Bai Liangyu[1], Tang Houjun, Lan Jianyu

Key Laboratory of Control of Power Transmission and Transformation, Ministry of Education，Shanghai Jiao Tong University

Analysis and Design Considerations for the Transcutaneous Energy Transmission System

Abstract. *Transcutaneous energy transmission (TET) systems are designed to deliver power from an in vitro primary power source to in vivo implantable secondary over relatively large air gaps via magnetic coupling. This paper proposes an optimization method with given output power to meet different practical application. The transmission efficiency is the objective function; primary and secondary coils are design variables; constraints are based on bifurcation phenomenon and components peak over-voltage and peak withstand current. We have used experimental prototype to verify the analytical results.*

Streszczenie. *System transmisji energii przezskórny TET stosowany jest do bezprzewodowego zasilania implant za pośrednictwem pola magnetycznego. W artykule zaprezentowano metody optymalizacji systemu na przykładach praktycznych aplikacji. (**Analiza i projekt przezskórnej transmisji energii**)*

Keywords: transcutaneous energy transmission (TET) system; transmission efficiency; power transfer capability
Słowa kluczowe: przeskórny system transmisji TET, implanty

1. Introduction

The implantable biomedical devices, including left ventricular assist devices (LVAD), pacemakers and implantable cardioverter defibrillators (ICD), are used to monitor and treat physiological conditions within the body [1][2]. Although these devices often save lives, they can occasionally malfunction because of shortage of power. The traditional way of charging these devices is to penetrate skin with wires, which results in the risk of infection and in the cost of patient's freedom of daily living activities. Fig 1 shows the power demand of several implantable devices.

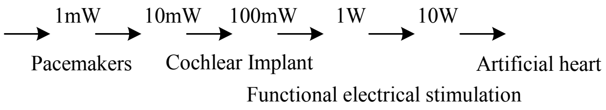


Fig.1. Power demand of several implantable devices

The transcutaneous energy transmission (TET) systems are designed to deliver power from a primary source to a secondary implantable device through a dermal skin layer via time-varying electromagnetic fields. A typical TET system is illustrated in Fig. 2. The electromagnetic field generated by the in vitro part of the TET system and produces an induced voltage in the in vivo part of the TET system, then used to charge the biomedical device.

Design optimization of the TET system has been studied extensively so far, different objectives have been considered, such as power transfer capability and transmission efficiency. First, several optimization methods have been proposed to increase the power transfer capacity. Wu H. H. has presented an optimal tuning capacitor values to maximize the power transfer capability. The maximum power transfer capacity can be three times greater than the traditional method. However, the efficiency is decreased to a relative low level [3]; Chwei-Sen Wang has used an inductor-capacitor-inductor load resonant inverter to achieve maximum power transfer [4].

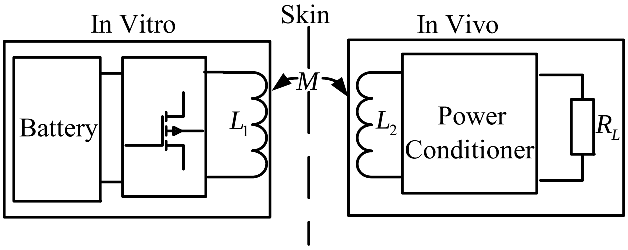


Fig. 2. The schematic of the TET system.

Second, Stanimir Valtchev has proposed a novel method for modeling and analysis of the series loaded series resonant power converters which are a better choice for loosely coupled transformer, and then optimizing it for the best possible efficiency [5].

Without a detail design optimization of the interactions between the primary and secondary parts of the system, it is usually quite difficult to achieve the satisfactory performance of the TET system. In order to achieve this goal, the mutual inductance coupling model and its equivalent parameters commonly used in TET system design have been introduced in Section 1. In Section 2, the optimization model of the TET system, based on the bifurcation phenomenon, components peak over-voltage and peak withstand current is analyzed in details. In Section 3, the constrained optimization via genetic algorithm is presented. Finally, conclusions are summarized in Section 4.

2. Electrical Model of the TET System

The TET system discussed here transfers power through two independent mutually coupled coils, which are being separated by human skin.

