ENERGY EFFICIENCY EVALUATION OF VOLTAGE CONTROL AND FREQUENCY CONTROL OVER AN INDUCTIVE POWER LINK FOR BIOMEDICAL IMPLANTS

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Abstract: This article presents the analysis of the efficiency of two control systems used to regulate the DC voltage in an implanted device fed by an inductive power link. Both control systems work outside the body, eliminating the voltage regulator in the implanted circuit (inside the body). These ways of voltage control reduce the power and heat dissipated inside the body. The first control system involves regulation of power supply voltage to the high frequency amplifier. The second control system adjusts the frequency of the inductive link. A laboratory prototype was built and experimental results were obtained. It is shown that for a range of distance between 0 mm and 11.8 mm the efficiency of the system is greater when using amplitude voltage control. Above that distance, the efficiency of frequency control is better. A difference of 20% was obtained in the optimal points.

1 INTRODUCTION

Over the past few decades, the inductive powering link has been studied and used for transmitting energy wirelessly to Implantable Microelectronic Devices (IMDs), such as cochlear prosthesis, visual prosthesis, cortical neuromotor prosthesis and implantable sensors, to name just a few. This kind of transmission energy avoids wires crossing the skin, which have a high risk of infection or other problems for the patient. It is also used to avoid placing rechargeable batteries inside the body, because they have a limited lifetime and will require new surgery to replace them (Ma et. al., 2010).

A basic remote powering link scheme has four main parts: A high frequency power amplifier, an inductive link, a high frequency rectifier, and a voltage regulator. MOSFET based Class D and Class E amplifiers are the most used high frequency power amplifiers because of their higher efficiency at high frequencies (Atluri and Ghovanloo, 2006). In the inductive link, the common resonance topology is a series L-C tuned primary circuit and parallel L-C tuned secondary circuit due to its high voltage gain and efficiency characteristics (over 80%) at low coupling ranges (Ali, Ahmad and Khan, 2009). The distance between coils varies the mutual inductance between primary and secondary coils, and hence, the coupling coefficient (k); therefore, the choice of shape, number of turns, diameter and size of the primary and secondary coils allows a good position tolerance. The high frequency rectifier is normally half or full bridge with very fast switching Schottky diodes (Dissanayake et. al., 2009).

External batteries are used to feed the wireless power transmission for implanted devices. These applications need to have a small size and light weight external control box for patient mobility and comfort. Battery lifetime must be maximized in order to give the patient more autonomy without the need of frequent changing the external battery.

Most of the implantable electronic devices need a constant supply voltage to work properly, which means that the voltage on the secondary coil has to be regulated for some kind of control system that produces a constant voltage. There are two main approaches: Magnitude voltage control and frequency control. The first one varies the magnitude of the power supply voltage that feeds the high frequency amplifier, in order to vary the power delivered to the inductive link (and consequently to the load) (Si et. al., 2007). And the second one varies the frequency of the voltage that feeds the inductive link, moving the frequency value around the resonant situation (Si et. al., 2008).

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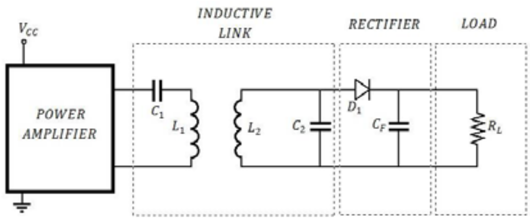

Figure 1: Four main parts of the circuit of the system.

Both control systems have the goal of maintaining a constant voltage at the load, improving the overall reliability of the system.

This paper analyzes the inductive link efficiency of both control systems when the distance between the primary and secondary coils is changed.

2 INDUCTIVE POWERING LINK

When analyzing the inductive powering link it is necessary to consider several parts.

2.1 System

The system used in this study consists in four main parts (showed in figure 1): High Frequency power amplifier, inductive link, high frequency rectifier, and load. A detailed description of each part is presented below.

2.1.1 Power Amplifier

There are several classes of power amplifiers (A, AB, B, C, D and E) that can be used. Class D and class E power amplifiers are the most used for inductive links, because of their high efficiency, over 80%. In this paper, a Class D Power Amplifier based on push-pull Mosfet's configuration is used. The amplifier works at 1MHz and is fed by a variable 30V power supply. The schematic circuit is shown in figure 2.

