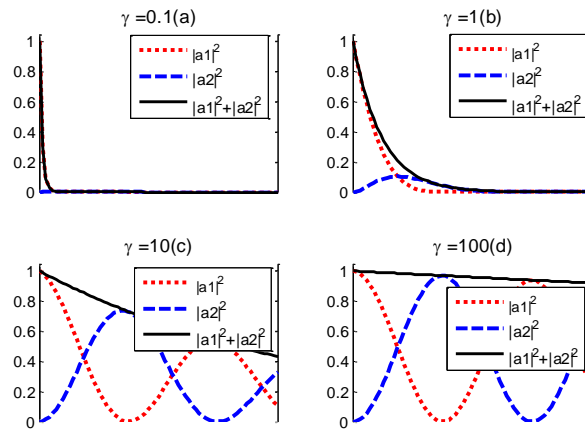


Fig 2. Energy transfer in different conditions.

As seen in Fig. 2(a) and Fig. 2(b), when $\gamma = 0.1$ and $\gamma = 1$, the energy in the transmitter and receiver and the total energy in the system both decay to zero quickly. There is no effective energy transfer between the transmitter and receiver.

As shown in Fig. 2(c) and Fig. 2(d), when $\gamma = 10$ and $\gamma = 100$, the energy in the transmitter and receiver and the total energy in the system show the trend of decay. But when $\gamma = 10$, the energy in the system decays faster. When $\gamma = 100$, the system can achieve a relative stable energy transfer. The above four cases can be seen: the energy attenuation in the system decreases gradually with the increase of γ .

3. SIMULATION

3.1. Simulation of Resonance Frequency of Coil

The coil dimensions used in the experiment and simulation are shown in Tab.1, the coil is wound by copper wire (Fig 3). The simulation model is shown in Fig 4. Generally, when a coil works in a

resonant state, the real part of the coil impedance is the largest and the imaginary part is zero. Fig 5 shows that the self- resonance frequency of the coil is 156 MHz.

Table 1. Coil Parameters.

Number	Inside diameter	Outside diameter	Turns	Wire diameter
1	7 mm	18 mm	20	0.25 mm

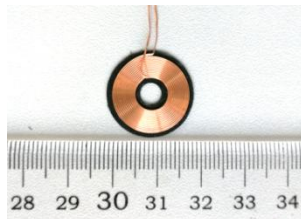


Fig 3. Coil.

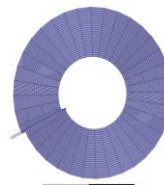


Fig 4. Coil simulation model.

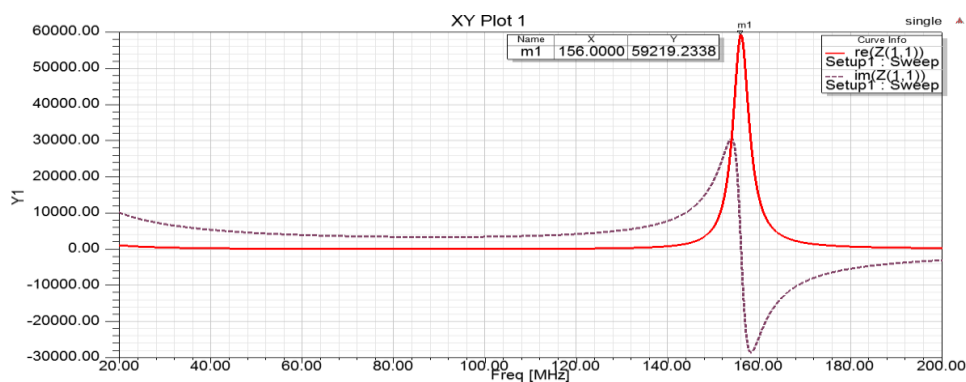


Fig 5. Simulation of coil impedance

3.2. Simulation of transfer efficiency

Considering the coil will be used in medical implantable devices, the coil can be turned to 13.56MHz by circuit matching. Firstly, we simulate the transfer efficiency in the air. Then we add two layers of human tissues (simulating the epidermis and muscle) between the transmitting coil and the receiving coil and embed receiving coil in the body tissues. In this way, we simulate the charging scene of implantable devices to obtain the transfer efficiency in human tissues. The magnetic field distribution of system are shown in Fig 6. The transfer efficiency is shown in Fig 7.

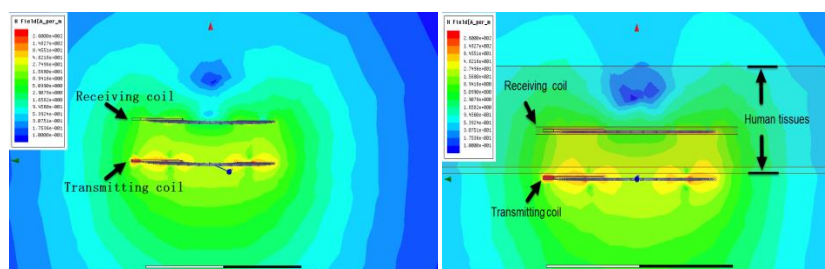


Fig 6. Magnetic field distribution of system in the air and human tissues.

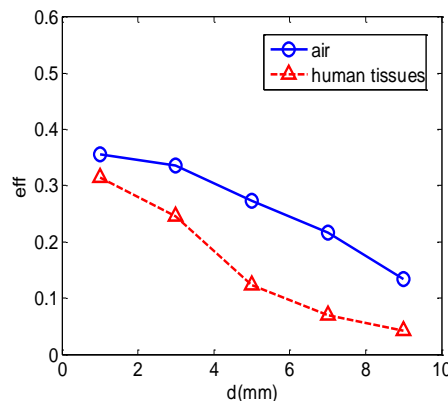


Fig 7. Transfer efficiency in the air and human tissues.

The results show that the system can reach energy transfer both in the air and human tissues. The transfer efficiency reduces gradually with distance. Due to the relative permittivity of human tissues is much larger than that of the air, the transfer efficiency in human tissues is lower. Meanwhile, when the transfer distance in human tissues is larger than 3mm, the transfer efficiency decreases significantly. The relative permittivity of the muscle is larger than that of the skin because there is blood in the muscle.

4. Conclusion

This paper studied the loss coupled-mode theory, and designed a micro-induction coil that can be used in implantable medical devices. Firstly, we simulated the coil's self-resonance frequency using Ansoft HFSS. Then, we simulated the transfer efficiency in the air. Finally, we simulated the charging scene of human implantable devices to obtain transfer efficiency in human tissues. The simulations showed that the system could achieve the energy transfer in both cases. Moreover, the larger the relative permittivity of transmission medium, the lower the transfer efficiency. In further study, pork will be used to simulate human tissues to verify the transfer efficiency of WPT system.

Acknowledgments

This work was financially supported by Qingdao innovation and entrepreneurship leading talent project (13-cx-2), Qingdao national laboratory for marine science and technology Aoshan science and technology innovation project (2016ASKJ07-4) and China International Scientific and Technological Cooperation Special (2015DFR10490).

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