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Two-objective optimization design for the transcutaneous energy transmission system

Abstract*. The Transcutaneous energy transmission (TET) systems suffer two major drawbacks, due to the weak mutual coupling and large leakage inductance: low efficiency and low power transfer capability. This paper proposes an optimization method which considers both efficiency and power transfer capability to meet different practical application. We have used MATLAB/SIMULINK to verify the analytical results. A comparison of the results validates our optimization method, and shows enhanced performance.*

Streszczenie. *Bezprzewodowy system transmisji energii TET stosowany przy implantach jest obarczony niedogodnościami – słabym sprzężeniem obwodów, dużą indukcyjnością rozproszenia i małą efektywnością. W artykule zaproponowano optymalizację tego systemu. (**Optymalizacja systemu bezprzewodowej transmisji energii stosowanej przy implantach**)*

Keywords: transcutaneous energy transmission (TET) system, transmission efficiency, power transfer capability, nonlinear constrained optimization, genetic algorithm, biomedical implantable devices.
Słowa kluczowe: bezprzewodowa transmisja energii, 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]-[4]. 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. 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.1. 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.

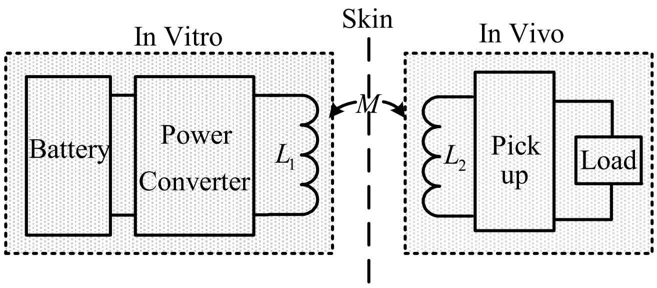


Fig.1. The schematic of the TET system

Proper performance of the TET system requires optimization of their component parameters. Due to a large winding separation, the TET system has relatively large leakage inductance and reduced magnetizing flux, and the mutual coupling is generally weak. Optimization of inductance of primary and secondary coils differs from that of tightly coupled transformers. Therefore, a specific optimization algorithm should be devised for them. Researches on the TET system have been presented based on different modeling techniques including mutual inductance coupling model [5] [6], generalized state space averaging (GSSA) model [7] [8] and T equivalent model [3] [9]. Mutual inductance coupling model has some advantages such as simplicity and suitability over other models for preliminary design of TET system. Therefore, in this paper a mutual inductance coupling model is used for the design optimization.

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 [10]. Second, the phase-locked loop has been introduced in [11] to obtaining high efficiency; the optimal number of secondary coil winding turns has been proposed in [9] for the highest efficiency under the nominal load and operating frequency; Stanimir Valtchev has proposed a novel method for modeling and analysis of the series loaded series resonant power converters which is a better choice for loosely coupled transformer, and then optimizing it for the best possible efficiency [12].

However, the heat from the power losses may have an adverse effect on the body and low efficiency which would result in more energy consumption. The system must be able to transfer enough power to the load during coupling variations between the in vivo and in vitro parts of the TET system. The optimization of the power transfer capability is indispensable to enable the TET system to meet short term high power demands [4] [9]. Unfortunately, improvement in power transfer capability might have an adverse effect on the power efficiency. Therefore, a compromise is needed between the two objectives.

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 2. In Section 3, 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 4, the constrained optimization via genetic algorithm is presented. Then validation of the algorithm based on the Simulink model of the system is analyzed, and discussion is shown in Section 5. Finally, conclusions are summarized in Section 6.

2. Electrical Model of the TET System

2.1 Mutual inductance coupling model

The TET system discussed here transfers power through two independent mutually coupled coils, which are being separated by human skin. The N-MOSFET (Negative-Channel Metal-Oxide- Semiconductor Field-Effect Transistor) H-bridge inverter is chosen as the power driving circuit. The equivalent mutual inductance coupling circuit model is shown in Fig.2. $j\omega Mi_2$ 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. r_1 and r_2 are the primary and secondary coil resistances respectively.

