Calculation method for the class E power amplifier parameters for transcutaneous inductive energy transfer systems

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Introduction

Improvement in wireless power supply technology is a promising direction for the development of implantable medical devices (IMDs). The rejection of implantable chemical elements and percutaneous wires for powering the device can reduce the risk of postoperative complications, reduce the cost of treatment, and also can help to downsize the system [1]. A possible way to realize wireless powering is to use inductive energy transfer (IET) systems. Wireless powering technologies based on IET are widely used [2, 3]. Among the main advantages of IET over other methods of wireless powering (such as ultrasound or optic methods) is the weak absorption of electromagnetic radiation by biological tissues, which makes it possible to provide the required level of output power for a wide range of IMPs [4].
Powering of IMD imply the use of mobile chemical energy sources. In the case of IET systems it means that the DC power source signal is applied to the DC/AC converter, which has high power losses. After this, the alternating current is applied to the power amplifier and then to the transmitting coil.
The equivalent circuit diagram of the IET system where the influence of the receiving part of the system on the transmitting part is included as the equivalent impedance of the receiving part of the Z_{eq}, is shown in Figure 1.

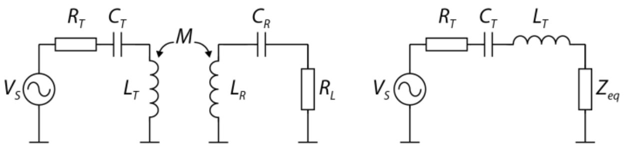

Figure 1: Equivalent circuit diagrams of the IET system

Because of high power losses on stages of converting signal and of transmitting power, it is necessary to use the most effective power amplifier (PA). Theoretically class E amplifier's efficiency equals 100% [6]. High efficiency is achieved by the absence of simultaneous non-zero current and voltage signals on the switch transistor *S*: when the voltage has a non-zero value, the current is zero and vice versa. However, the class E PA is extremely sensitive to changes in the parameters of the circuit [8]. At the same time, the mutual misalignment of the coil pair is a significant problem of the IET systems [5]. The source of the misalignments is the motor performance of the patient and also the postoperative edema of the tissues. Misalignments lead to changes in the mutual inductance of the coil pair, which reduces the efficiency of the class E PA. The purpose of this work is to develop an algorithm for calculating the parameters of the class E PA, which used in the IET system.

Materials and Methods

Circuit diagram of the class E PA is shown in Figure 2. When using an amplifier as part of the IET system, the L_T coil, which enters the load network, acts as a transmission coil. For compensating the reactive power of the transmitter coil a pair of C_{TS} and C_{TP} capacitors are used. The load is the reflected impedance of the receiving part of the IET system Z_{eq}.

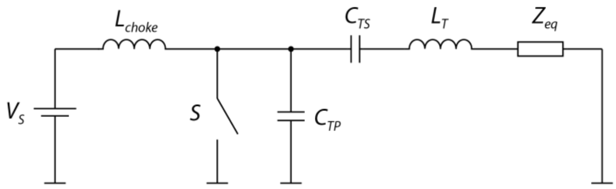

Figure 2: Class E power amplifier circuit diagram [7]

Methods for calculating the parameters of class E PA for a fixed resistive load are exist [7, 8, 9]. But in the IET system, a resonant circuit with a variable value of the equivalent impedance, depending on the mutual inductance of the coils. This impedance acts as a load of the PA, which changes when the mutual position of the coils changes.
In this paper, an algorithm for calculating and selecting the circuit parameters of the IET system with the class E PA, considering the misalignment of the coil pair, is proposed.

1. Defining design constraints

Since the class E PA is calculated for a IMD having certain load characteristics that are expressed through R_L, it must be tuned to a fixed value of the mutual inductance, which in turn corresponds to a certain misalignment of the coil pair. The range of misalignment were chosen for the use of IET systems with the auxiliary circulation systems [10]. For this IMD the axial and lateral misalignments has a range from 5 to 25 mm. The operating point of the IET system was chosen for 15 mm of axial misalignment and 0 mm of lateral misalignment. A number of features must be taken into account during designing of the IET system. The size of the implantation area for the receiving part of the system is limited by anatomic features. Accordingly, restrictions are imposed on the geometric parameters of the coils (usually on the outer diameter of the implanted coil).

2. Calculation of the internal Inductances

After the geometrical parameters of the coil pair are determined, it is necessary to calculate the internal inductance of the transmitting and receiving coils (L_T and L_R, respectively), as well as the mutual inductance of the coils M for a certain range of misalignments. For this the Neumann formula can be used [11].

3. Choosing frequency

For the operation of the IET system, frequencies in the range from 100 kHz to 10 MHz are considered optimal due to the electromagnetic properties of the human body tissues. Accordingly, the operating frequency of the system f is selected within this range.

