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A TRANSCUTANEOUS WIRELESS ENERGY TRANSMISSION BASED BATTERY RECHARGER FOR IMPLANTED PACEMAKER

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***Abstract* —** A transcutaneous wireless energy transmission system exploiting resonant inductive coupling to recharge the battery of a pacemaker is proposed. Pacemakers are electronic biomedical devices necessary for the treatment of specific cardiovascular diseases. Energy provision required by the pacemaker to operate is usually granted by means of long lasting batteries, that anyway require periodical checks and substitution. Wireless energy transfer to medical implants is therefore desirable, since it offers a non-invasive way to recharge batteries of implanted devices, viz. it could allow to delay surgery for substitution. The proposed system shows that transcutaneous energy transfer can be attained by coupling the electronics of the implanted hardware with an external energy source. In particular it supplies a primary coil, which is positioned at contact with the chest of the patient, with an alternate current to produce a magnetic flux; the latter enfolds a secondary coil, which is instead implanted in the human body in the proximity of the pacemaker, and allows to retrieve the energy to recharge the implanted battery. To limit the eddy currents that would be induced in the titanium case of the pacemaker and could produce undesired heating and/or malfunctioning, the proposed system utilizes a magnetic shield; the shield is also useful to avoid that the aforementioned parasitic coupling worsens the energy transfer efficiency.

Keywords — Implanted medical devices; pacemaker; battery recharging; resonant structure; magnetic coupling.

1. INTRODUCTION

The number of implanted medical devices such as pacemakers, artificial hearts, and nerve stimulators is rapidly increasing with the continuing advancements of biomedical technologies. Such devices are usually energized by means of long lasting batteries [1].

Batteries usage is a very debated topic. Many scientists maintain that batteries are unavoidable for biomedical devices and therefore support research efforts aimed at miniaturization and efficiency increments; their goals are small size long lasting batteries that make surgery the least invasive one. Many others believe that the use of battery-powered devices has to be more and more often discouraged, especially if the battery replacement appears troublesome or invasive, as it is for implanted medical devices whose replacement needs surgery. They favorably look at wireless energy transmission approaches that can allow remotely powering of biomedical devices and thus to avoid surgery for regular substitution of the battery of the implanted device, or else of the device as a whole.

For pacemakers high energy density and prolonged longevity embedded batteries are typically employed [5]-[7]. Depending on their operation mode and related frequency of stimulation, the batteries of pacemakers can last up to seven years. Nonetheless, in the course of the battery lifetime, patients undergo to regular check-ups, during which the battery life could be extended by means of intermediate recharge operations. In fact, if the pacemaker was preventively equipped with the necessary hardware to retrieve the energy spanned by an external source, the recharge could be attained without any surgery, but just by means of a few hours treatment during which an active coil is positioned upon the chest of the patient [8]-[18].

At present the use of radio frequency (RF) systems to radiate energy from an external source to the implanted battery [19]-[20] has been already proposed in the literature. Similarly transcutaneous energy transmission that exploit magnetic induction principles have been also considered [21]-[23]. Some contributions published in the scientific literature demonstrate throughout careful numerical analyses how the performance of an energy transmission system depends on the selected frequency and can be improved by shielding the pacemaker with a foil characterized by high magnetic permeability [24].

In this work an experimental approach is instead adopted to investigate the feasibility of a wireless energy transmission system to recharge the implanted battery. To this aim a prototype is built up and several experiments with different system configurations are carried out in order to both analyze its performance in quasi-real operating conditions and highlight how coils positions affect the energy transfer efficiency [25]-[27]. Also, the important role of the magnetic shield is examined throughout the experiments.

In the following, Section II illustrates the principle of operation of the proposed system by first giving a general outline and then describing in details the main parts of the system; Section III shows how to build up the prototype adopted to perform the experiments; Section IV reports the experimental results assessing the performance of the system; finally, Section V gives the conclusions.