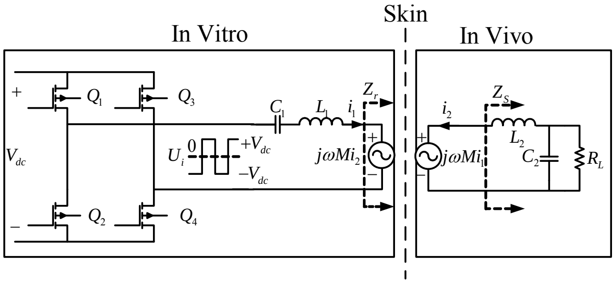


Fig. 3. Mutual inductance coupling model of the TET system.

From Fig. 3, $j\omega Mi_2$ is the reflected voltage in the external primary part due to the secondary current i_2, while the induced voltage in the implantable secondary part due to the primary current i_1 is equal to $j\omega Mi_1$. M is the mutual inductance between the primary and secondary and ω is the angular operational frequency. Z_r is the reflected impedance from the implantable secondary to the external primary. Z_s is the impedance of the implantable secondary. r_1 and r_2 are the primary and secondary coil resistances respectively. The subscripts 1 and 2 stand for the primary and secondary respectively. The resistance R_L represents the load on the implantable secondary. Similar optimization methods can be calculated for the other three basic topologies, such as Series-Series, Parallel-Parallel, and Parallel-Series. The topology analyses for these alternatives can be found in [4].

The TET system voltage U_i is supplied by an H-bridge inverter is shown in Fig. 3, which is a square wave.

The power transferred from the external primary to the implantable secondary P_2 is determined by:

$$P_2 = \frac{8\,\mathrm{Re}\,Z_r V_{dc}^2}{\pi^2 Z_{in}^2} \tag{1}$$

where Z_{in} is the amplitude of the load impedance seen by the power supply.

Poor transmission efficiency not only shortens the life span of the TET system, but also could cause a severe heating effect and health concerns, such as generation and dissipation of excessive heat which will lead to tissue damage. When a TET system is used to supply the correct amount of power matching the operation of the biomedical implantable devices, the transmission efficiency becomes a very important issue for the application. To reduce system weight and temperature rise, core losses should be eliminated. The most feasible way to minimize the core losses is to maximize efficiency.

TET system, using air-core coils, has been clinically applied for a totally biomedical implantable device. Due to the high operating frequency, the skin effect can become an important limitation for the application. Litz wires are commonly considered to have lower ac resistances than solid wires. Not only the skin effect but also proximity effect is drastically reduced. So in this study air core coils with litz wire are used for the primary and secondary coils.

The power efficiency of a TET system is the ratio between the power delivered to the medical device over the power taken from the in vitro battery supply. So the transmission efficiency can be derived as:

$$\eta = \frac{R_L I_o^2}{r_1 I_1^2 + r_2 I_2^2 + R_L I_o^2} \tag{2}$$

Theoretically, the system is operated at the secondary resonant frequency: $\omega_0 = 1/\sqrt{C_2 L_2}$ .Then, the system transmission efficiency can be simplified as:

$$\eta = \frac{R_L}{r_2 + R_L + \dfrac{r_1 r_2^2}{\omega_0^2 k^2 L_1 L_2} + \dfrac{r_1 L_2}{k^2 L_1} + \dfrac{r_2 R_L^2}{\omega_0^2 L_2^2}} \tag{3}$$

where $k = M/\sqrt{L_1 L_2}$ is the coupling coefficient.

The transmission efficiency η is a function of coil inductances, coupling coefficient and coil resistances as indicated above.

3. Optimization model of the TET system

Optimizations would be necessary if we want better performances. In this section, an optimization model will be built for the TET system, including the design variables, the objectives, and the constraints.

Design variables are those parameters that will change during the optimization process. L_1 and L_2 are design variables.

The power transfer capability and transmission efficiency are two objectives considered in this model. For clinical application, the biomedical implantable devices have power requirements in the range of 10-30W [6]. A more realistic application is optimal transmission efficiency with given rated power.

Constraints: (1) Constrained inequality based on bifurcation phenomenon. When optimizing the TET system, it is desirable to analyze the bifurcation region based on stability consideration [4]. In such a region, the operating frequency will either drift away from the ideal operating point or move in an unstable state. Therefore, we must ensure these proposed optimization parameters operate out of the bifurcation region.