4. Calculation of the receiver total impedance

Series reactive compensation for the receiving part of the IET was chosen. The impedance of the secondary circuit Z_R in this case is calculated using the following expression:

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

where C_R is the compensating capacitance, ω is the angular frequency of the system. The value of this capacitance is chosen such that the resonant angular frequency of the receiving contour ω_{res} coincides with the working angular frequency of the circuit ω. In this case, the reactive components of the receiving loop completely compensate each other, and the impedance of the receiving loop becomes equal to the load resistance R_L. The resonant angular frequency is determined by the following equation:

$$\omega_{res} = \frac{1}{\sqrt{L_R C_R}}. \quad (2)$$

5. Determination of the choke inductance

There are no equations calculating of the choke inductance L_{choke} in the literature devoted to the class E PA. The existing experience in designing shows that the inductance of the choke is selected 20-100 times more than the inductance of the transmitting coil. The choice of the choke inductance value depends on the required purity of the signal. If the insignificant presence of harmonics in the signal is permissible, then the inductance of the choke must be 20-50 times greater than the inductance of the transmitting coil. If a signal with maximal purity is required, the inductance of the choke must be 50-100 times greater than the inductance of the transmitting coil. Further increasing of the choke inductance, as a rule, does not improve the purity of the signal and can lead to loss of power of the main signal.

6. Calculation of the reflected impedance

The analytical expression for the reflected impedance of the receiving part can be obtained by analyzing the equivalent circuit diagram of the IET system using the Kirchhoff rules:

$$Z_{eq} = \frac{\omega^2 M^2}{Z_R}. \quad (3)$$

Taking into account the transformations for the impedance of the receiving circuit in the clause 1, the expression for the reflected impedance of the receiving part of the IET system takes the following form:

$$Z_{eq} = \frac{\omega^2 M^2}{R_L}. \quad (4)$$

7. Calculation of the class E PA capacitors, the choice of power supply and control signal

Substituting the obtained expression for the reflected impedance of the receiving part of the IET system into the formulas for Q and capacitances of the class E PA [6], the values of the series and parallel capacitances for a given mutual inductance can be obtained:

$$Q = \frac{L_2 R_L}{\omega M^2}, \quad (5)$$

$$C_1 = \frac{R_L}{\omega^3 M^2 \left(\frac{\pi^2}{4}+1\right)} \left(0{,}99866 + \frac{0{,}91424}{Q} - \frac{1{,}03175}{Q^2}\right) + \frac{0{,}6}{\omega^2 L_{choke}}, \quad (6)$$

$$C_2 = \frac{R_L}{\omega^3 M^2} \left(\frac{1}{Q - 0{,}104823}\right)\left(1{,}00121 + \frac{1{,}01468}{Q - 1{,}7879}\right) - \frac{0{,}2}{\omega^2 L_{choke}}. \quad (7)$$

The power supply voltage is selected based on the required output power, taking into account the power losses in the system. A transient signal is applied to the base (gate) of the transistor with a duty cycle of 0.4-0.5 of such amplitude that the transistor operates in a switch mode.

8. Adjustment of the transmission coil internal inductance

When calculating the capacitances values, a situation may arise where negative values of the capacitances are obtained. In this case, the quality factor Q turned out to be too low and it is necessary to take the transmitting coil with a lower inductance. This will lead to a decreasing of the mutual inductance value at the selected operating point of the IET system, and, consequently, to an increasing of the quality factor, which will allow to obtain positive values of the capacitances during calculations.

9. Assessment of system characteristics and adjustment of parameters

It should be noted that the characteristics of the output signal of the class E PA are influenced by the output parameters of the transistor. At the same time, the analytical expressions presented in the literature do not take into account their influence in explicit form. A possible way to account for them is to manually adjust the components using the method of N. Sokal [6]. As a control characteristic, the voltage U_{DS} (U_{CE}) is used.

Testing the calculation method for the class E PA

Calculating method for the class E PA parameters in the IET systems was tested using LTspice XVII electronic circuit simulator. Sets of transmitting and receiving coils (L_T and L_R, respectively) whose geometric parameters correspond to the values of internal inductance 3.4 μH, 4.21 μH, 7.29 μH were chosen. The load R_L is 20 Ohm, the inductance of the L_{choke} choke is 75 μH, the capacitance of the compensating capacitor C_R in the secondary circuit is 4.5 nF. The duty ratio of the control pulse signal is 0.5. Voltage V_S 10 V. The values of the operating frequencies *f*, the capacitors of the C_{TP} and C_{TS} for each system are shown in Table 1.