Due to a large winding separation, the TET system has relatively large leakage inductance and reduced magnetizing flux. Compensation for loose coupling can be achieved through the use of resonance circuits which enable the boosting of voltage or current in the secondary to usable levels. The primary coil is compensated in order to minimize the VA (Volt-Ampere) rating of the supply. Compensation is often needed for the secondary coil to increase the power transfer capability. For the purpose of this paper, series compensation is applied to the primary and parallel compensation to the secondary. 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 [5].

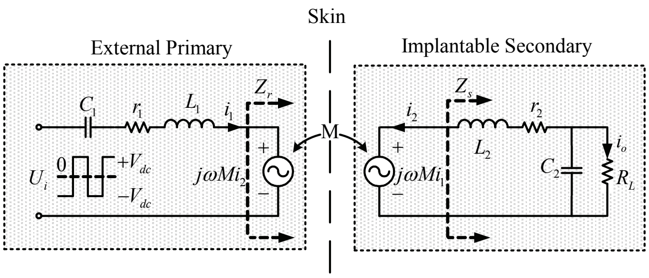


Fig. 2. Mutual inductance coupling model of the TET system

2.2 Power transfer capability

The TET system voltage U_i is supplied by an H-bridge inverter is shown in Fig.2, which is a square wave. The amplitude of the U_i can be considered as a constant. The U_i can be factorized as a Fourier series, and can be derived as:

(1) $$U_i = \frac{4U_{dc}}{\pi}(\sin\omega t + \frac{1}{3}\sin 3\omega t + \frac{1}{5}\sin 5\omega t + \cdots)$$

The RMS (Root-Mean-Square) value of the fundamental component of U_i is:

(2) $$U_1 = \frac{2\sqrt{2}V_{dc}}{\pi}$$

According to the mutual inductance coupling model, the reflected impedance Z_r from the implantable secondary to the external primary is dependent on the mutual inductance M and the angular operational frequency ω, and can be expressed as:

(3) $$Z_r = \frac{\omega^2 M^2}{Z_s}$$

where Z_s is the impedance of the implantable secondary, whose value depends on the secondary compensation circuit as shown in:

(4) $$Z_s = j\omega L_2 + r_2 + \frac{R_L}{1 + j\omega C_2 R_L}$$

The power transferred from the external primary to the implantable secondary can be defined as:

(5) $$P_2 = I_1^2 \times \mathrm{Re}\, Z_r = (\frac{U_1}{Z_{in}})^2 \times \mathrm{Re}\, Z_r$$

where Z_{in} is the amplitude of the load impedance seen by the power supply, as shown in:

(6) $$Z_{in} = \sqrt{(r_1 + \mathrm{Re}\, Z_r)^2 + (\omega L_1 - 1/(\omega C_1) + \mathrm{Im}\, Z_r)^2}$$

Substituting (2) into (5), the power transferred from the external primary to the implantable secondary P_2 is determined by:

(7) $$P_2 = \frac{8\,\mathrm{Re}\, Z_r V_{dc}^2}{\pi^2 Z_{in}^2}$$

2.3 Transmission Efficiency of the TET system

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 [18]. 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:

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

Theoretically, the system is operated at the secondary resonant frequency [5], which is determined by:

(9) $$\omega_0 = \frac{1}{\sqrt{C_2 L_2}}$$

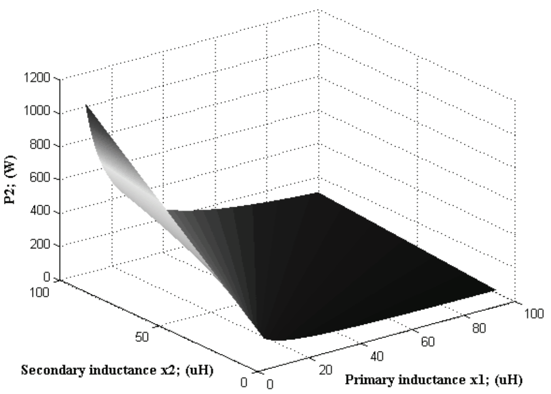
Then, the system transmission efficiency can be simplified as:

(10) $$\eta \cong \frac{R_L}{r_2 + R_L + \frac{r_1 r_2^2}{\omega_0^2 k^2 L_1 L_2} + \frac{r_1 L_2}{k^2 L_1} + \frac{r_2 R_L^2}{\omega_0^2 L_2^2}}$$

