Development of experimental prototype’s module functional schemes for battery wireless recharging implants

A V Rabin, M A Merkova and V A Kilimnik

Saint-Petersburg State University of Aerospace Instrumentation - SUAI, 67, Bolshaya Morskaia St., Saint-Petersburg, 190000, Russia

E-mail: alexey.rabin@guap.ru, mmerkova@yandex.ru, kil-aanet@yandex.ru

Abstract. The paper describes the result of development of prototype’s module functional schemes for implantable device using wireless inductive energy transfer for charge of the built-in battery. The analysis of the physical prerequisites and technical characteristics of the developed device is made. The main functions of the device are considered. The functional schemes of the transmitting and receiving modules of the device are presented. An assessment of the performance and reliability of the device design is given. The possibilities and features of the device are described.

1. Analysis of the device performance operations

Problem solution of power supply for implantable devices has two main approaches - the use of either non-rechargeable power sources or batteries charged by wireless energy transfer. Non-rechargeable power supplies are effective in the case of low power consumption along with the ability to ensure an adequate lifetime of the implantable system (pacemakers, subcutaneous cardiac monitors for short-term use). In the case of more resource-intensive tasks of multichannel stimulation, telemetric collection of a set of parameters in order to achieve a sufficient period of operation, it is advisable to use wireless power transmission.

The transmitting and receiving modules of the device for wireless recharging of the implant batteries (Devices) cannot be considered as independent functional units during operation, we will consider them as a single system with interconnected circuits and multi-loop feedback.

The purpose of the Device is to form a charging cycle [1] for the battery while minimizing and limiting heat losses in the receiving module of the Device.

To monitor the implementation of this goal in the process of developing functional schemes, the module’s feedback software of wireless power transmission of the implanted device was developed to ensure thermal safety of its use [2]. The presented program is intended for processing, analysis and transmission to the device of externally generated information about the operation of wireless power transmission module of the implanted device in order to prevent excessive heating of the latter’s body. In particular, data on the temperature of the implanted Device body, charge current and battery voltage, input power of the generator are processed [2]. This program is a foundation for further engineering documentation development of the experimental prototype of the transmitting module for wireless recharging of implant batteries and wireless power supply of non-accumulator implants, as well as software for the transmitting and receiving modules of the experimental prototype of the Device.
The interaction of the transmitting and receiving module circuits is the basis of the Device operation [3, 4]. Let’s consider their analytical description. Since the systems of resonant circuits are characterized by harmonic signals with one common frequency $f$ for all considered blocks at a particular time, the method of complex amplitudes can be used for their analytical description. One of the possible approaches to describe the whole system is restricted by the method of equations system solving composed in accordance with G. Kirchhoff’s rules in a matrix form [5].

2. The description of the device operation

Before describing the transfer function $W(tj\omega)$ depicting the interaction of inductors we shall consider the analytical description of the load system of inductive circuits $Z_L$ illustrated by the scheme shown in figure 1.

![Figure 1](image)

**Figure 1.** The combined scheme considered for the analytical load description.

Let us express the dependence of the voltage and current at the output of the rectifier on the current in the transmitting circuit (TC) and analyze the results of the analytical description of the interaction of circuits.

The current’s amplitude in the inductor of receiving circuit (RC) $I_{2a}$ and induced electromotive force (EMF) on induction $E_{2a}$ are related by the expression

$$E_{2a} = I_{2a} (Z_{\Sigma} + j(\omega L_2 - 1/\omega C_{R2})),$$

where $Z_{\Sigma}=Z_L$ is the total load resistance of RC, $Z_{CR2}$ is the complex resistance of the resonant capacitor $C_{R2}$, $\omega$ is the frequency of the generator.

In turn, the amplitude values of $E_{2a}$ and TC current $I_{1a}$ can be linked through the value of the coupling coefficient $k$ of coils $L_1$ and $L_2$

$$E_{2a} = \omega k \sqrt{L_1 L_2} I_{1a},$$

(2)

From (1) and (2), getting the resonance condition applied $\omega L_2 = 1/\omega C_{R2}$, we obtain:

$$I_{2a} = I_{1a} \frac{\omega k \sqrt{L_1 L_2}}{Z_{\Sigma}},$$

(3)

The total load resistance of RC $Z_L$ is formed with the parallel included resistance of the charge control $R_{Chg}$ and Zener diode (voltage regulator diode) $R_Z$ (denote it as $R_{||}$), as well as the resistance of the RC inductor $R_{pl2}$, alternately working in each of the half-periods of the diode $R_{VD}$ and transistor $R_{DS}$ of rectifier

$$Z_{\Sigma} \approx R_{pl2} + R_{VD}(V_d) + R_{DS} + R_f(V_{in}, V_{bat}),$$

(4)
where $V_d$ is the diode voltage drop, $V_{in}$ is the rectifier’s output voltage, $V_{bat}$ is the battery voltage.

