The influence of the antennas geometry on the stability of the inductive wireless power transfer systems

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Introduction

Implantable medical devices (IMD) are an important part of modern medicine. Such devices are used to replace, support or restore the functions of human organs, such as the organs of the cardiovascular system, the musculoskeletal system, the digestive system, the central nervous system, etc. [1]. Progress in the field of electronics, micro- and nanotechnology has significantly expanded the scope of IMD, allowed to reduce the size of devices and increase their stability and reliability of work [2].

The development of energy supply methods is one of the key directions for the improvement of IMD technologies. Strict requirements for reliability, safety, biocompatibility and size significantly complicate the development of the power supply systems. At the same time, the characteristics of a particular system are largely determined by the characteristics of the IMD for which it is intended [3]. In this regard, the borrowing of existing industry solutions is virtually impossible, and the choice of energy supply method is becoming one of the main stages of IMD development [4].

Nowadays, many suitable methods of power transfer for supplying IMD have been discovered. The use of wireless transmission systems helps to avoid unnecessary surgical procedures, the risk of infection through the transdermal wires and allows to reduce the size of the implanted device. High reliability and efficiency, the ability to integrate with other devices [5] and the continuing interest of the world scientific community for more than 10 years has led to the choice of inductive energy transfer systems.

The main value of the inductive energy transfer is mutual inductance *M*. Its calculation can be carried out according to the Neumann formula:

$$M = \frac{\mu_0}{4\pi}\oint\oint\frac{\overrightarrow{dl_t}\overrightarrow{dl_r}}{R_{tr}}; \qquad (1)$$

where dl_t and dl_r are the filament elements, R_{tr} is the distance between them, and μ_0 is the magnetic constant of the vacuum.

It follows from the Neumann formula that the mutual inductance is determined by the mutual arrangement of the antenna pair. It should be noted that the misalignments of the antennas relative to each other is a characteristic feature of the inductive energy transfer systems. Therefore, one of the main tasks in the development of power supply systems of IMD is to compensate for the misalignments of antennas. A rather promising way to compensate for displacements of flat round antennas is to optimize the geometry of the antenna pair [6].

The aim of this work is to investigate the influence of geometry of antennas with the same inductance on the stability of the main output value of inductive energy supply systems - output power.

Materials and Methods

Stand review

One of the main output characteristics of inductive wireless power systems is the power transferred to the load (output power P_L). This characteristic depends both on the operating frequency of the system and on the mutual arrangement of the antennas.

To ensure high values of output power, a pair of LC oscillation circuits tuned to one resonance frequency [7], which can be calculated by the following formula:

$$f_{res} = \frac{1}{2\pi\sqrt{L_T C_T}} = \frac{1}{2\pi\sqrt{L_R C_R}}; \qquad (2)$$

where L_R and L_T, are the inductances of the receiving and transmitting antennas, C_R and C_T are the capacities of the receiving and transmitting boards.

When a certain value of the coupling coefficient k_{crit}, called the critical coupling coefficient, is reached, the maximum output power of the system is ensured. The magnitude of the critical coupling coefficient k_{crit} can be determined using the following expression [8]:

$$k_{crit} = \frac{1}{\sqrt{Q_T Q_R}}; \qquad (3)$$

where Q_T and Q_R are the Q-factors of the receiving and transmitting circuits:

$$Q_T = \frac{1}{R_T}\sqrt{\frac{L_T}{C_T}}; \qquad (4)$$

$$Q_R = \frac{1}{R_L}\sqrt{\frac{L_R}{C_R}}; \qquad (5)$$

R_T, R_L - the resistance of the transmitting board and the load resistance of the receiving board, respectively.

Simulation of the system of inductive wireless energy transmission, working in the frequency of resonance and critical coupling of antennas for an axial distance between them equal to 5 mm was carried out. The equivalent circuit of the system is shown in fig. 1. The parameters of the modeled system are presented in tab. 1.