2. PROPOSED SYSTEM

2.1. Outline

In an induction based wireless energy transmission system the primary circuit has to produce a time varying magnetic flux, which is typically attained by injecting an alternate current into one or more coils. The use of more coils is typically exploited to widen the range of coverage of the system at the expense of the complexity of the whole architecture.

Due to the complex structure, and above all the non-rigid configuration of the system, the circuit that drives the primary coils is designed in order to take advantage of resonance conditions, that allow the adaptation to a natural resonant frequency of the system for the alternate current rising into the coils.

Specifically, the magnetic flux produced by the primary circuit is partially concatenated by the coil of the secondary circuit, which is connected to a capacitor to form a resonant structure. A full bridge rectifier complemented with a low pass anti-ripple filter on the side of the secondary circuit adapts the parameters of the electrical power in order to supply the load, or, as it is in the case of the pacemaker, recharge the battery.

Actually, the proposed system uses a primary coil, in which an alternating current originates a magnetic field to excite a corresponding current in the implanted secondary coil [28], and maximizes the efficiency by pursuing resonant conditions that are arranged by introducing in the circuitry capacitors [29].

The primary system is directly connected to the external energy source and exhibits a body interface including one single coil to be applied to the outer surface of a cutaneous layer on the chest of the patient. It is locked to the chest of the patient using adhesive tape or other appropriate supporting material. The secondary coil is instead implanted in the body of the patient, in the vicinity of the pacemaker separated from it by a magnetic shield that prevents pacemaker heating and coupling interference. Nonetheless, the secondary coil has to be compliant with several important requirements related to size, weight, and above all biocompatibility [30]-[32]. The secondary coil of the proposed system has to grant a constant power demand of 2.5 W, that is sufficient to recharge the battery in a reasonable time.

2.2. Primary circuit

Fig. 1 shows a diagram of the primary circuit adopted to inject the alternate current into the LC structure to sustain the power transmission. The circuit is made up of two identical conducting branches, each one consisting of a MOSFET transistor, a diode (MUR860) and a 220 Ω resistor. Each MOSFET is complemented with a dedicated snubber circuit and a free-wheeling diode (by398) that assure protection during the switching transients. The central tapped inductor made up of 0.5 μH twin inductors, parallel connected to the capacitor, represent the front-end coil that is coupled to the secondary circuit of the system. The 20 μH inductance connected to the central tap of the coil limits inrush currents from the DC supply at MOSFET switching.

The primary circuit works as an inverter transforming the energy provided by the DC supply into AC energy. Specifically, the inverter oscillates at the resonant frequency that characterizes the LC structure: at steady state the MOSFET transistors work in push-pull mode by complementary switching on and off upon the polarity alternation of the sinusoidal voltage across the capacitor. The voltages and currents in the LC structure are characterized by a natural resonant frequency, that can be observed when the primary circuit is unloaded. In loaded conditions the resonant frequency changes because of the mutual coupling.

At design stage a resonant frequency equal to 88 kHz has been chosen for the system; consequently the inductances, capacitances, and distances between the coupled structures that affect the mutual coupling have been coherently selected.

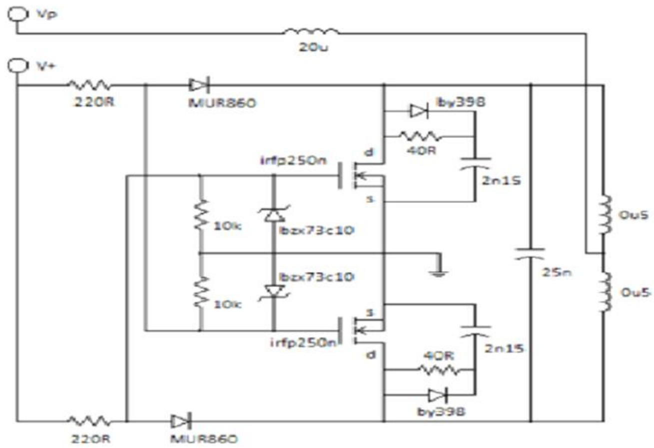

Fig. 1. Layout of the primary circuit including the resonant structure that sustains the magnetic flux to perform the energy transmission.