The resistance of the $R_{VD}$ diode was described by means of the Shockley’s equation, and the resistance of the $R_{DS}$ was assumed to be a constant.

To describe the current-voltage characteristic of Zener diode [6], a piecewise linear approximation of the characteristic points declared by the manufacturer was used.

$$I_Z(V_d) = \begin{cases} V_d \frac{I_r}{V_r}, & V_d \leq \frac{R_d I_z - V_z}{R_d I_r / V_r - 1}, \\ \frac{V_d - V_z}{R_d} + I_z, & V_d > \frac{R_d I_z - V_z}{R_d I_r / V_r - 1}, \end{cases}$$

where $V_r$ is the characteristic voltage before a breakdown at the current $I_z$, $V_z$ is the characteristic operating voltage at the current $I_z$, $R_r$ is the differential resistance at the point $[V_z; I_z]$.

The equivalent resistance of the battery charge module was also described by a piecewise linear approximation for the three ranges available from the power source: below the required level to provide the minimum charging current (pre-charge) of the $I_{ChgMIN}$, from the previous to the level of providing the set charging current (constant current) of the $I_{ChgSET}$, above the required (constant voltage) (here in after respectively mode 1, 2 and 3).

In case the battery is not discharged to a voltage less than 2.8 V, the pre-charge cycle (or trickle charge) is not applied (figure 2) [1].

![Figure 2. Diagram of main charge cycles (recharging) of Li-Ion battery.](image)

With regard to the current self-consumption $I_{sup}$ and resistance drain-source restrictive transistor $R_{ChgD}$ of the charge, the resistance $R_{Chg}$ is expressed as:

$$R_{Chg}(V_{in}, V_{bat}) = \begin{cases} \frac{V_{in}}{I_{sup}}, & V_{in} < R_{ChgDS}I_{ChgMN} + V_{bat}, \\ \frac{V_{in}}{R_{ChgDS} + I_{sup}}, & R_{ChgDS}I_{ChgMN} + V_{bat} \leq V_{in} \leq R_{ChgDS}I_{ChgSET} + V_{bat}, \\ \frac{V_{in}}{(I_{ChgSET} + I_{sup})}, & R_{ChgDS}I_{ChgSET} + V_{bat} < V_{in}. \end{cases}$$

(6)
The rectified current value is defined as the effective value of the current in the receiving circuit (RC), that is $I_{2a}/\sqrt{2}$. Taking into account the expressions (3)-(6), $V_{in}$ and $I_{VD}$ can be calculated by solving the system of equations:

$$Z^*I = A, \quad (7)$$
$$I = Z^{-1^*}A, \quad (8)$$

Where appropriate to take into account the internal resistance of the amplifier ($R_{e}$ is the equivalent resistance of the source of sinusoidal voltage and $R_{pl,l}$ is the active resistance of the inductor $L_l$), the current in the $TCI_{1a}$ can be expressed through the no-load current of TC through the theory of reflected impedance:

$$I_{1a} = I_{k0} \frac{R_e + R_{pl,l}}{R_e + R_{pl,l} + \omega^2 M_{12}^2 / \left( R_{pl,2} + R_{DS} + R_i(V_{in}, V_{pul}) + R_{VD}(V_d) \right)}, \quad (9)$$

where $M_{12} = k\sqrt{(L_1L_2)}$ $I_2 = k\sqrt{(L_1L_2)}$ is the mutual inductance between $L_1$ and $L_2$.

For a more detailed description of the transfer function $Wt(j\omega)$ with regard to the parasitic capacitances, it is possible to write a system of equations for the two inductors shown in figure 3. The mutual influence of currents flowing through the inductors $L_d$ and $L_l$ is expressed through the introduction of additional sources of EMF, which are the equivalent of the load for the TC and the voltage source for the RC.

In general, the solution is written as a matrix equation:

$$\begin{bmatrix}
V_{in} = I_{VD}(V_d) R_i(V_{in}, V_{pul}) \\
\omega M_{12} I_{1a} / \sqrt{2} = I_{VD}(V_d) \cdot (R_{pl,2} + R_{DS}) + V_{in} + V_d,
\end{bmatrix} \quad (10)$$

where $I$ is the vector column of currents, $Z$ is the matrix of impedances, $A$ is the vector column of right parts of the equations.

