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An Inductive-Link with a Regulated Secondary Voltage based on Frequency Adjustment

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Abstract—**This paper shows a wireless powering system for implantable biomedical devices that does not need a voltage regulator inside the body. The regulated voltage is obtained in the secondary of an inductive link and is controlled by varying the operating frequency of the inductive link. This frequency operation varies between 950 kHz and 1.2 MHz when the distance between the coils varies between 0mm and 40mm. The results show that it is not necessary to elevate the supply voltage of the external circuit to regulate the internal voltage. This scheme eliminates the necessity of a voltage regulator inside the body, reducing the implant operating temperature.**

I. INTRODUCTION

The use of implantable electronic devices allows to assist and improve the quality of life of people. Applications range from sensing and monitoring different biological parameters, such as continuous glucose blood level [1] or recording of ECG signals [2], to stimulation of different parts of the body, such as neural stimulation [3] or spinal cord stimulation (SCS) [4].

In all applications, it is necessary to supply energy to the implanted electronic device. In order to achieve this, there are different options. One of them is by using transcutaneous cables for continuous powering from the outside of the body. This has the disadvantage of been uncomfortable for the patient, and a high risk of infections or skin damage. Another option is implantable batteries, but they have the disadvantage of a potential battery fluid leakage, undesirable batteries replacements, and a bigger implant size [5].

As an alternative, in the last decades emerges wireless power transfer through inductive links to feed implantable devices [5], [6]. The inductive link is mainly composed of four parts: a high frequency power amplifier, the inductive link, the rectifier, and the load.

The implanted supply voltage required by any electronic device must be regulated, in order to ensure proper and secure operation. This implies the necessity to maintain a constant output voltage of the system. This can be realized by using a voltage regulator between the rectifier and the load [6], but it has the disadvantage of producing a bigger size of the implant, reduce the reliability by adding extra components, and increasing the dissipated power in form of heat inside the body, which could produce biological tissue damage.

Another possibility is by achieving voltage control from the external circuit. There are two main approaches for doing this control: Amplitude control and frequency control. The amplitude control sense the implanted voltage of the system, and according to its variations, modifies the supply voltage of the power amplifier outside the body, by changing the voltage gain of the inductive link [7]. This has the disadvantage of not taking into account the difference between the resonance frequency and the operating frequency of the system, reducing the voltage gain and efficiency of the system. Also, the voltage necessary to compensate the separation of the coils has an exponential relationship with the distance, increasing the requirements of the semiconductors.

On the other hand, frequency control proposed in previous investigations modifies the resonance frequency of the inductive link, changing the capacitive value of a series LC tuned with a limited number of steps [8]. It has the disadvantage that it only changes the resonance frequency of the primary circuit, resulting in lower energy transfer.

This paper presents a frequency controlled wireless power transfer for implantable devices. The voltage power supply of the implanted device is controlled by varying the operating frequency, looking for the varying natural resonant frequency due to changes in mutual inductance. The resonance frequency of the inductive link is fixed (fixed LC components). The results show that is possible to produce a regulated implantable voltage for different axial distances between coils.

II. THEORETICAL BACKGROUND

There are two main factors that influence the inductive link operation. First, the coils parameters (number of turns, coil diameter, conductor diameter) determine the self inductance. Second, when a system is working with two coils close to each other, there is a mutual inductance due to coupling, which depends on the distance between the coils.

When a series resonance topology is used in the primary circuit and a parallel resonance topology in the secondary circuit, there is a frequency where there is maximum efficiency and voltage gain. Therefore, the resultant impedance of the primary circuit at the resonance frequency is given by the expression presented in [9], and shown in (1).

$$Z_1 = R_1 + \frac{\omega^2 M^2}{Z_2} \tag{1}$$

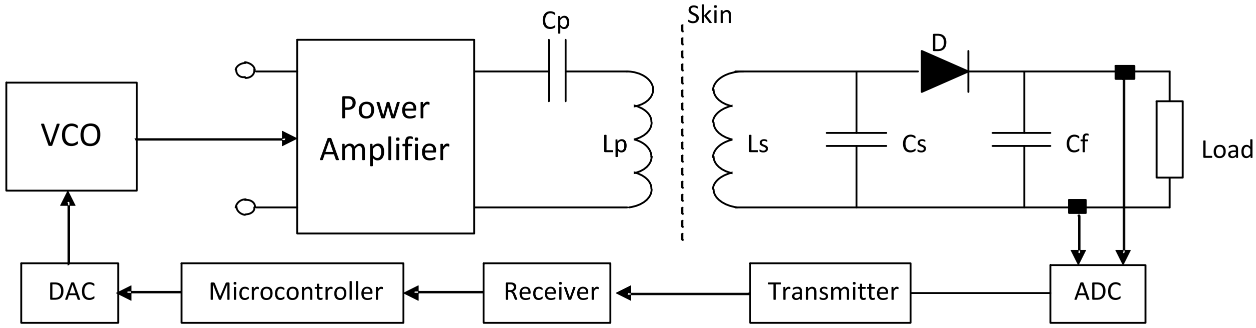

Figure 1.Inductive Link Diagram with Frequency Control.