The major advantage in the use of this kind of oscillator consists in its inherent self-tuning capability, which assures a natural tracking of the maximum power transmission condition. An inverter driven to operate at a given frequency, without auxiliary systems implementing articulated feedback control logics, would exhibit poor efficiency due to unavoidable detuning effects related to parametric variations, mainly due to changes in the system configuration. In fact, the changes of the geometrical configurations imply modifications of the mutual inductances that would determine changes in the resonant frequency, making it deviate from the operating one.

2.3. Secondary circuit

The available power picked up by the secondary circuit needs to be transformed into DC power in order to be utilized to supply ordinary loads. The conversion involves both rectification and voltage level stabilization. To this purpose the proposed system uses at the secondary side a light solution made up of a rectifier and an anti-ripple capacitor as low pass filter. The rectifier is a full bridge circuit realized by means of 4 fast diodes FR302, whereas the low pass anti-ripple filter consists of a cheap electrolytic capacitor. Ripple effects are characterized by a frequency equal to 176 kHz and are easily cancelled by means of the capacitor. Specifically, at the resonant frequency f = 88 kHz, the capacitance of the anti-ripple capacitor is chosen according to:

$$C = 1.2 \frac{I_l}{f V_r} \quad (1)$$

in which, I_l is the load current, V_r is the amplitude of the residual voltage ripple and 1.2 represents a constant that includes a 20% margin.

Typically the use of identical LC structures at the primary and secondary sides, meaning that the two front-end coils have the same geometry, the same self-inductance, and are connected to identical capacitors, assures the best working conditions. Unfortunately for the considered application, the secondary circuit has to be implanted together with the pacemaker, thus its design has to satisfy additional constraints that is not convenient to retain for the primary circuit design.

3. PROTOTYPING

For the primary coil a circular geometry is chosen and optimized in order to obtain sufficient intensity for the magnetic induction at the center of the distant secondary coil. The primary coil is realized with a copper wire conductor characterized by cross-section equal to 1.5 mm^2, wrapped around a cylinder without overlaps for a number of turns equal to 10; the width of the coil along the longitudinal direction is equal to 15 mm (Fig. 2). The inductance measured by the Agilent 4263B LCR impedance meter, at 100 kHz is 7.28 µH.

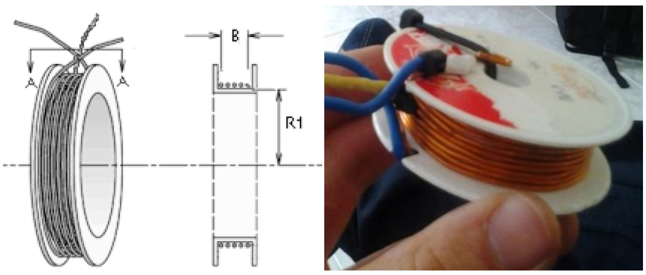

Fig. 2. Primary coil design and prototype.

The secondary coil is realized taking into account the constraints related to position and size. In fact the coil has to be placed in the same cavity of the body hosting the implanted device. In particular, the elliptical spiral type geometry shown in Fig. 3 is adopted. The coil is glued on a plastic support and it is characterized by the following average parameters: outer semi-major axis 22 mm, inner semi-major axis 14 mm, outer semi-minor axis 16 mm, inner semi-minor axis 8 mm, coil planar width = 8 mm. The elliptical geometry allows the deployment of a sufficient number of turns, maximizing the surface area enfolded by the induction field. Due to the different geometry and inductance of the secondary coil with respect to the primary coil, it is not possible to use capacitors characterized by equal values of capacitance. The capacitor connected to the secondary coil is chosen in order to let the two structures resonate at the same target frequency.