Table 1: Class E PA parameters for different coil pairs

3.4 μH	
C_{TP}, nF	2.85
C_{TS}, nF	15.15
f, kHz	1280
7.29 μH	
C_{TP}, nF	1.32
C_{TS}, nF	14.3
f, kHz	879
12.27 μH	
C_{TP}, nF	2.7
C_{TS}, nF	15.32
f, kHz	677

Results

As a result of the simulation, for each coil pair a sine signal on the output was obtained, the maximum efficiency value of each circuit is observed with the value of the mutual inductance corresponding to 15 mm of the axial misalignment and 0 mm of the lateral misalignment of the coils. The work of the of the class E PA changes due to changes in the mutual inductance value. It is worth noting that both increasing and decreasing mutual inductance leads to a drop in the efficiency of energy transfer in the IET system. Figures 3-8 show the dependencies of the IET system coupling factor, efficiency and the output power from axial and lateral misalignments.

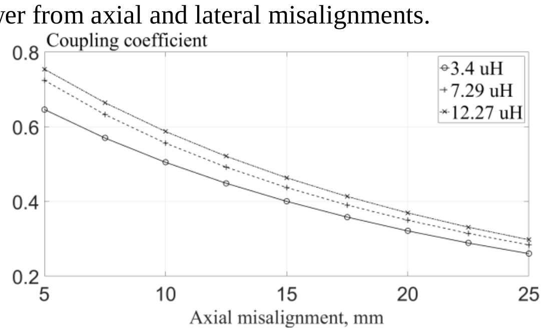

Figure 3: Dependence of the IET system coupling coefficient on the axial misalignment

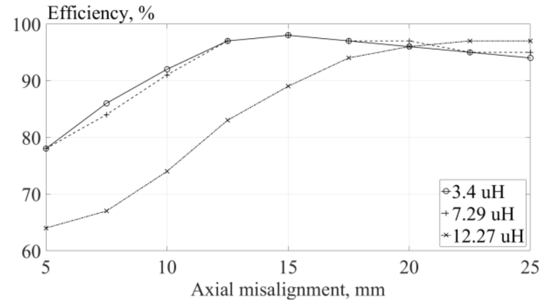

Figure 4: Dependence of the IET system efficiency on the axial misalignment

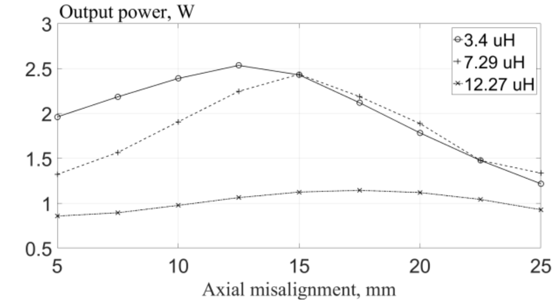

Figure 5: Dependence of the IET system output power on the axial misalignment

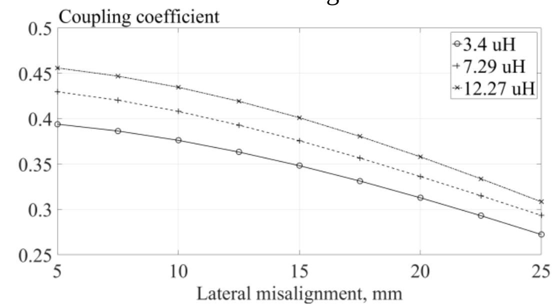

Figure 6: Dependence of the IET system coupling coefficient on the lateral misalignment

