2017 International Conference on Electrical Engineering and Automation Control (ICEEAC 2017)
ISBN: 978-1-60595-447-9

Wireless Energy Transmission System for Implantable Device

Yan-Hong LI[1,2,a], Guo-Qiang LIU[1,2,b,*], Hui-Lin AN[1,2,c] and Chao ZHANG[1,2]

[1]Institute of Electrical Engineering, Chinese Academy of Sciences, China

[2]University of Chinese Academy of Sciences, China

[a]liyanhong@mail.iee.ac.cn, [b]gqliu@mail.iee.ac.cn, [c]anhuilin@mail.iee.ac.cn

* Corresponding author: Guo-Qiang LIU

Keywords: Wireless energy transmission, Magnetic coupling resonance, Implantable device.

Abstract. A wireless energy transmission system based on magnetic coupling resonance was put forward for implantable device. Combining the calculation of self-inductance and mutual inductance between the transmitting and receiving spiral coil, the paper used circuit theory to model and simulate the characteristic of transmission system, the coil parameters including radius and number of turns can be determined accurately. The wideband Class-E power amplifier was used to drive the transmitting coil, its structure and working state were described in detail. Finally this paper carried on the experimental analysis to verify the theoretical derivation and system characteristics.

Introduction

Implantable device which is embedded in the human body will play an important role in biotechnology engineering because of its outstanding effectiveness. The key and difficult issue is how to provide long-term, stable, efficient power, the traditional power supply mode is battery for small power equipment, when battery power is exhausted, and patients suffer physical or emotional pain again. For implantable devices with high power levels, implantable battery cannot provide long-term power, scholars are trying to adopt contactless power transmission technology to design new energy supply mode.

Wireless energy transmission system for biomedical implants has been brought into focus by relevant researchers [1-3]. An adaptive wireless power telemetry system for a retinal prosthetic device was presented by Guoxing, a maximum of 250mW power transmitted through an optimized coil pair drived by Class-E power amplifier [4-5]. The core type transcutaneous energy transmission system which applied for the implantable devices was developed in paper [6]. Paper [7] improved the transcutaneous energy transmission system utilizing ferrite cored coils for artificial hearts. An efficiency above 65% can be obtained within the distance comparable to the diameter of the resonator (60.5mm), and small-sized copper coil of 3 mm of diameter was investigated [8]. SangWook Optimized WPT system for power transfer into a small transfer of 50mm and receiver of 10mm radius at the 50mm transfer distance [9]. A 13.56 MHz wireless power transfer system for biomedical implants was presented by Xing Li, the measured maximum received power and efficiency were 102mW and 92.6% [10].

Wireless power transfer via strongly coupled magnetic resonances which was established by MIT is lossless resonant coupling, comparing with electromagnetic induction [11-12], it has the farer transmission distance and higher transmission efficiency. This paper introduces wireless energy transmission system for implantable device based on magnetic coupling resonance, it utilizes the Class-E power amplifier and planar spiral coils, and uses circuit theory and calculation of self-inductance and mutual inductance between the transmitting and receiving coil to model and simulate the characteristic of the resonant wireless power transmission system, it is worth mentioning that quick selection of coil parameters can be achieved and the paper provides solutions for the design of efficient broadband system, those are insufficient a little in other literatures.

Topology of Main Circuit

Wireless energy transmission system for implantable device is divided into two parts, transmitting unit and receiving unit. The transmitting unit is located in vitro, its HF power amplifier transmits the transmitting coil, forming the alternating magnetic field. The receiving unit contain the receiving resonator, energy management system and implantable device load. Fig.1 shows the structure diagram of wireless energy transmission system for implantable device.

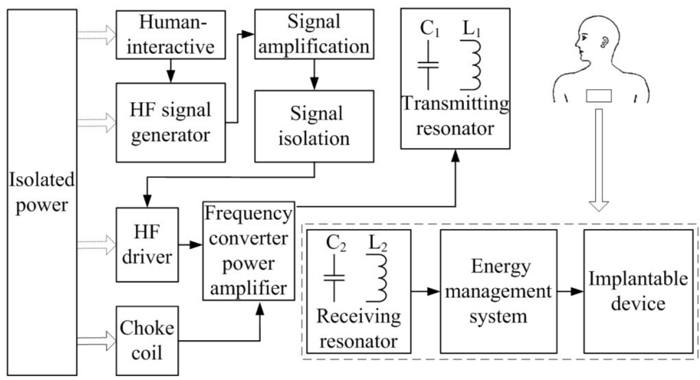


Figure 1. The structure diagram of wireless energy transmission system for implantable device.