Where Z_1 is the impedance of the primary circuit, R_1 is the resistance of the primary circuit, ω is the angular frequency of the system, M is the mutual inductance, and Z_2 is the impedance of the secondary circuit.

When the distance between the coils changes, the mutual inductance will be modified, due to the variation of the magnetic flux perceived by the secondary coil. The relationship between the mutual inductance and the magnetic flux is given by (2).

$$M = N_2 \frac{\Phi_2}{I_1} \tag{2}$$

Where N_2 is the number of turns of the secondary coil, Φ_2 is the magnetic flux through the secondary coil, and I_1 is the current in the primary coil. The magnetic flux produced depends on the magnetic flux density, as shown in (3).

$$\Phi_{12} = \boldsymbol{B_1} A_2 \tag{3}$$

Where $\mathbf{B_1}$ is the magnetic flux density produced by the primary coil, and A_2 is the inner core area of the secondary coil (in this case, an air core).

Thus, changes in the distance between coils produces a variation in the resonance frequency of the primary and secondary LC circuits shown in the Fig. 1. This means that the resonance will be produced at another frequency that will generate a different induced voltage at the secondary coil.

By implementing a frequency control system it is possible to change the operation frequency of the inductive link, moving it close to the new resonance frequency.

III. IMPLEMENTED SYSTEM

The system is composed by a high frequency power amplifier, an inductive link, a high frequency rectifier, and the load (Fig.1).

The power amplifier consists in a Class D amplifier, widely used in this kind of applications [10], [11]. The implemented circuit uses MOSFET Transistors working around 1MHz. The power supply was fixed on 9V and the commutation signal comes from a VCO.

TABLE I. *PARAMETERS OF THE IMPLEMENTED PRIMARY AND SECONDARY COILS.*

Parameters	Primary Coil	Secondary Coil
Number of turns	30	10
Coil diameter	50 mm	50 mm
Wire diameter	0.32 mm	0.28 mm
Resistance	3.46 Ω	1.04 Ω
Inductance	64.831 µH	10.544 µH
Capacitors	390 pF	2400 pF

The inductive link is composed by a LC series resonant primary circuit, and a LC parallel resonant secondary circuit, in order to increase the efficiency and voltage gain [12]. Polystyrene capacitors where used for their good response at high frequencies. The coils where made with coating wire on cylindrical shape. Specifications of capacitors and coils used are shown in Table 1.

The high frequency rectifier is a half wave rectifier. This rectifier has a higher efficiency than a bridge rectifier because the current flows across one diode only. The waveform of the dc voltage is improved including a capacitor as a simple filter.

Finally, for experimental purposes, the load was implemented by a 100 **Ω** resistor.

Different tests of the system where done. First, using a fixed frequency, the distance between the coils was changed until 40mm and the load voltage at the implanted device was measured. The objective of this experiment is to find the maximum load voltage produced at this frequency. By repeating this experience for different frequencies, it is possible to see that there is an optimal frequency for each distance, where a maximum output voltage is obtained, as shown Fig. 2.

From this experience it is possible to infer that a frequency control can be implemented. Each distance has a specific frequency where the maximum output voltage is obtained. Fig. 3 shows indirectly the frequencies where the maximum voltage was obtained at different distances. This experience was made for an axial distance between the primary and secondary coil from 0 mm to 40 mm.

From Fig. 3, it is possible to see that for an axial distance up to 36 mm it is possible to obtain a load voltage greater or equal to 3.3V. This means that it is possible to implement a frequency control system to maintain a constant output voltage of 3.3V for this distance range.

The frequency range from 950 kHz to 1280 kHz is needed to achieve frequency control. However, in a practical biomedical application, the axial distance between the primary and the secondary coil will be at least 8 mm due by the skin and fat [13]. This means that the real frequency range needed to implement the frequency control is between 950 kHz and 1000 kHz.

IV. Implanted Voltage Control with Frequency Operation Adjustment

In order to maintain a constant output voltage in the system, a frequency control is implemented by using a Voltage Controlled Oscillator (VCO). This circuit allows to modify the operation frequency of the power amplifier, and therefore, works around the resonance frequency of the primary and secondary LC circuits (Fig. 1).