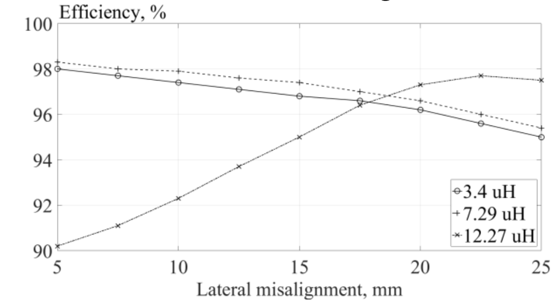

Figure 7: Dependence of the IET system efficiency on the lateral misalignment

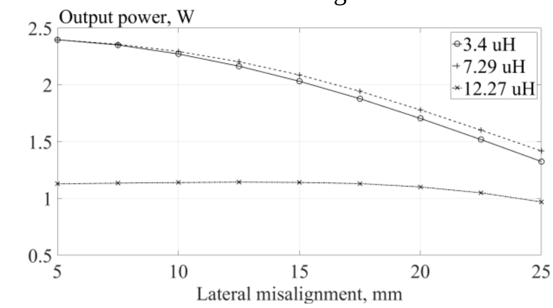

Figure 8: Dependence of the IET system output power on the lateral misalignment

Discussion

It was found that the dependencies of overall efficiency on axial misalignments (figure 4) can be divide into two areas: one with relatively high drop due to changes in the distance between coils (for axial misalignments lesser than 15 mm), and other, with relatively stable output. Based on this the misalignment values for the operating point should be chosen lesser than the middle point of the misalignment range. That will make system working in the flat area and increase its stability. Also the output power for the 12.27 μH coils is lower than for the 3.4 and 7.29 μH, but has less spread in values and acts more stable within all ranges of the axial misalignments (figure 5). A similar statement can be made for the dependencies of the efficiency and output power on the lateral misalignment (figures 7, 8). The operating point shifted for 3.4 and 12.27 μH both for axial misalignments, and for 12.27 μH operating point shifted for lateral misalignments due to fixed value of the load resistance R_L and adjusting only the amplifier's capacitances. With the fixed value of the load resistance R_L and inductance L_T, it is impossible to completely adjust the amplifier for some coil sets only changing capacitors. For large values of the lateral misalignment, where the reflected impedance Z_{eq} of the system with 12.27 μH coils approaches the value of the reflected impedance Z_{eq} of the systems with 7.29 and 3.4 μH coils, the dependences of efficiency and output power take the same form as the other coil sets.

That's why during calculating the IET system with class E PA the value of the optimal internal inductance must be chosen according the load resistance and desired operation mode of IMD. If IMD needs regular recharges it is relevant to use lower inductances due to its high output power values. For IMD which works permanently and needs continuous powering it is relevant to chose coils with higher inductances due to its stable total efficiency despite its low output power parameter (in comparison with coils with lower inductances for the same load resistance).

Conclusions

This article presents a method for calculating and further adjusting the IET system using a class E power amplifier. The method is based on an understanding of the specifics of the operation of the IET system, the mutual inductance calculation procedures developed by the research team, and the algorithm for calculating the parameters of the class E PA, known for the works of N. Sokal. The verification of the presented method for the geometric parameters of the coil pair characteristic of the auxiliary circulation system is demonstrated. The system's performance was verified by computer simulation in the LTspice environment. The maximum values of power on the load and overall efficiency are observed at the operating point of the IET system with the class E PA for the 7.29 μH coil pair, to which the amplifier was tuned (in the example shown corresponds to an axial misalignment of 15 mm) and shifted for the 3.4 and 12.27 μH coil pairs. IET system efficiency and output power decreases both during increasing and decreasing mutual inductance of the coil pair.

References

[1] P. Eldridge, B. Simpson, J. Gilbart. The Role of Rechargeable Systems in Neorumodulation. European Neurological Review, 6(3): 187-192, 2011.

[2] B.A. Achfar, B.K. Ammar, C. Hung. Power approaches for implantable medical devices. Sensors, 15: 28889 – 28914, 2015.

[3] N.K. Bocan, E. Sejdic. Adaptive transcutaneous power transfer to implantable devices: a state of art review. Sensors, 16, 2016.

[4] A.A. Danilov, G.P. Itkin, S.V. Selishchev. Progress in methods for transcutaneous wireless energy supply to implanted verticular assist devices. Bioedical Engineering, V. 44, Issue 4, 125-129, 2010

[5] K.V. Schuylenbergh and R. Puers. Inductive powering. Springer Science + Business Media, 2009.

[6] F. H. Raab. Effects of Circuit Variations on the Class E Tuned Power Amplifier. IEEE Journal of solid-state circuits, SC-13(2): 239 – 247, 1978.

[7] Sokal N.O. Class-E RF power amplifier. QEX, Jan/Feb: 9–20, 2001.

[8] M. A. A.-R. Firas. Design of input matching networks for class-E RF power amplifier. High frequency electronics, Jan: 40–48, 2011.

[9] K. Chen, D. Peroilis. Design of high efficient broadband class-E power amplifier using synthesized low-pass matching networks. IEEE Transactions on microwave theory and techniques, 59(12): 3162–3173, 2011.

[10] O. Knecht, R. Bosshard, J.W. Kolar. High Efficiency Transcutaneous Energy Transfer for Implantable Mechanical Heart Support Systems. IEEE Transactions on Power Electronics, 30(11): 6221–6236, 2015.

[11] A.A. Danilov, E.A. Mindubaev, S.V. Selishchev. Design and Evaluation of an Inductive Powering Unit for Implantable Medical Devices Using GPU Computing. Progress In Electromagnetics Research. 69: 61–73, 2016.

Acknowledgements

This study was supported by the Ministry of Education and Science of the Russian Federation (agreement № 14.579.21.0144, id RFMEFI57917X0144).