In this paper, a wideband Class-E amplifier is presented to realize frequency converter and power amplifier, it drives the transmitter coil. The paper describes how to reduce the loss and improve the efficiency in wideband conditions. Fig.2 shows the circuit of transmitting unit.

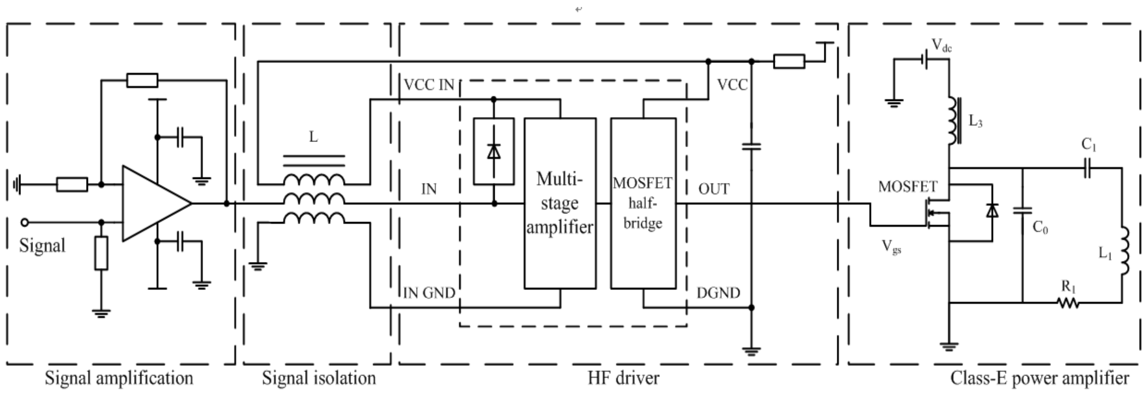


Figure 2. The circuit of transmitting unit.

The amplification of driving signal contains the signal amplification, signal isolation and HF driver. The working state of MOSFET can be adjusted by changing the bypass capacitor, and the optimum working frequency of designed system is from 150 kHz to 8MHz. The voltage waveform of load and experimental photo are shown in paper.

Transmission Characteristics

The implant dimensions are often strictly limited. Combining the calculation of self-inductance and mutual inductance between the transmitting and receiving coil, this paper model and simulate the characteristic of the resonant wireless power transmission system.

For coaxial planar circular coils, the mutual inductance can be calculated as Eq. (1).

$$M = \mu_0 N_1 N_2 \sqrt{r_1 r_2}\left[(\frac{2}{k'} - k')K - \frac{2}{k'}E \right] \tag{1}$$

Where r_1 and r_2 are the coil radius, N_1 and N_2 are the turn numbers, h is the distance between the transfer coil and receiver coil, and K and E are the complete elliptic integrals of the first kind and second kind to the modulus $k^{'}$, respectively, as represented as Eq.(2), Eqs.(3) and (4).

$$k' = \sqrt{4r_1r_2 / ((r_1 + r_2)^2 + h^2)} \tag{2}$$

$$K(k') = \int_0^{\frac{\pi}{2}} \frac{d\theta}{\sqrt{1 - k'^2 \sin^2 \theta}} \tag{3}$$

$$E(k') = \int_0^{\frac{\pi}{2}} \sqrt{1 - k'^2 \sin^2 \theta} d\theta \tag{4}$$

The inductance of the spiral antenna can be calculated as Eq.(5).

$$L = \mu_0 N^2 r_{avg} \left[\ln\left(\frac{2.46}{p}\right) + 0.2p^2 \right] \tag{5}$$

Where μ_0 is the magnetic permeability, p is the fill ratio as $p = (r_{out} - r_{in}) / (r_{out} + r_{in})$, r_{avg} is the average radius as $(r_{out} + r_{in}) / 2$, and N is the turn number.