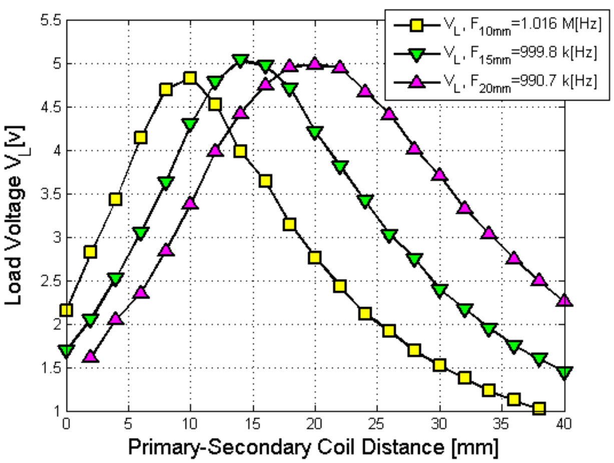

Figure 2. Output voltage curves for different frequencies and axial distances.

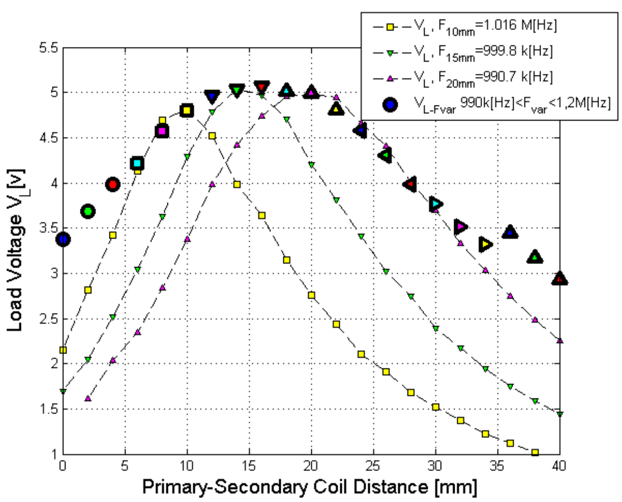

Figure 3. Maximum output voltage for each distance at a particular frequency.

The control uses a feedback stage, measuring the output voltage of the system from the implantable circuit, which varies when the distance between the coils change. Since this variation is reflected at the output voltage, this signal can be used as a feedback to modify the operation frequency by the control system.

The measured output voltage is digitalized and sent wirelessly from the implantable circuit to the external circuit. The implemented system uses two Zigbee transceivers (XBee modules). Then, the signal is passed to a microcontroller (ATMega64), who controls the analog VCO.

V. Experimental Results

The complete system is evaluated (Fig. 4), including the implemented frequency control for an axial distance range between coils from 6 mm to 20 mm. It is possible to observe that the voltage range needed for the VCO was between 5.5 V and 2.3V. The VCO voltage decreases when the axial distance is incremented, producing a variation in frequency from 1003 kHz to 958 kHz, as shown in Fig. 5. Variation of the operation frequency helped maintain a constant 3.3 V output voltage, as expected, demonstrating that the implemented system works properly.

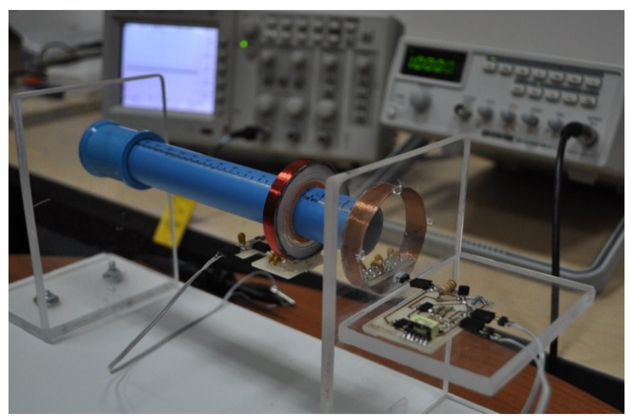

Figure 4. Wireless Powering System

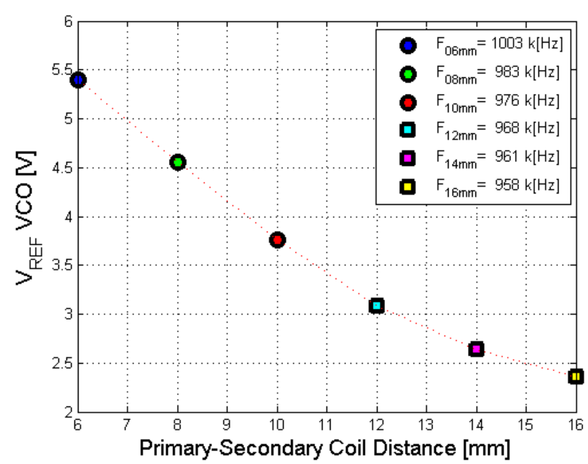

Figure 5. Reference voltage needed for the VCO to modify the system frequency to maintain a constant 3.3V output voltage.