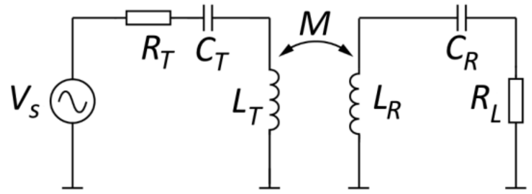

Figure 1: The scheme of the experimental stand

As can be seen in fig. 1, the system uses SS-compensation. Therefore, the output power can be calculated by the following expression:

$$P_L = \frac{\omega^2 M^2 {V_S}^2 R_L}{(Z_T Z_R + \omega^2 M^2)^2}; \quad (6)$$

where ω is the angular operating frequency of the system, Z_T and Z_R are the impedances of the transmitting and receiving boards:

$$Z_T = j\omega L_T + \frac{1}{j\omega C_T} + R_T; \quad (7)$$

$$Z_R = j\omega L_R + \frac{1}{j\omega C_R} + R_L. \quad (8)$$

Table 1: Stand parameters

Parameter	Value
V_S, V	5
R_T, Ohm	8.33
R_L, Ohm	20
L_T=L_R, µH	1.5
C_T=C_R, nF	4.5

Analysis of the effect of antenna geometry

To determine the effect of the antenna geometry, two sets of parameters as shown in fig. 2 were taken:

1) Antennas with 5 turns, outer diameter 50 mm, inner diameter 30 mm, and pitch between turns 2.5 mm;

2) Antennas with 4 turns, outer diameter 112 mm, inner diameter 40 mm, and pitch between turns 12 mm.

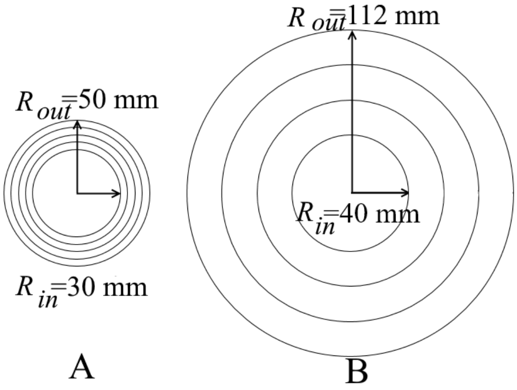

Figure 2: The first (A) and second (B) set of antenna geometric parameters

The antenna parameters were chosen so that the inductance values were close to the value given in tab. 1. The calculated resonant frequency of the system is 2 MHz. The critical coupling factor is 0.7. Therefore, the point of critical coupling of the antennas is located at a close distance between the antennas (≈ 3 mm of the axial distance).

Results

Fig. 3-6 show the results of numerical modeling of inductive wireless power transmission systems for two sets of antenna parameters. Fig. 3 and 4 show the dependence of the output power on the axial distance between the antennas and the operating frequency, fig. 5 and 6 show the dependence of the output power on the lateral misalignment and the operating frequency with axial distance 5 mm.

As can be seen from fig. 3 and 4, with a small distance between the antennas, the system can operate over a wide frequency range, providing sufficiently high output power.

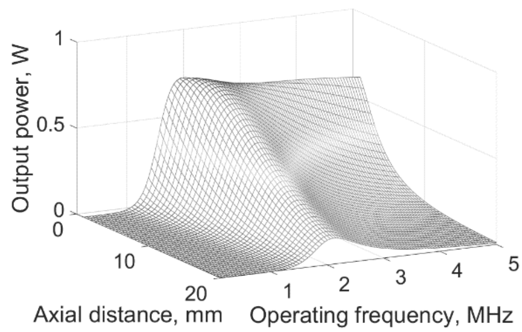

Figure 3: The dependence of the system output power on the axial distance between the antennas and the system operating frequency for antennas with 5 turns, outer diameter 50 mm, inner diameter 30 mm, and pitch between turns 2.5 mm

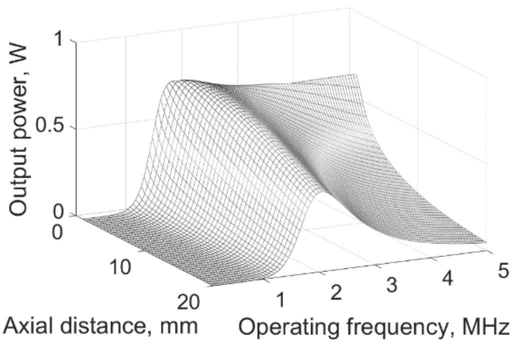

Figure 4: The dependence of the system output power on the axial distance between the antennas and the system operating frequency for antennas with 4 turns, outer diameter 112 mm, inner diameter 40 mm, and pitch between turns 12 mm