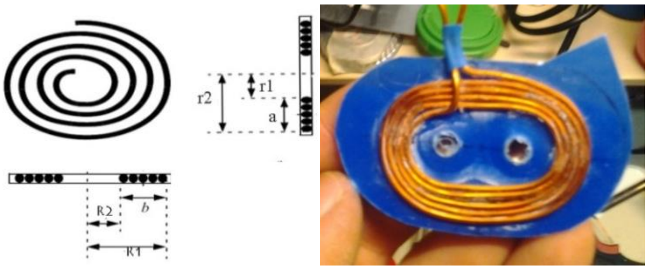

Fig. 3. Secondary coil design and prototype.

In the realization of the prototype it is also necessary to accurately measure the inductance exhibited by the secondary coil during the effective operating conditions. The measurement has to be carried out when the secondary coil is positioned on the outer top surface of the pacemaker and is separated from it by a ferromagnetic shielding layer. The shield is necessary to avoid that the magnetic flux induces eddy currents in the titanium frame of the pacemaker. The main effects of eddy currents in the titanium would consist of heating and supplemental undesired loading that would reduce the energy transmission. For the prototype a ferrite enclosure, made up of four 0.225 mm foils is employed to surround and shunt the magnetic flux sustained by the primary circuit. Table I shows the inductance of the coil of the secondary circuit measured in different operating conditions; in the presence of the ferrite shield no appreciable changes between the value measured with and without the presence of the titanium pacemaker are observed. The presence of the ferrite shield also prevents the temperature increments of the titanium case due to heating produced by eddy currents. Conversely, it can be appreciated how the absence of the magnetic shield involves a 45% diminution of the inductance.

Table I. Secondary coil inductance: the use of ferrite shields mitigate the presence of the titanium medium.

Test type	[µH]
In-air coupling	**1.09**
Secondary coil metal case and no ferrite layer	0.59
Secondary coil metal case and a single ferrite layer	0.75
Secondary coil metal case and 4 ferrite layers	**1.08**
Secondary coil and no metal case and a single ferrite layer	1.16

4. PERFORMANCE ASSESSMENT

In order to assess the performance of the proposed prototype an experimental set up including: a primary circuit with a push-pull inverter and a resonant LC structure (1), a secondary system with a resonant LC structure and a full bridge rectifier (2), a power resistor for emulating a load (3), a pacemaker (4), a DC laboratory power source (5), and further measurement equipment (6) has been arranged (Fig. 4).

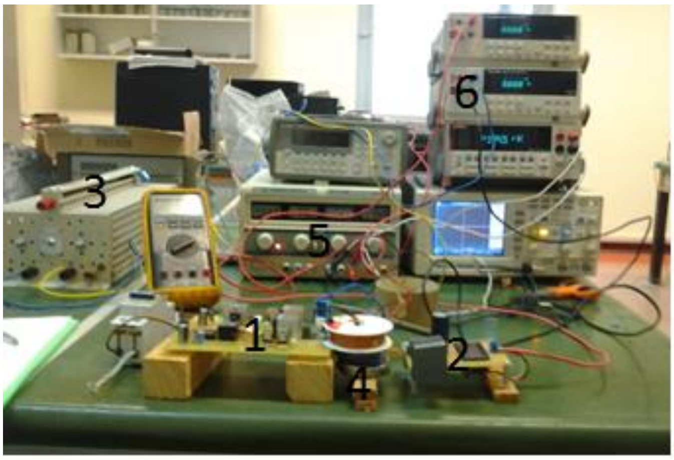

Fig. 4. Experimental setup including the main parts of the proposed system and the instruments adopted during the prototyping stage.

Although for the specific application the distance between primary and secondary coils is very short, the axial alignment between the two coils cannot be well verified and granted. In fact the implanted device, although fixed by stitches, can move a little around the implanted point. The physician cannot locate with sufficient accuracy without the help of radio imaging systems the exact position of the implanted secondary coil. To assure energy transfer the system has to grant acceptable performance even in the presence of axial misalignments, undesired tilt angles, and excessive distance.