The voltage reference for VCO is within the power supply used in the system, which means that it is not necessary to use a second voltage source. By using a frequency control, it is not necessary to modify the supply voltage, which allows using a 9V battery to supply a constant voltage to the system without an additional dc-dc converter.

The system reached a power deliver of 250 mW, with a constant output voltage of 3.3V for an axial distance range between the primary and secondary coil from 6 mm to 20 mm.

VI. Conclusions

This paper presented a frequency controlled inductive link, by using a VCO which control the operational frequency of the system. The feedback voltage signal was sent wirelessly using a ZigBee transmitter and receiver, allowing doing a control strategy outside the body. This eliminates an internal voltage regulator, reducing the size of the implanted device and reducing the power dissipation inside the body.

On the other hand, by changing the frequency of the system, it is possible to compensate the variations in resonant frequency of both the primary and secondary circuits, which allows for a better voltage regulation.

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References

[1] G. A. Jullien M. M. Ahmadi, "A Wireless-Implantable Microsystem for Continuous Blood Glucose Monitoring," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 3, no. 3, pp. 169 - 180, June 2009.

[2] H. Harjunpaa, S. Arra, J. Kokko, M. Mantyla, J. Kaihilahti, P. Heino, M. Kellomaki, O. Vainio, J. Vanhala, J. Lekkala, J. Hyttinen, J. Riistama, J. Vainasen S. Heinisuo, "Wireless and inductively powered implant for measuring electrocardiogram," *Med. & Bio. Eng. & Comput., 45*, pp. 1163 - 1174, Oct. 2007.

[3] G. A. Clark, R. R. Harrison, B. K. Thurgood, D. J. Warren N. M. Ledbetter, "A Wireless Integrated Circuit for 100-Channel Charge-Balanced Neural Stimulation," *IEEE Transactions on Biomedical Circuits and Systems*, vol. 3, no. 6, pp. 405 - 414, Dec. 2009.

[4] C. C. Wang, C. H. Hsu, S. B. Tseng Y. Hsieh, "One-Time-Implantable Spinal Cord Stimulation System Prototype," *IEEE Transactions on Biomedical Circuits and Systems*, June 2011.

[5] J. Edvinsson, D. H. Rivas, H. Naas, L. S. Y. Wong, S. Hossain A. Ta, "A very low-power CMOS mixed signal IC for implantable pacemaker applications," *IEEE J. Solid-State Circuits*, vol. 39, no. 12, pp. 2446 - 2546, Dec. 2004.

[6] N. N. Donaldson, "Voltage Regulators for implants powered by coupled coils," *Med. & Biol. & Comput.*, pp. 756 - 761, 1983.

[7] J. W. Hsu, M. Chiang, Y. Wang, S. Malpas, D. Budgett, P. Si A. P. Hu, "Wireless Power Supply for Implantable Biomedical Device Based on Primary Input Voltage Regulation," *2nd IEEE Conference on Industrial Electronics and Applications (ICIEA 2007)*, pp. 235 - 239, 23-25 May 2007.

[8] A. P. Hu, S. Malpas, L. Bennet, A. Taberner, L. Booth, D. Budgett T. D. Dissanayake, "Experimental Study of a TET System for Implantable Biomedical Devices," *IEEE Transactions on Biomedical Circuits adn Systems*, vol. 3, no. 6, pp. 370 - 378, December 2009.

[9] T. A. Perkins N. N. Donaldson, "Analysis of resonant coupled coils in the design of radio frequency transcutaneous links," *Med. & Biol. Eng. & Comput*, pp. 612 - 627, 1983.

[10] R. L. White, D. C. Galbraith M. Soma, "A wideband efficient inductive transdermal power and data link with coupling insensitive gain," *IEEE Trans. Biomed. Eng.*, vol. BME-34, no. 4, pp. 265 - 275, Apr. 1987.

[11] X. Shangang, W. Ying Y. Luguang, "Modeling and performance analysis of a new contactless power supply system," *Proc. ICEMS*, vol. 10, pp. 2849 - 3852, 2005.

[12] S. A. Khan, H. Ali T. J. Ahmad, "Mathematical modeling of an inductive link for optimizing efficiency," *IEEE Symposium on Industrial Electronics & Applications (ISIEA 2009)*, vol. 2, pp. 831 - 835, 4-6 Oct. 2009.

[13] C. H. Raine, "Skin Flap Thickness in Cochlear Implant Patients - Prospective Study," *Cochlear Implants Int.*, vol. 8, no. 3, pp. 148 - 157, Sept. 2007.