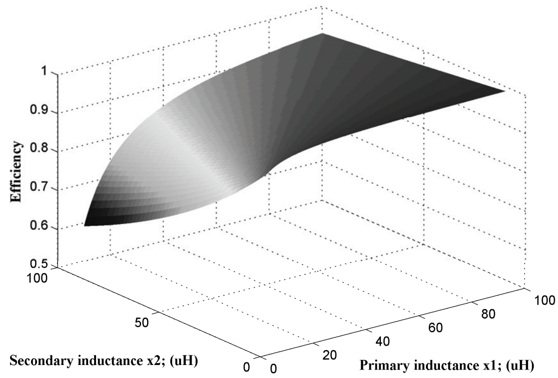
where $k = M/\sqrt{L_1 L_2}$ is the coupling coefficient.

The transmission efficiency η is a function of coil inductances, coupling coefficient and coil resistances as indicated above. When L_1 increases, the efficiency rises, if L_1 approaches infinity, the efficiency tends to 1. However, the coil resistance increased with the rises of the coil inductance. k_a is set to the upper bound of L_1.

The variations of the transfer power capability and the transmission efficiency in terms of the primary and secondary inductance are shown in Fig 3(a) and (b), respectively. It indicates an increase in the secondary inductance L_2 and a reduction in the primary inductance L_1 can lead to an increase in the power transfer capability and a decrease in transmission efficiency.



(a) Transfer power capability



(b) Efficiency

Fig. 3. Objective function variation with primary and secondary inductance

It is observed that the primary and secondary inductance have a different effects on the power transfer capability and the transmission efficiency. An increase in one of them may have an adverse effect on the other one. Thus an optimization method is required to meet all sorts of practical applications.

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.

A. Design variables

Design variables are those parameters that will change during the optimization process. L_1 and L_2 are design variables, and they are set to x_1 and x_2 respectively.

B. Objectives

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 [4] [14]. A more realistic application is optimal transmission efficiency with given rated power.

C. 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 [5]. 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]:

$$Q_1 > Q_2 + \frac{1}{Q_2} \tag{11}$$

where Q_1, Q_2 are the primary and secondary quality factors.

The bifurcation region can be derived as:

$$L_2 < \frac{kR_L}{\omega_0\sqrt{1-k^2}} = k_b \tag{12}$$

The secondary inductance L_2 should be chosen out of the bifurcation region, as shown in equation (12). 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_b, 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_b (dotted line) is the bifurcation boundary is shown in Fig. 4. If L_2 is higher than k_b, 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_b, there are three zero phase angle frequency points and the bifurcation occurs.

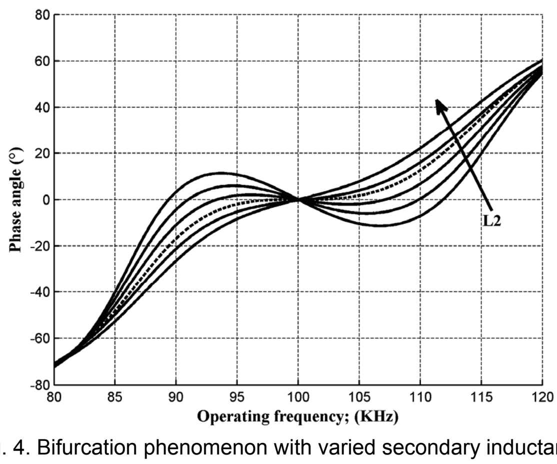


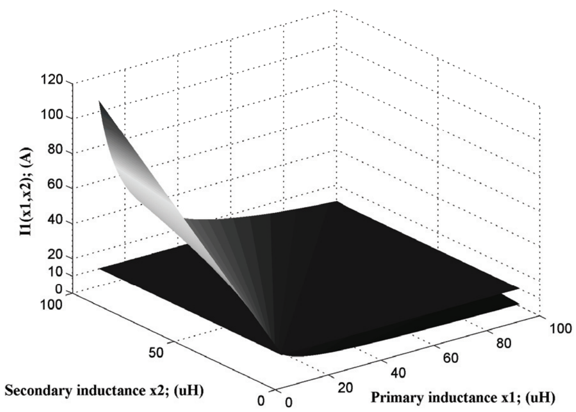
Fig. 4. Bifurcation phenomenon with varied secondary inductance