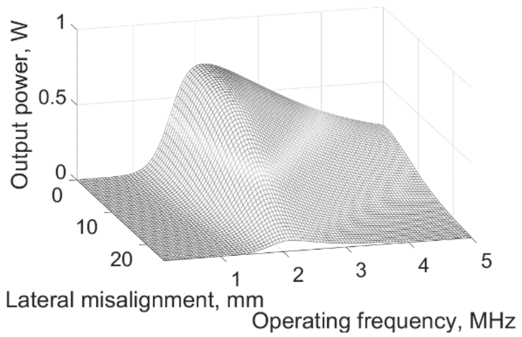

Figure 5: The dependence of the system output power on the lateral misalignment of the antennas with axial distance 5 mm and the system operating frequency for antennas with 5 turns, outer diameter 50 mm, inner diameter 30 mm, and pitch between turns 2.5 mm

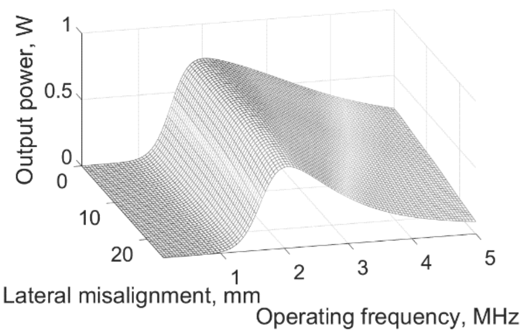

Figure 6: The dependence of the system output power on the lateral misalignment of the antennas with axial distance 5 mm and the system operating frequency for antennas with 4 turns, outer diameter 112 mm, inner diameter 40 mm, and pitch between turns 12 mm

However, already at an axial distance of more than 5 mm, the working frequency width is greatly reduced to a frequency range close to the resonant frequency. Therefore, to reduce the sensitivity of the system to misalignments, it is necessary to ensure operation at the resonant frequency.

Discussion

As can be seen from fig. 3 and 5, antennas with the first set of parameters are fairly sensitive to axial and lateral displacements. Even with a 15-millimeter displacement (axial and transverse), there is a noticeable drop in output power. At the same time, according to fig. 4 and 6 it can be seen that antennas with a second set of parameters give more stable output values to the misalignments.

Using antennas with a larger pitch and/or larger outer diameters allows to increase the stability of inductive wireless power transmission systems. Usually increasing the size of the device is undesirable for IMDs. Thus, first of all it can be said that implantable (receiving) antenna should be as big as possible from the medical point of view. Furthermore, external antenna should have the same or some bigger size.

It is also should be noted, that high-stable output is more important in the case of continuous powering of IMD, than in the case of recharging. Stable output is even more important in the case of life-critical IMD, such as ventricular assist devices. So, in this case medical restrictions for antennas size should be not so strong.

Conclusions

In order to investigate the influence of geometry of antennas on the stability of inductive energy supply systems we perform numerical modelling. We have compared two sets of antennas with relatively close inductance values and significantly different pitch (namely, 2.5 and 12 mm).

It was shown that antennas with greater pitch and diameter have much stable output characteristics. The output power in the range of the axial distance from 3 to 20 mm for antennas with the first set of parameters is reduced by 80% (from 0.74 W to 0.15 W). With lateral misalignments up to 25 mm and an axial distance of 5 mm, this characteristic decrease by a factor of 10 (from 0.71 W to 0.071 W). For antennas with a second set of parameters, the output power for axial misalignments decreases by 39% (from 0.74 W to 0.46 W), with lateral misalignments decreases by 15% (from 0.74 to 0.63).

Our results are mainly applicable in the case of continuous powering of IMD, especially life-critical IMD. Our future works will be focused on the incorporation of presented results in the optimization algorithm for design of inductive powering unit.

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