Matrix equation for a scheme with parallel resonance in the RC, placing the voltage equations in the first four lines of $Z$ and current equations in the last two, is shown on top of (11) and (12).
Accordingly, for the scheme with the successive resonance of TC (11), (12) bottom matrix equation. Similarly, you can write for three (one additional equation) and for four inductors (two additional equations).

The advantages of this method, provided that the mathematical calculation programs (MATLAB [7], Mathcad [8]) are used to solve the matrix equation, include the minimum number of equivalent transformations for writing the system of equations, the visibility of the circuit reflection in the impedance matrix, and the one-stage calculation of all currents in the circuit.

3. Functional schemes of the transmitting and receiving device modules

Functional schemes of the transmitting and receiving modules of the experimental prototype of the Device are presented in figures 4 and 5, respectively. Since the transmitting and receiving modules of the device cannot be considered as independent functional units during operation, a functional scheme (figure 6) of the device for charging (recharging) the implant battery and wireless power supply of non-accumulator implants, designed on the basis of the structural scheme, was developed. The perturbation action for the inductors $W(t(j\omega))$ system of the device is the change of their relative position in the process of battery charge, that is, the change of the parameter $k(t)$, the coupling coefficient of inductors.

The frequency and output power of the generator is set by a pulse width modulator (PWM), the change in the duty cycle of which according to the signal $P(t)$, allows to adjust the input power to the transmitting circuit (TC). The frequency of PWM operation, determined by the parameter $f$, must correspond to the resonant frequency of inductors to maximize the efficiency of the wireless power transmission. The output signal PWM $u(t)$ is supplied to the input of a class $E$ power amplifier, the output stage of which is loaded with the transmission circuit of the wireless power transmission device.

The signal $P(t)$ depends on the feedback signals received at the input of the control device (CD). Accordingly, $U_{out}(t)$ is the signal at the input of the charger, $I_{char}(t)$ is the charging current, $U_{bat}(t)$ is the battery voltage (BT). The signal $u(t)$ also depends on the temperature of the implanted device (ID) elements $T(t)$, which is registered by the sensing element (SE). Since the feedback is negative, it stabilizes the battery charging process and is able to limit the heating of the body of the implanted device (ID) [9].

![Figure 4. Transmitting module’s functional scheme of the experimental prototype of the Device.](image)

Matrix equations for RC scheme with parallel resonance (top), scheme with the successive resonance of TC (bottom):
The equations are given as follows:

\[
\begin{bmatrix}
I_E \\
I_{C_{pld}} \\
I_{td} \\
I_{E_{pld}} \\
I_{ZL}
\end{bmatrix} = \begin{bmatrix}
R_e + \frac{1}{j\omega C_d} & -\frac{1}{j\omega C_{pld}} & 0 & 0 & 0 & 0 \\
0 & 0 & j\omega L_d + R_{pld} & -j\omega M_{dl} & 0 & 0 \\
0 & 0 & -j\omega M_{dl} & j\omega L_d + R_{pld} & -\frac{1}{j\omega C_{pld}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{j\omega C_{pld}} Z_L + \frac{1}{j\omega C_c} \\
1 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & -1
\end{bmatrix}^{-1} \begin{bmatrix}
E \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}, \quad (11)
\]

And:

\[
\begin{bmatrix}
I_E \\
I_{C_{pld}} \\
I_{td} \\
I_{E_{pld}} \\
I_{ZL}
\end{bmatrix} = \begin{bmatrix}
R_e + \frac{1}{j\omega C_d} & -\frac{1}{j\omega C_{pld}} & 0 & 0 & 0 & 0 \\
0 & 0 & j\omega L_d + R_{pld} & -j\omega M_{dl} & 0 & 0 \\
0 & 0 & -j\omega M_{dl} & j\omega L_d + R_{pld} & -\frac{1}{j\omega C_{pld}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{j\omega C_{pld}} Z_L + \frac{1}{j\omega (C_{pld} + C_c)} \\
1 & 1 & -1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 1 & -1
\end{bmatrix}^{-1} \begin{bmatrix}
E \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}, \quad (12)
\]

Figure 5. Receiving module’s functional scheme of the experimental prototype of the Device.
The receiving module of the Device is made on a printed circuit board with built-in antenna, which allows to reduce the size of the module and improving manufacturability due to the absence of the need to implement the connection using wires or a connector. Depending on the ratings and parameters, passive surface-mounted components with a size of at least 0201 are used, which allows to increase the density of mounting components on a printed circuit board and meeting the requirements of the TOR.