In the series compensated primary and parallel compensated secondary topology, the bifurcation boundary is shown in [5]: $Q_1 > Q_2 + 1/Q_2$. where Q_1 , Q_2 are the primary and secondary quality factors.

The bifurcation region can be derived as:

$$L_2 < \frac{kR_L}{\omega_0\sqrt{1-k^2}} = k_a \tag{4}$$

The secondary inductance L_2 should be chosen out of the bifurcation region. It can be seen from this equation that the primary inductance L_1 is independent of the bifurcation boundary.

When the secondary inductance L_2 is higher than k_a , the system will be operated out of the bifurcation region. To show the influence of the secondary inductance on the bifurcation phenomenon, it can be seen in Fig. 4 that how phase angle of the load impedance varies when the secondary inductance increases. k_a (dotted line) is the bifurcation boundary. If L_2 is higher than k_a , it can be seen that the zero phase angle frequency is unique and equal to the secondary resonant frequency. If L_2 is lower than k_a , there are three zero phase angle frequency points and the bifurcation occurs.

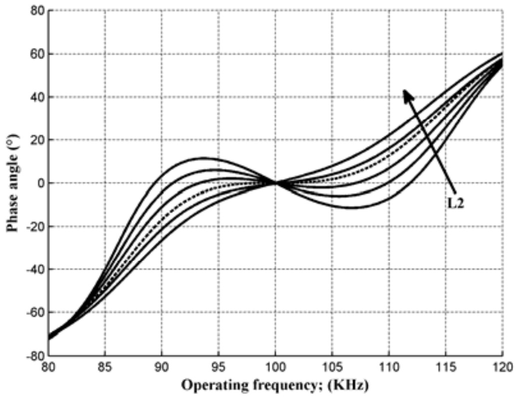


Fig. 4. Bifurcation phenomenon with varied secondary inductance

(2) Constrained inequality based on components peak over-voltage and peak withstand current

To achieve the required performance, each component must function properly through the operation period. The components of the system should be operated under the peak over-voltage and peak withstand current.

As shown in Fig. 3, $I_1(L_1, L_2)$, $V_1(L_1, L_2)$, $I_2(L_1, L_2)$ and $V_2(L_1, L_2)$ are the functions of the primary current, primary compensation capacitance voltage, secondary current and secondary compensation capacitance voltage, respectively. $I_{stress1}$, $I_{stress2}$, $V_{stress1}$ and $V_{stress2}$ denote peak withstand currents and the peak compensation capacitance over-voltages in the primary and secondary circuits respectively.

4. Integration and optimization

This section presents an optimization procedure to find the optimum of the primary and secondary inductance, and meet the different requirements of the biomedical implantable devices. To realize a more realistic design, some constrained functions introduced in the previous sections are applied to the optimization procedure. To obtain an optimal design considering transmission efficiency, $\eta(L_1, L_2)$ is proposed to the design factor.

The optimization problem based on this study can be described as follows:

$$\begin{aligned} &\textit{Minimize} && -\eta(L_1,L_2) \\ &\textit{Subject To} \quad g(x_1,x_2)= && \begin{cases} P_2 = P_{given} \\ I_1(L_1,L_2) < I_{stress1} \\ V_1(L_1,L_2) < V_{stress1} \\ I_2(L_1,L_2) < I_{stress2} \\ V_2(L_1,L_2) < V_{stress2} \\ k_a < L_2 \end{cases} \end{aligned} \tag{5}$$

where k_a is lower bound of L_2, as indicated above, P_{given} is the given value of the power transfer capability.

Fig. 5 shows the flowchart of the genetic algorithm. Genetic algorithm is a family of computational models inspired by evolution, and provides a random search technique to find a global optimal solution. In this section, the constrained optimization via genetic algorithm is introduced. The Roulette wheel method is used for selection and at each generation the elite individual is sent to the next population.

To explain the optimization problem as indicated above, we set P_{given} to 50W, the parameters as shown in Tab 1.