Hereinafter, the results of a number of experimental tests highlight how the system behaves in the presence of the aforementioned system shortages. The tests are carried out by supplying the system at constant voltage equal to 15 V and progressively varying the parameters that identify the configuration under test. The transmission distance is equal to 17 mm, corresponding to the distance for a device that is correctly implanted. To emulate the 2 W power absorption of the battery during recharge, a 19 Ω resistive load has been connected at the output of the recharger circuit.

4.1. Axial misalignment

In these tests, keeping constant to 17 mm the distance between the primary and secondary coil, the primary coil is moved along the minor axis of the receiving elliptic coil, starting from a perfect alignment condition, and the power dissipated on the test resistor is measured Fig. 5.

Similarly, under the same test conditions mentioned above, the primary coil is moved along the major axis of the secondary elliptic coil and the power dissipated on the test resistor connected to the battery recharger is measured Fig. 6.

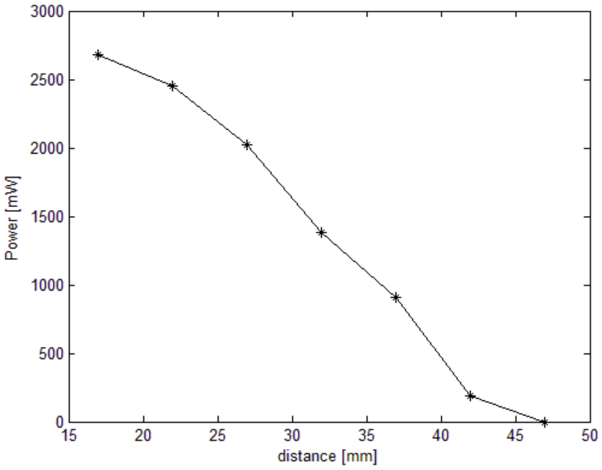

Fig. 5. Power absorbed by the resistive load connected to the recharger versus misalignment distance; the primary coil moves in the direction of the minor axis of the ellipse.

4.2. Tilt angle

The primary coil is also gradually rotated, keeping its center aligned with that of the secondary coil, up to a maximum tilt angle equal to 25 degrees. The results obtained in this test are shown in Fig. 7.

4.3. Excessive distance

In these tests the primary coil is progressively moved away from the secondary coil, which should be set at 30 mm from it, until the power transferred to the load is below 10% of the necessary power Fig. 8. During these tests, no tilt angle and perfect axial alignment are considered.

In all tests the overall efficiency at a distance equal to 17 mm is equal to 7%. Fig. 9 shows the trend of overall efficiency measured during the tests related to excessive distance between primary and secondary coils.

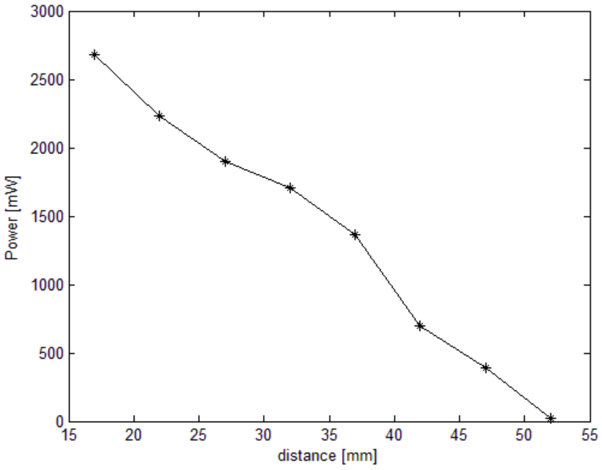

Fig. 6. Power absorbed by the resistive load connected to the recharger versus misalignment distance; the primary coil moves in the direction of the major axis of the ellipse.