Applied integrated circuits and other semiconductor components are also designed for surface mounting. The only component soldered through the through mounting platforms is a miniature pin connector, which must be installed on the transmitting module printed circuit board of biotelemetry and is intended for informational communication between them.

The telemetry transmitting module is also made on a single printed circuit board with an antenna. It uses passive surface-mounted components with a size of at least 0402. Integrated circuits and other semiconductor components are designed for surface mounting. Pulse voltage transducers and a power supply connector are mounted into mounting holes.

Both printed circuit boards require one-sided installation of components. The components are manually installed after the soldering paste application by the manual dispenser. Halogen-free, lead-free solder paste ULF-208-98 is used or mounting.

Solder is melted in a special oven with the temperature profile recommended by the soldering paste manufacturer. Mounted components comply with European Union Directive 2011/65/EU RoHS, which, according to environmental laws, limits the use of certain hazardous substances. Mounted components allow short-term heating up to 250°C during the reflow of the solder in the oven.

Printed circuit boards are manufactured in accuracy class 5, according to GOST 23752-79, on fiberglass FR4 RoHS. Since the printed circuit boards use QFN components with thermal pins under the case and others that have a small lead pitch, immersion gilding (ENIG - electroless nickel / immersion gold, ImAu) is used as the finishing coating for the pads.

Disposal of the product must be carried out in accordance with directive 2012/19/EC.

Products are intended for single production, which, according to GOST 14.004-83, characterized by a small volume of identical products production, the re-production and repair of which, as a rule, is not provided. There are no special requirements for the manufacturability of the product design.

4. Calculations confirming the performance and reliability of the device design

To confirm the operability of the experimental sample of the device, the theoretically achievable values of the output current of the receiving module model of the device were calculated, the results of which are shown in figure 7.
There are no specific requirements for reliability, dependability, durability, maintainability and maintainability of products due to the need for a single production of the product.

![Figure 7. Distribution of output current [A] depending on the lateral (X) and axial displacement [m] of the antenna of the receiving module relative to the antenna of the transmitting module.](image)

**5. Description of the organization of work using the developed device**

The prototypes under development are designed to confirm the correctness of the selected circuitry and algorithmic solutions, as well as to conduct tests aimed at establishing the conformity of TOR required parameters.

At the first stage, to perform these tasks, work with products should be carried out in a laboratory room at a research stand equipped with:

- antistatic laboratory furniture with work surfaces and storage areas for components;
- soldering equipment, magnifying devices, auxiliary tools and consumables for the installation and dismantling of components and auxiliary elements;
- a micromanipulator for setting the distance between the transmitting and receiving antennas of the module models;
- control measuring equipment of linear dimensions;
- a personal computer, programmer, immitance meter, current and voltage meters and an oscilloscope for setting up the hardware of the products, as well as for developing and debugging software for modules models, evaluating the output obtained parameters, including controlling the data transfer rate between the modules models.

The receiving module of the Device must be connected to the transmitting module of biotelemetry for further testing. The printed circuit board of the products is parallel arranged to each other and connected with a pin connector by soldering from the side of the receiving module of the Device and finally fixed relative to each other by means of a gasket glued between them. After completing the integration of products and carrying out the required preparation of the transmitting module of biotelemetry, the products should be hermetically encapsulated with biocompatible materials. Further, the products can be used in trials in a simulation environment of a biological object and on a laboratory animal in specialized research institutions in accordance with the methods in order to identify the degree of impact on a biological object and the suitability of the chosen technical solution for feeding implantable electronic devices for various purposes.

Storage of products is allowed at a humidity of no more than 80% and a temperature of no more than 40 °C. Engineering and scientific personnel with appropriate qualifications and work permit with electrical equipment and / or laboratory animals and medicines required during operations and care time for animals.
6. Conclusion
As a result of the mathematical analysis and modeling of the processes of the Device operation, the functional schemes of the transmitting and receiving modules of the Device have been developed, that allows the circuit implementation of the transmitting and receiving modules of the Device to be applied.

Functional schemes describe all the processes operating inside the Device. The selection of the element base of the Device is performed on the basis of the functional scheme. This takes place with regard to the technical and operational parameters specified in the technical specifications. To ensure the required operational characteristics of the Device, the output power of the transmitting module of the Device is regulated by negative backward signal from the receiving module to the transmitting one through the information transmission channel from the receiving module by load modulation of the transmitting module of the Device.

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