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Calculation of the Magnetic Coupling between two Coils of Transcutaneous Energy System

Joel Flores[1], Jorge Becerra[2], Javier Herrera[3]

ICE, ESIME-ZAC/IPN, Mexico City, Mexico[1,2,3]

ABSTRACT: This paper describes the development and analysis of a magnetic coupling between two coils of a transcutaneous power system R.F., which consists of a Class E driver and a parallel LC circuit, to evaluate the magnitude of voltage induced by a transmitting coil to a receiving coil implanted in an animal model, with the purpose of consider it as energy stage of implantable electronic devices for recording bioelectric signals.

Keywords:Magnetic coupling, Transcutaneousenergysystem, Implantablecoil, DriverclassE.

I. INTRODUCTION

The most common way to power electronic devices implanted in living bodies is through the use of small batteries included in the receiver's capsule. They require to be recharged through an RF coupling between a pair of coils [1]. However, in most cases the life of these systems is limited to a few days or weeks in a continuous manner [2], [3]. During the powering of the system a stage of temperature control must be included in order to prevent damage to the batteries by overcharge, as well as a commutation stage to disconnect the system in case of inactivity [1]. These characteristics could be considered a form of criteria to disregard this form of energization, since it means bigger volume requirements for the electronic circuitry (increased system size); it has a limited lifespan; the recharging time can get increased after every recharge and risk of infection arises in case of surgical intervention in order to change the batteries [4].

In order to avoid such problems caused by the use of batteries, it is of the most importance to extendthe operation time [5]. In the case of substituting the batteries by a system of coupled coils, RF supply is used [6]. This method was first introduced by Schuder et al. [9], based on Maxwell´s law of electromagnetic induction [7], which presentsa way topenetratetheskinwithout damaging it, by irritationorinfection[6], [8], [9].

This proposed solution of powering a transcutaneous electronic system through a magnetic coupling between a pair of coils [10], [11], involves the use of a class E driver [9], [12], because of its simplicity and high efficiency in transferring energy [4], [13] to implanted electronic devices, thus reducing or eliminating the use of batteries [4], [7]. This paper is organized as follow: Section I gives the Introduction of the problems caused by the use of batteries. Section II is helpful to understand the background of the Transcutaneous Energy System. Section III shows the results and calculations of the Magnetic Coupling and the last section IV concludes the paper and followed by the references.

II. DESCRIPTION

The proposed transcutaneous magnetic link is formed by a class E driver and a power supply. The class E power amplifier consists in a multi frequency load network and one transistor operating as a switch at the carrier output signal frequency of the driver [14]. The load network is formed by a resonant circuit (C_4 and L_2) in series with a load resistor (R_5).

The driver yields and outputs signal with a frequency of 10 MHz from a crystal oscillator, it then goes through an inverter that gives to it a certain level of amplitude. Later, a power amplifier (Darlington pair) supplies the needed amount of current and, by means of the resonant circuit's coil; a sinusoidal signal is induced by RF. This signal is high enough in amplitude as to provide the energy required by the implanted circuitry to operate, but also lower in frequency to the limit established for implantable devices (50 MHz) [7]. A tank circuit (parallel LC) tuned in frequency with the driver (10 MHz) together with a filtering circuit, a rectifier (Schottky diodes bridge) and a regulator, produce a ± 5 V DC voltage, coming from the driver's sinusoidal signal [1], see Fig. 1.