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

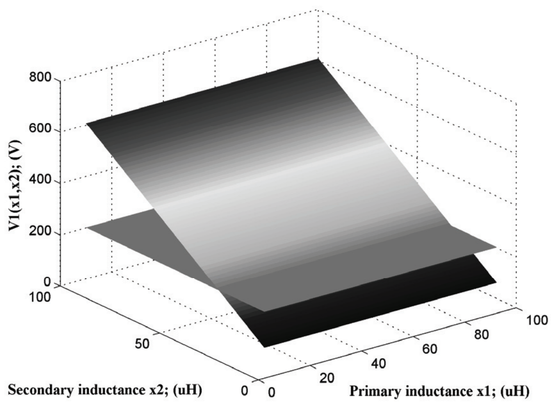
To achieve the required performance, each component must function properly through the operation period. The components of the system should be operated under the peak over-voltage and peak withstand current. Under these conditions, four nonlinear constrained inequalities can be obtained, as shown in:

$$\begin{cases} I_1(x_1,x_2) < I_{stress1} \\ V_1(x_1,x_2) < V_{stress1} \\ I_2(x_1,x_2) < I_{stress2} \\ V_2(x_1,x_2) < V_{stress2} \end{cases} \quad (13)$$

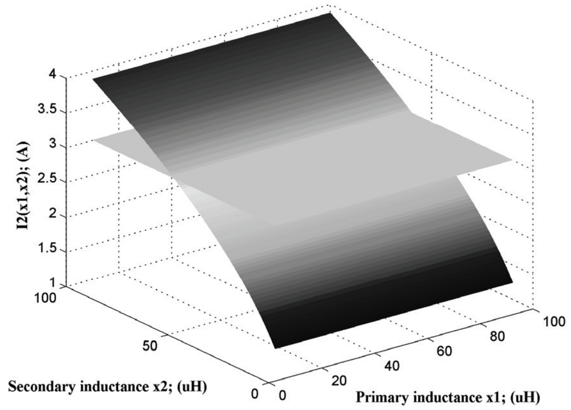
As shown in Fig. 2, $I_1(x_1,x_2)$, $V_1(x_1,x_2)$, $I_2(x_1,x_2)$ and $V_2(x_1,x_2)$ are the functions of the primary current, primary compensation capacitance voltage, secondary current and secondary compensation capacitance voltage, respectively. $I_{stress1}$, $I_{stress2}$, $V_{stress1}$ and $V_{stress2}$ denote peak withstand currents and the peak compensation capacitance over-voltages in the primary and secondary circuits respectively. In 0, the constrained conditions variation with primary and secondary inductance is shown. It is seen from 0, the fitness function should be chosen below the plane. $I_{stress1}$, $I_{stress2}$, $V_{stress1}$ and $V_{stress2}$ are set to be 10A, 200V, 3A and 100V respectively, which are based on the system behaviors.



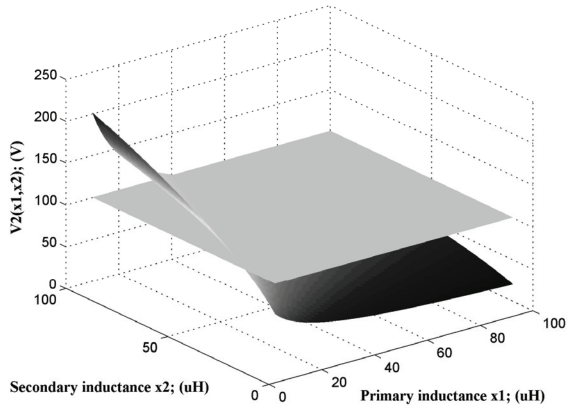
(a) $I_1(x_1,x_2)$ versus $I_{stress1}$



(b) $V_1(x_1,x_2)$ versus $V_{stress1}$



(c) $I_2(x_1,x_2)$ versus $I_{stress2}$



(d) $V_2(x_1,x_2)$ versus $V_{stress2}$

Fig. 5 Constrained conditions variation with primary and secondary inductance

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 power transfer capability and transmission efficiency, a new design factor $k_D(x_1,x_2)$ is proposed to achieve the different objectives. Such a design factor provides a higher degree of freedom in selecting appropriate design variables. $k_D(x_1,x_2)$ is defined as follows:

$$k_D(x_1,x_2) = \eta(x_1,x_2)^{k_1} P_2(x_1,x_2)^{k_2} \quad (14)$$

where $\eta(x_1,x_2)$ and $P_2(x_1,x_2)$ are the functions of the transmission efficiency and power transfer capability of the system, respectively; k_1 and k_2 are the power coefficients to meet the different clinical applications.