The Eq.(6) can be got basing on the circuit model.

$$\begin{bmatrix} U \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega M \\ j\omega M & Z_2 + R \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \tag{6}$$

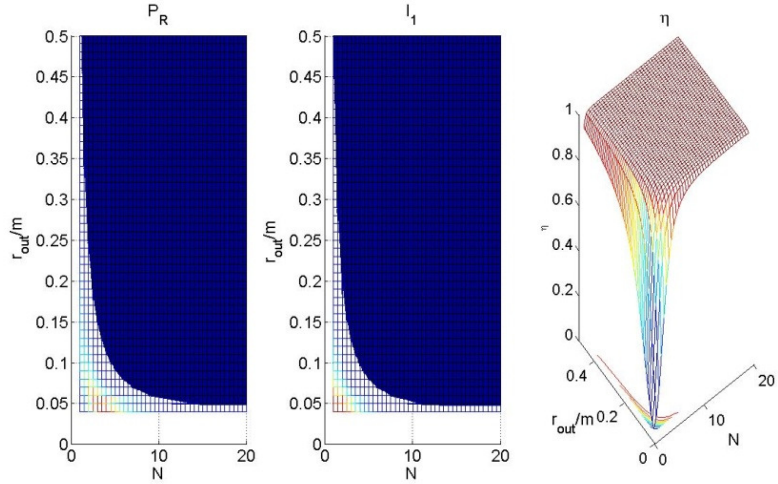
Where Z_1 is the loop impedance of transmitting coil as $Z = j\omega L_1 + 1/ j\omega C_1 + R_1$, Z_2 is the loop impedance of receiving coil as $Z = j\omega L_2 + 1/ j\omega C_2 + R_2$. R_1 and R_2 are the resistance of the transmitting and receiving coil, C_1 and C_2 are the resonant capacitor of the transmitting and receiving coil, L_1 and L_2 are the self-inductance of the transmitting and receiving coil, R is the load.

The emission current I_1, the power of the load and transmission efficiency can be calculated basing on the circuit model and the equations. The relationship between the transmission characteristics and coil parameters can be obtained. When the coil parameters have been selected, the relationship between transfer characteristic and h can be acquired. In this paper, the transmission characteristic with the change of the radius and turns of planar spiral coils can be presented.

However, in the actual design process, the coil parameters are unknown and should be in accordance with the actual needs of design, combining Eq. (5) this paper determines the coil parameters. For instance, the coil parameters can be calculated by setting fixed resonant frequency to 2MHz, transfer distance to 5cm and input voltage to 12V. the turns of planar spiral coils are set from 1 to 20 as well as the step to 0.5, the outer radius are set from 4cm to 50cm as well as the step to 1cm, the wire diameter is 2mm, and the load is set to 50Ω, then the transmission characteristic with the change of the radius and turns of planar spiral coils can be presented. Fig.3 shows the transfer characteristic with N and radius of coils.

Three-dimensional curve of transfer characteristic which contain load power, emission current and transmission efficiency can be achieved. In order to determine the coil parameters, sections are selected in 3-D curve of load power with 8watts and emission current with 1.5A, For fig.3 a), the power of the load is 8watts on the boundary, it is less than 8watts on the right side of the boundary, and it is greater than 8watts on the left side of the boundary. Similarly, fig.3 b) provides the influence of N and radius of coils to emission current. According the efficiency curve of fig.3 c), the coils parameters will be selected over 95% transmission efficiency. Finally, combining transfer characteristic the coil parameters can be selected quickly according to specific condition.

The coil parameters are determined according to fig.3. The size of the coil is 50mm radius and 2mm thick, the number of turns of the coil is 14.



a) b) c)

Figure 3. The transmission characteristic with radius and turns of coils.

Experiment Analyses

Through above system design and characteristic analysis, the coils and the circuitry are developed to made experiment. The transmitting and receiving coil are wound by litz wire, the size of the coils are 50 mm radius and the number of turns of the coils are 14. Set the parameters of the circuit as shown in Tab.1. The Class-E power amplifier and planar spiral coils are utilized to perform experiments at 2MHz.