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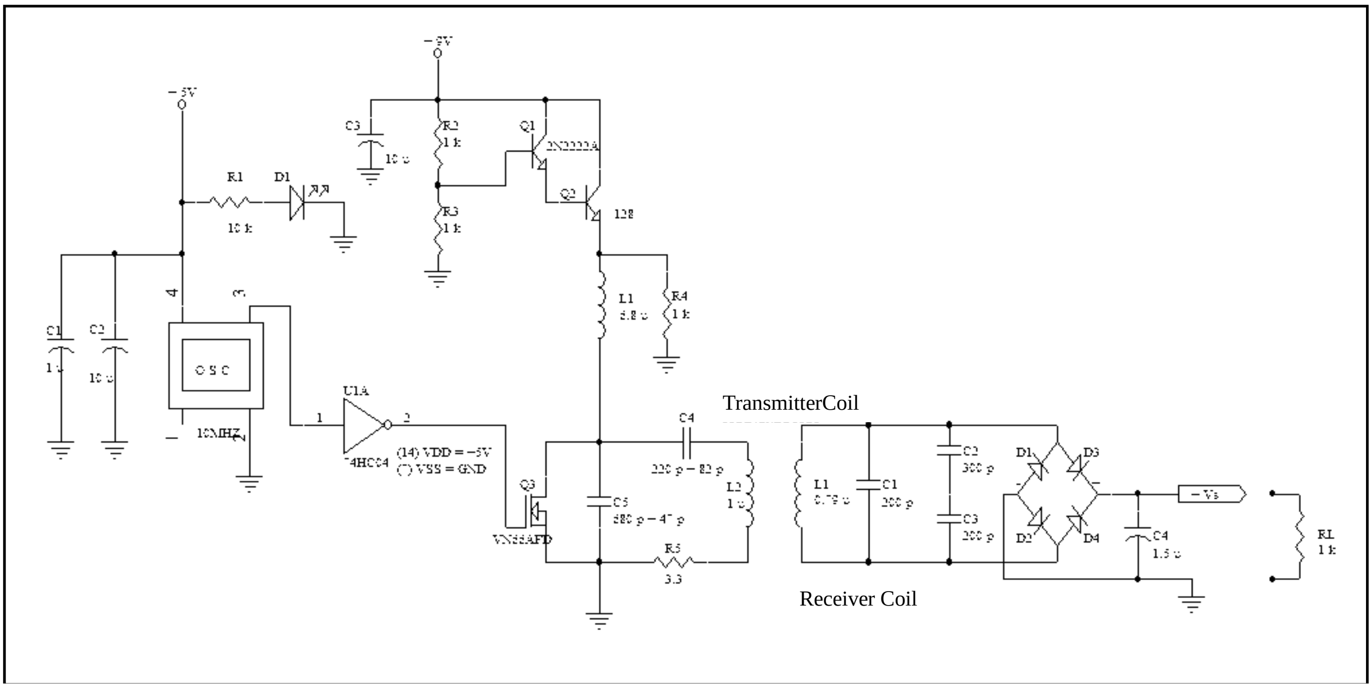

Fig.1.Circuitfor determiningtheenergytransmission

Many factors are to be considered for the design of a transcutaneous link for an implant, such as: size; shape; coils' cores, location and direction; tolerance to displacement between the coils; power requirements; efficiency (coupling factor); bandwidth; complexity and volume of the transmitter-receiver circuitry; the power source and the form of communication. Tolerance to displacement between transmitter and receptor, and the form of communication are the focus of design.

A circular and plane shape for both transmitter and receiver coils is proposed here. The receiver coil is smaller than the transmitter coil, due to the fact that the coupling factor *k* will remain constant as soon as the receiver coil is within the perimeter of the transmitter coil, thus yielding stable induced voltage. With this approach the coils may move relative to each other with acceptable tolerance in both lateral and rotational ways; outside these conditions changes in *k* will occur [12].

Frequently, the implantable device is designed first, and then the transcutaneous link is designed for the specific conditions the implanted device is under. A test frequency of around 10 MHz is selected for transmission-reception of power in order to generate power levels not exceeding the limit of 10 mW/cm^2 of tissue [1], proposed by the ANSI C95.1 (American National Standards Institute) standard [15].

III. RESULTS

Since the power is transmitted by RF through the coupling between two coils (one external and the other implanted) [4], [6], it is necessary to evaluate the amount of energy transmitted in order to confirm that the voltage level is high enough to supply the transcutaneous electronic system.

The characteristics of the coils are:

- External coil (driver):

L = 1 µH, ϕ_{coil} = 2.7 cm, ϕ_{wire} = 0.3 mm, N = 4 turns

- Internal coil (implantable):

Encapsulated 1: Epoxicresine
L = 0.75 µH, ϕ_{coil} = 10 mm, ϕ_{wire} = 0.3 mm

Encapsulated 2: Medical grade silicone
L = 0.77 µH, ϕ_{coil} = 10 mm, ϕ_{wire} = 0.3 mm

Theencapsulated coilsareimplanted intorabbits,inwhichTable1 shows thedataofthephysical features of therabbitforeachencapsulated.

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TABLE I.
Dataimplantin an animal model

ENCAPSULATED COILS	ENCAPSULATED 1	ENCAPSULATED 2
RABBITDATA		
Race	New Zealand	New Zealand
Sex	Male	Male
*Weight	2 Kg.	2 Kg.
*Age	3 months	3 months
IMPLANT DATA		
Date of Implant	4 – February – 97	6 – February – 97
DateSacrifice	27 – March – 97	25 – July – 97
ImplantPeriod	1 month, 23 days	5 months, 19 days
Histological Sample	NO	YES, (6)
Duration of Surgery	1:30 Hrs.	2:55 Hrs.

* The weight andagewere obtainedat the time ofimplant.

Testswereonlyfor the encapsulated2, due to removal of encapsulated 1 from the biological medium because of inadequate mechanical coupling in the area of implantation. The test consisted in, first, sedating the animal model to keep it still; next, the driver coil is put on the skin close to the point where the encapsulated 2 is already implanted. This is connected to the tuning, rectifying and filtering stages, through the percutaneous connector, which defines azone where maximum output voltage is obtained, see Fig. 2.