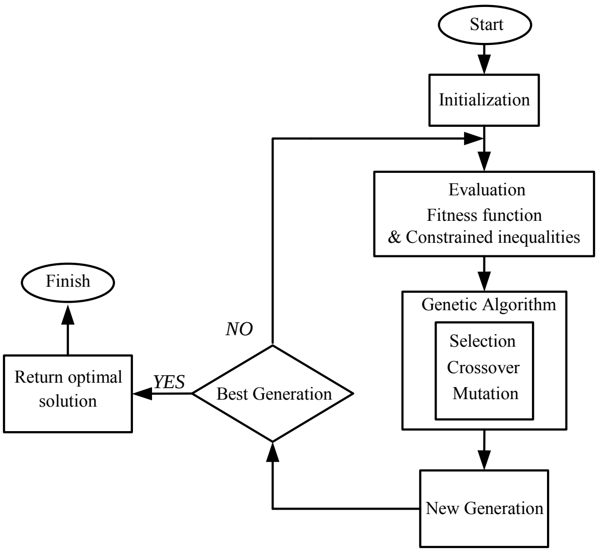
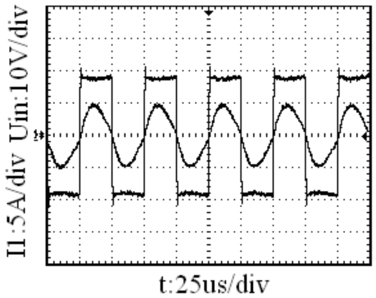


Fig. 5. Genetic algorithm flowchart

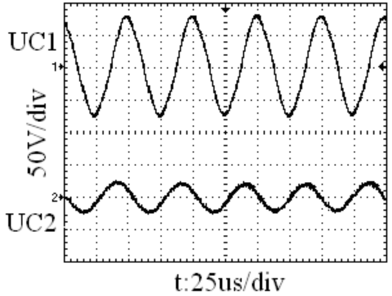
Table 1 The solutions of algorithm

L_1	180 μH	C_2	0.62 μF
L_2	102 μH	f	20kHz
M	64μH	R_L	10 Ω
C_1	0.45 μF	U_{dc}	20 V

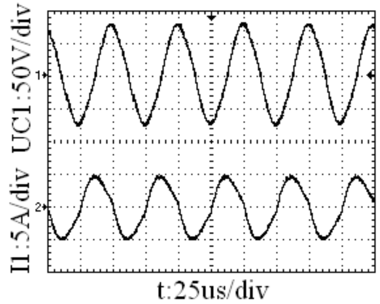
In order to verify the viability of the proposed design method, a prototype TET system was built and its parameter as shown in Table 1. Fig.6 shows the measured waveforms of TET system.



(1) Waveforms of Uin and I1



(2) Waveforms of UC1 and UC2



(3) Waveforms of UC1 and I1

Fig. 6. The waveforms of TET system

In Fig.6. primary resonant circuit current I_1 is 3.60A, primary compensation capactance voltage V_{C1} is 65.49V, output power is 51.2W. The good agreement between algorithm and experimental results confirms the validity of the optimization model.

Conclusion

This study proposed a coil inductance design method using the constrained optimization for optimal transmission efficiency under given output power. In practical applications, constrained conditions based on the components peak over-voltage, components peak withstand current and the bifurcation boundary are proposed. This simulation model is built with MATLAB/SIMULINK to validate the power transfer capability and transmission efficiency. The genetic algorithm is also introduced which has several advantages, such as simple computational steps, assured convergence to near optimal solutions, independence from choosing the initial values and reduced number of iterations, etc. This optimization method has succeeded in optimizing the transmission efficiency under given power transfer capability.

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Bai Liangyu was born in Shanxi province, China, in 1983. He received the B.S. degree in electrical engineering from Yanshan University, Qinhuangdao, China, in 2004, and M.S. degree in electrical engineering from Guangxi University, Nanning, in 2008. He is currently working toward his Ph.D. degree in electrical engineering at Shanghai Jiao Tong University.

His research interests include power electronics and wireless power transfer.

Tang Houjun was born in Shandong province, China, in 1957. He received B.S. and M.S. degrees in 1982 and 1988 respectively. He received Ph.D. degree in Yamagata University, Japan, 1997. He is Professor of the Department of Electrical Engineering, Shanghai Jiao Tong University.

His current research interests include automotive electronics, wireless power transfer.

Lan Jianyu was born in Fujian province, China, in 1980. He is currently working toward his Phd degree in electrical engineering at Shanghai Jiao Tong University.

His research interests include power electronics and wireless power transfer.