Adjusting the main circuit parameters make the resonator and load match the emission source well, those reduce switch wastage and make MOSFET work in ideal state.

Table 1. The parameters of the circuit.

Parameter	value	Parameter	value	Parameter	value
L_1/μH	16	C_1/pF	416	R_1/Ω	0.5
L_2/μH	16	C_2/pF	416	R_2/Ω	0.5
r_{out}/m	0.05	N_1/N_2	14	R/Ω	50

The distance between the transmitting and receiving coils is 5cm, the circuit system reliability is improved in plate making and debugging, when choke coil L_3 is 18uH and the bypass capacitor C_0 is 611pF, the resonator and load match the emission source well, those reduce switch wastage and make MOSFET work in ideal state as fig.4. Channel 1 is driving signal, channel 2 is the voltage of MOSFET, channel 3 is the voltage of the transmitting coil L_1, channel 4 is the voltage of the load. The state of MOSFET is shown in channel 2, it provides zero-voltage turn on for the Class-E switch.

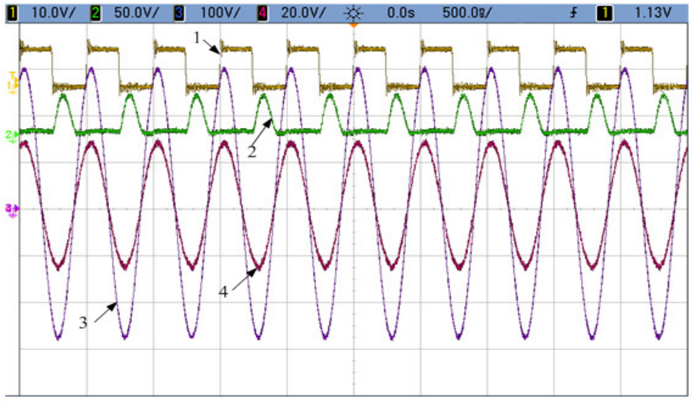
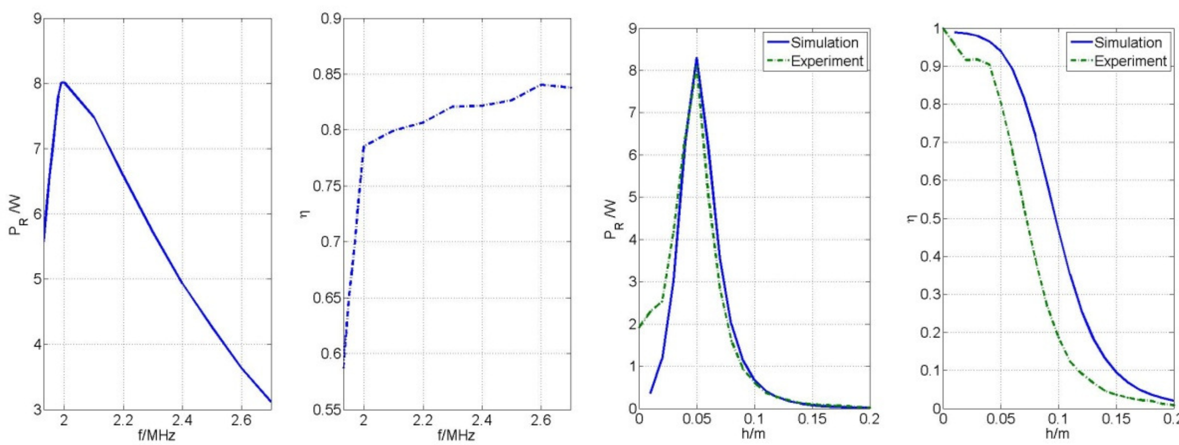


Figure 4. Waveform of the system.

The relationship between the driving frequency, transmission distance and transmission characteristic including the power of the load and transmission efficiency can be established when the coil parameters are determined, as shown in Fig.5 a) and Fig.5 b). The relationship between transmission distance and transmission characteristic can be obtained by the test, the step is 0.01m. Fig.5 c) shows the relationship between distance and load power, the results of experiment and simulation demonstrate that the theoretical analysis is an effective method.



a)Load power with frequency b) Efficiency with frequency c) Load power with distance d) Efficiency with distance

Figure 5. The experiment results.