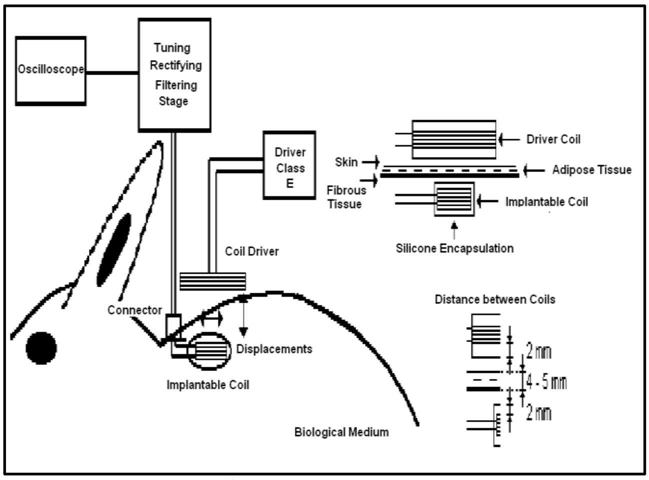

Fig. 2.Methodfor obtaining thevoltagebetweencoils

Finally, for recording the voltage magnitude for the condition of forwards and backwards displacements between both coils, two scales with 5 mm tickmarks were drawn on the model's skin, with its reference point at the position of maximum voltage. One scale extended in the direction of the central dorsal portion (L_1) and the other line in distal right lateral direction (L_2), as shown in Fig. 3.

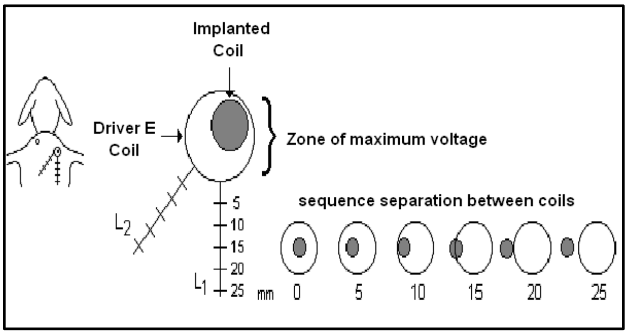

Fig. 3. Drawing of L_1 and L_2scales on the models´s skins

Following the directions mentioned above, the driver coil was displaced in 5 mm steps and the voltage magnitude recorded for each position, having a load resistance (R_L) of 1 kΩ.The measured rms values of the voltage are shown in Fig. 4.

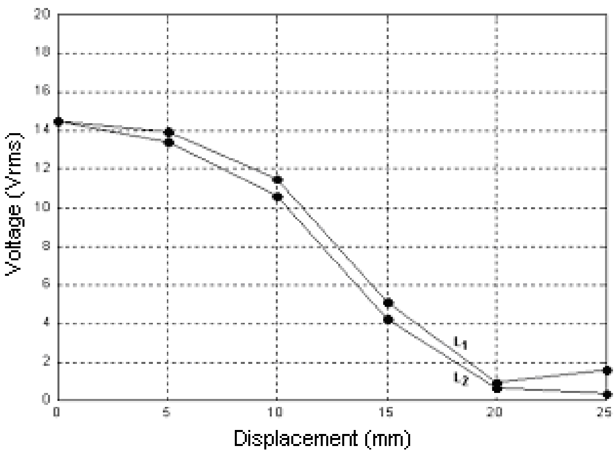

Fig. 4. RMS Voltage measurements for different coil positions (5mm steps)

As the magnetic coupling between the two coils, the coil driver(external) has a voltageof90Vppandthe receiving coil of the LC circuit (internal or implanted) has a voltageof57Vpp, determine the coupling factor; data important to consider the voltage to be supplied to the driver class E power loss occurs between the two coils, the following are calculations which determine the coupling factor.

Inductance coil driver:

$$L_{11} = \frac{1}{2\pi f}\sqrt{\frac{|V_1|^2}{|I_1|^2} - r_i^2} = \frac{1}{2\times 3.1416\times 10\times 10^6}\sqrt{\frac{(31.815)^2}{(0.5)^2} - 9.8^2} = 1.00\mu Hy$$

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Therefore:

$$|I_1| = \frac{|V_1|}{|Z_{L1}|} = \frac{31.815}{62.832} = 0.5A$$

where: $Z_{L1} = j\omega L = j2\pi\times10\times10^6\times1\times10^{-6} = j62.815\ \Omega$
$|Z_{L1}| = 62.815\ \Omega$