Genetic algorithm is a family of computational models inspired by evolution, and provides a random search technique to find a global optimal solution [17]. In this section, the constrained optimization via genetic algorithm is introduced. The optimization problem based on this study can be described as follows:

$$Minimize \quad -k_D(x_1,x_2)$$

$$(15) \qquad Subject\ To \quad g(x_1,x_2)=\begin{cases} I_1(x_1,x_2)<I_{stress1} \\ V_1(x_1,x_2)<V_{stress1} \\ I_2(x_1,x_2)<I_{stress2} \\ V_2(x_1,x_2)<V_{stress2} \\ 0<x_1<k_a \\ k_b<x_2 \end{cases}$$

where k_a is upper bound of x_1, k_b is lower bound of x_2, as indicated above.

Fig.6 shows the flowchart of the genetic algorithm. As seen in equation (14), the importance of the power transfer capability and the transmission efficiency are adjusted by k_1 and k_2 with regard to the desirable performance.

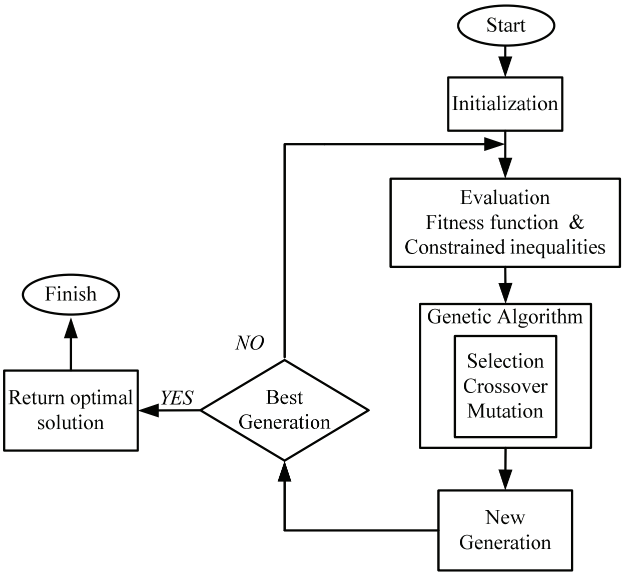


Fig. 6 Genetic algorithm flowchart

The Roulette wheel method [17] is used for selection and at each generation the elite individual is sent to the next population. The solutions of optimization are shown in Table 1. For clinical application, the biomedical implantable devices have power requirements in the range of 10-30W [4] [14]. A more realistic application is optimal transmission efficiency with given rated power. Hence, adding an equality constraint to equation (15), the optimization problem can be described as follows:

$$Minimize \quad -k_D(x_1,x_2)$$

$$(16) \qquad Subject\ To \quad \begin{cases} P_2=P_{given} \\ g(x_1,x_2) \end{cases}$$

where P_{given} is the given value of the power transfer capability.

To explain the optimization problem as indicated above, we set five values of P_{given} in the range of 10W-40W, as shown in Table 1, 10W, 20W, 30W, and 40W, respectively.

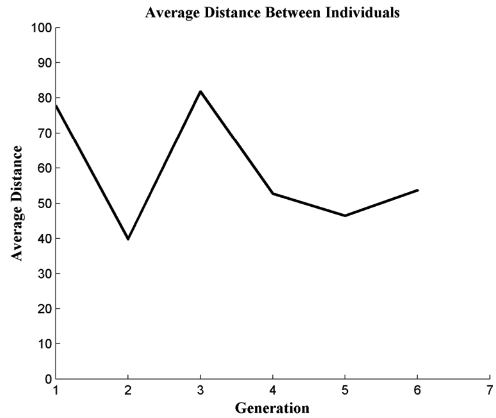
Table 1 The solutions of algorithm in different states