The results of experiment and simulation demonstrate that the theoretical analysis is an effective method. When the coil spacing varied 5cm, the optimized efficiency of the system was about 80.32% when the output power was 8.1watts, the optimized efficiency of the system was even from 90.4% to 95.6% when coil spacing varied from 4cm to 1cm.

Conclusion

This paper introduces wireless energy transmission system for implantable device based on magnetic coupling resonance. It designed the wideband class-E power amplifier and provides a solution to maintain higher system efficiency in proper working condition. The paper used circuit theory and inductive characteristics to model and simulate the characteristic of the system, then the coil parameters can be selected accurately. The optimized system efficiency was about 80.32% when the coil spacing varied 5cm. The efficiency of the whole system was even from 90.4% to 95.6% when coil spacing varied from 4cm to 1cm. For the future, whole system efficiency will be improved future, and we will consider the miniaturization design of the coil for implantable devices.

Acknowledgement

Thanks the National Natural Science Foundation of China (51407175, 51207150).

References

[1] Sai Chun Tang. A Low-Operating-Voltage Wireless Intermediate-Range Scheme for Energy and Signal Transmission by Magnetic Coupling for Implantable Devices. Emerging and selected topics in power electronics. 2015, 3(1):242-251.

[2] Ho, J. S., Sanghoek Kim, Poon, A. S. Y. Midfield Wireless Powering for Implantable Systems. Proceedings of the IEEE. 2013, 101(6): 1369-1378.

[3] Qingyun Ma, Ray, L., Haider, M. R. A Miniaturized Spiral Antenna for Energy Harvesting of Implantable Medical Devices. Electrical and Computer Engineering, 2014 International Conference on. 2014, 180-183.

[4] Wang Guoxing, Liu Wentai, Sivaprakasam Mohanasankar, et al., Design and analysis of an adaptive transcutaneous power telemetry for biomedical implants, IEEE Transactions on Circuits and Systems I: Regular Papers, 2005, 52 (10): 2109-2117.

[5] Wang Guoxing, Liu Wentai, Bashirullah Rizwan, et al., A closed loop transcutaneous power transfer system for implantable devices with enhanced stability. Circuits and Systems, 2004. ISCAS '04. Proceedings of the 2004 International Symposium on. 2004, IV-17-IV-20.

[6] Watada, M., Saisho, R., Yong-Jae Kim. et al. The re-design at the transformer portion of transcutaneous energy transmission system for all implantable devices. Engineering in Medicine and Biology Society. 2007:1035-1038.

[7] Miura, Hidekazu; Arai, Shinsuke; Kakubari, Y. et al. Improvement of the transcutaneous energy transmission system utilizing ferrite cored coils for artificial hearts. IEEE Transaction on Magnetics. 2006, 42(10):3578-3580

[8] Wei Wang, Hemour, S., Ke Wu. Coupled Resonance Energy Transfer Over Gigahertz Frequency Range Using Ceramic Filled Cavity for Medical Implanted Sensors. Microwave Theory and Techniques, IEEE Transactions on. 2014, 62(4): 956-964.

[9] Sang Wook Park, Haelyong Kim, Junho Cho, EunHa Kim, SeoCheol Jung. Wireless Power Transmission Characteristics for Implantable Devices inside a Human Body. Electromagnetic Compatibility, 2014 International Symposium on. 2014, 1190-1194.

[10] Xing Li, Chi-Ying Tsui, Wing-Hung Ki. A 13.56 MHz Wireless Power Transfer System with Reconfigurable Resonant Regulating Rectifier and Wireless Power Control for Implantable Medical Devices. IEEE Journal of solid-state circuits. 2015, 50(4): 978-989.

[11] Kurs A, Karalis A, Moffatt R, et al. Wireless power transfer via strongly coupled magnetic resonances. Science, 2007, 317:83-86.

[12] Karalis A, Joannopoulos J D, et al. Efficient wireless non-radiative mid-range energy transfer. Annals of Physics, 2008, 32(3):34-48.