Inductance implantedcoil:

$$L_{22} = \frac{1}{2\pi f}\sqrt{\frac{|V_2|^2}{|I_2|^2} - r_i^2} = \frac{1}{2\times3.1416\times10\times10^6}\sqrt{\frac{(20.14)^2}{(0.4)^2} - 8.32^2} = 0.79\mu Hy$$

Therefore:

$$|I_2| = \frac{|V_2|}{|Z_{L2}|} = \frac{20.14}{49.63} = 0.4A$$

where: $Z_{L2} = j\omega L = j2\pi\times10\times10^6\times0.79\times10^{-6} = j49.63\ \Omega$
$|Z_{L2}| = 49.63\ \Omega$

Mutual inductance:

$$L_M = \frac{|V_2|}{2\pi f |I_1|} = \frac{20.14}{2\times3.1416\times10\times10^6(0.5)} = 0.64\mu Hy$$

Coupling factor:

$$K = \frac{L_M}{\sqrt{L_{11}L_{22}}} = \frac{0.64\times10^{-6}}{\sqrt{1\times10^{-6}\times0.79\times10^{-6}}} = 0.72$$

where: V_1=Voltage in the transmitter coil= 90 Vpp= 45Vp=31,815Vrms

V_2 =Voltage in the receiving coil = 57Vpp= 28.5 Vp=20.14Vrms

I_1 =Current in the coil of the transmitter tank circuit
I_2=Current in the coil of the receiver tank circuit

r_i=Internal resistance of the coil
Z_L=Impedance of the coil

Fig. 5 showsthesimulationofthe voltage ratiobetween the twocoils, according to thecalculatedcouplingfactor.

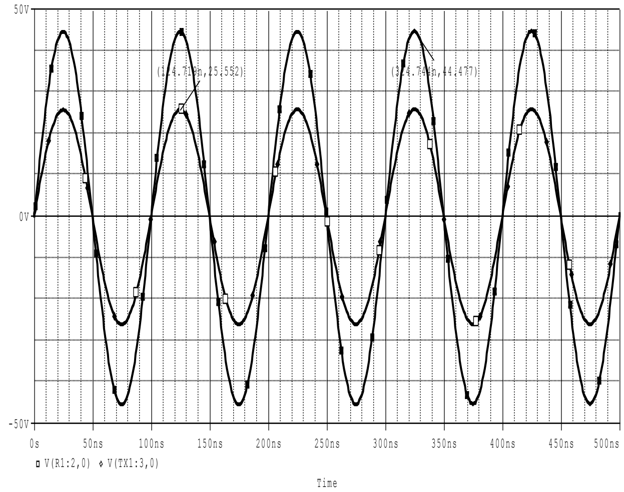

Fig. 5.Simulation ofmagneticcouplingbetweentwo coils

IV. CONCLUSION

Thelateraldisplacementsforward-backward, indicate thatat a distance less than 15 mm are maintained 5V regulated accordingly follows that the coil must be implanted within the circumference of the coil driver to ensure that the value save sufficient voltage magnitude to be regulated.

Another important aspect isthevoltagepresented by theattenuationoccurringin the couplingtransmission meansusing assilicone,the biological mediumandthe air.Accordingtotherelationshipbetweenthevoltageproduced by thedrivercoilandthe receiving coilofthe LC circuit,indicatingan attenuationof the order of63.3%, instead ofswitching a resistive load (R_L) of 1 kΩwas obtain a voltage in thecircuitLC49Vpp, so that the attenuation was around54.4%.

According to these results the feedback stage was satisfactory because it supplies enough power to drive an electric-operated implantable± 5Vrms, untila separation distanceof10 mm. As long as you connect a high impedance load.

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Biography

Joel Flores Martínez received his B.Sc. in electronics and communications engineering from ESIME Zacatenco IPN, Mexico, in 1997 and M.Sc. degree in Bioelectronics from CINVESTAV IPN, Mexico in 2000. Currently he is a Professor at the Department of Electronics and Communications engineering in ESIME Zacatenco. His research interests are in acoustics and biomedical engineering.

Jorge Becerra Garcíareceived his B.Sc. in electronics and communications engineering from ESIME Zacatenco IPN, Mexico and M.Sc. degree in Bioelectronics from CINVESTAV IPN, Mexico. Currently he is a Professor at the Department of Electronics and Communications engineering over 38 years' experience in ESIME Zacatenco. His research interests are in acoustics and biomedical engineering.

Javier Herrera Espinosa received his B.Sc. in electric engineering from UAM-Azcapotzalco Mexico and M.Sc. degree in electric engineering from SEPI-ESIME-Zacatenco-IPN Mexico. Currently he is a Professor at the Department of Electronics and Communications engineering. His research interests are machinecontrolusingintelligentcontroland power electronics.