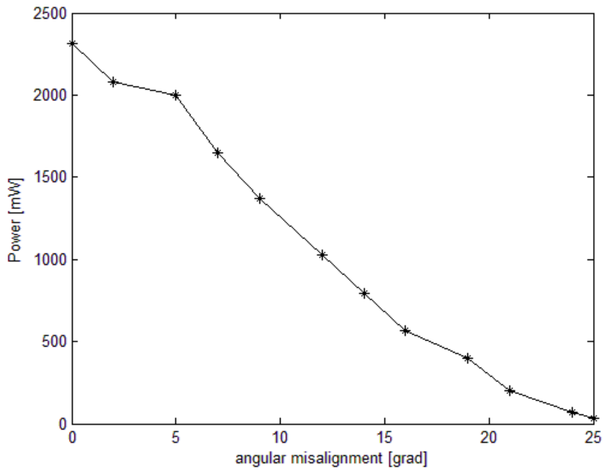

Fig. 7. Power absorbed by the resistive load connected to the recharger versus tilt angle up to a maximum of 25 degrees.

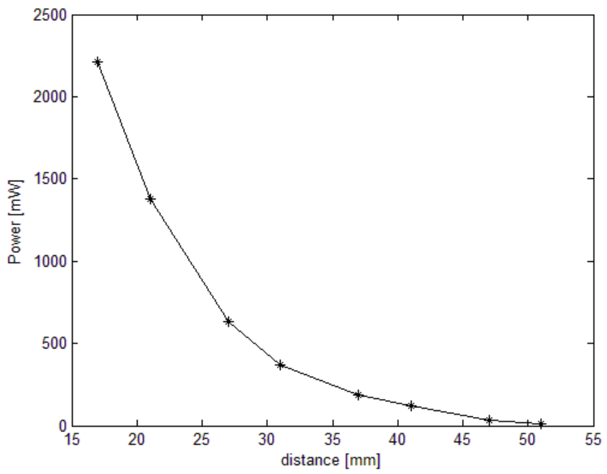

Fig. 8. Power absorbed by the secondary coil versus distance.

5. CONCLUSIONS

A transcutaneous wireless energy transmission system exploiting resonant inductive coupling to recharge the battery of a pacemaker has been proposed. Differently from several works published in the scientific literature, in which systems are theoretical analyzed and their performance assessed by means of simulations, here an experimental approach to verify the feasibility of the proposal and highlight its weaknesses has been presented. In particular, the basic principles of the proposed system have been first discussed, then a detailed description of the building up of a prototype system has been also given commenting on several choices done at the development stage. Finally the results of some experiments carried out on a real pacemaker equipped with the prototype have been shown in order to highlight its performance in the presence of some common shortages.

Forthcoming studies related to biological and electromagnetic compatibility issues, as well as investigations related to tissues heating due to the transcutaneous magnetic fields and/or to the functioning of the supplemental electronics are expected in the future.

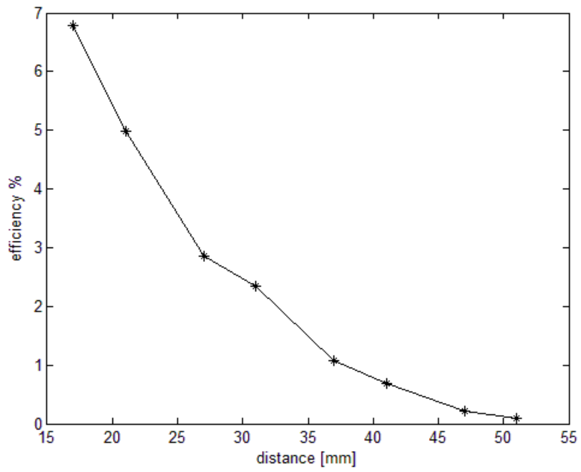

Fig. 9. Overall efficiency measured for increasing distance between primary and secondary coils.

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