	1	2	3	4	5	6
Item	η_{max}	P_{max}	10W	20W	30W	40W
η **(%)**	89.22	81.2	88.2	86.66	85.02	83.11
P_2 (W)	3.67	49.90	10.09	19.97	29.50	40.11
$x_1(\mu H)$	199.9	56.57	83.52	67.17	60.61	54.86
$x_2(\mu H)$	10	46.53	11.67	18.95	26.27	33.88

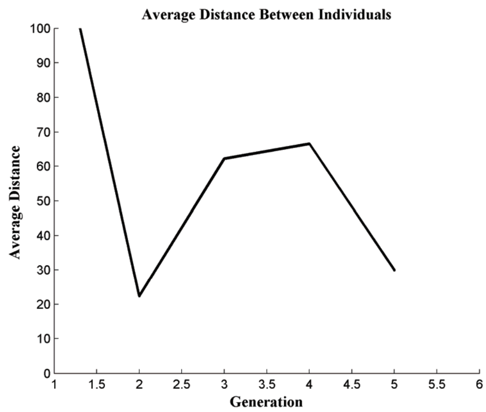
When $k_1=1$ and $k_2=0$, maximum transmission efficiency η_{max} is achieved, as shown in Table 1, Opt 1. It is seen that secondary inductance achieves the bifurcation boundary, and the system may be unstable. When $k_1=0$ and $k_2=1$, maximum power transfer capability P_{max} is obtained, as shown in Table 1, Opt 2.

Fig.7 (a) (b) and (c) show the average distance between individuals at each generation. It is seen that the diversity is better suited to the problem, so genetic algorithm return more desirable results than those of in the interior point algorithm. Fig.7 shows Opt 1, Opt 2 and Opt 3 respectively. The other values of P_{given} are similar.

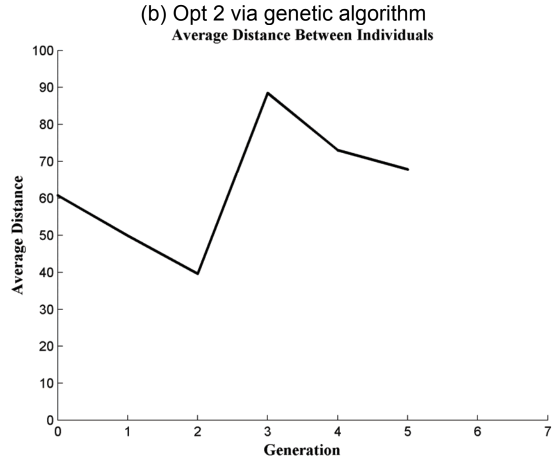
To verify the theoretical design a simulation model of the TET system, based on the Simulink toolbox, is built, tested and carried out to confirm the proposed optimization method. The optimal solutions of the system are also listed in Table 1.



(a) Opt 1 via genetic algorithm



(b) Opt 2 via genetic algorithm



(c) Opt 3 via genetic algorithm

Fig.7 Fitness function average distance from GA

5. Discussion

In the Opt 1, only the transmission efficiency is optimized which is achieved 89.22%, but the power transfer capability (3.67W) is much lower than Opt 2, can not reach the requirement of the system. In this state, the system tends to bifurcation boundary, and has poor stability.

In the Opt. 2, only the power transfer capability is optimized which is reached at 49.90W, while the transmission efficiency is decreased to 81.25%. The components reach the withstand values approximately.

It is highly desirable to deliver the required amount of power matching the load demand in order to maintain the operation of the implantable medical device. Any excessive power delivered will be dissipated as heat within the body; however, tissue is more susceptible to heat. Therefore, these two groups of optimization methods have no obvious practical application.

In the Opt 3-7 (Table 1), the given power transfer capability and the optimal efficiency are achieved via the constrained genetic algorithm. The solutions are also within the constrained inequalities.

Table 2 Optimal value of the system with different methods

Optimization method	Output power	efficiency
Traditional method[3]	45.8W	45.8%
New method	44.96W	82.20%

Table 2 shows the output power and the efficiency of the TET system, the traditional method is only optimal capacitance value; the new method is the algorithm which is proposed in this paper. Table 2 shows that more efficiency can be delivered via this new method under the same output power.

6. Conclusions

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. The combined fitness function comprises both the objective of power transfer capability and transmission efficiency. 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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