2.1.2 Inductive Link

The inductive link is composed of the external primary coil and the implanted secondary coil. There are different options of circuit configurations, where the resonance topology is the most effective option, because it makes the final circuit band limited, improving the voltage gain and link efficiency. Studies proposed that the series-tuned primary and parallel-tuned secondary circuit is the ideal configuration because of its good displacement tolerance, high voltage gain and efficiency characteristics at low coupling ranges (Ali, Ahmad and Khan, 2009).

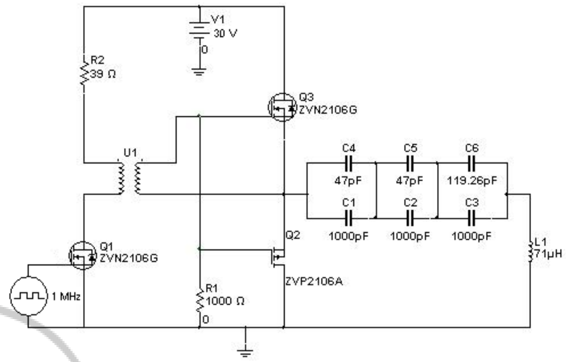

Figure 2: Power amplifier, driver and series tuned primary coil.

We decided to work with circular coils. The parameters of the resultant inductive link are listed in table 2.

Table 1: Parameters of the series tuned primary and parallel tuned secondary coils.

Parameters	Primary	Secondary
Number of turns	30	20
Coil Diameter	50 mm	50 mm
Wire Diameter	0.28 mm	0.28mm
Inductance	71 µH	42 µH
Resistance	1.1 Ω	0.7 Ω

2.1.3 Rectifier

A simple half-wave rectifier is used to rectify the AC signal generated on the implanted tuned coil. This topology is appropriate to this application because it has less consumption than a full-wave rectifier (because it has only one diode). The rectifier is composed of a 1N5819 Schottky diode. The high frequency of the inductive link (1MHz) reduces the size of the parallel capacitor used as a filter, in order to have a continuous voltage with an acceptable ripple (less than 10%).

2.2 Model of Inductive Link

We need to consider model of the inductive link, in order to gain more knowledge about the coupling coefficient, critical coupling, voltage transfer ratio, and efficiency of the link.

2.2.1 Coupling coefficient and Critical Voltage Transfer Ratio

The coupling coefficient of the system is defined by (1).

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}} \quad (1)$$

Where k is the coupling coefficient of the inductive link, M is the mutual inductance between the two coils, L_1 is the self-inductance of the external coil (primary), and L_2 is the self-inductance of the implanted coil (secondary).

The inductive link frequency was selected considering the limitation on power density within the body (<80mW/cm^2) (Zumsteg, 2004) in order to avoid tissue damage. In this case the frequency used was 1MHz. In resonance condition, the resonant frequency (ω_0) of the system is defined by (2)

$$\omega_0 = \frac{1}{\sqrt{L_1 \cdot C_1}} = \frac{1}{\sqrt{L_2 \cdot C_2}} \quad (2)$$

2.2.2 Definition of Overall Efficiency

The model presented in (Donaldson and Perkins, 1983) shows that the transmitter has a resistance R_1, and the receiver has a resistance R_2, which means that in every stage there are power losses, which change the overall efficiency (η_o) of the system. This efficiency can be expressed by (3).

$$\eta_O = \frac{P_G}{P_A + P_B + P_C + P_D + P_E + P_F + P_G} \quad (3)$$

Composed of the power consumption off the oscillator (P_A), dissipation in ouput stage not accounted by the oscillator (P_B), and the power consumption dissipated in circuits; on the transmitter side: by the power in the resistance of the power supply voltage (P_C), power in the resistance of the primary coil (P_D), and in the receiver side, by the power in the resistance of the secondary coil (P_E), the power in the rectifier (P_F), and the useful power (P_G).

3 CONTROL METHODS FOR A REGULATED VOLTAGE

The control of the load voltage is important to obtain a steady output voltage during coupling variations between the primary and the secondary coil, which could be used as the power supply to some implanted circuit. This can be done by two main methods: Amplitude voltage control and frequency control. The amplitude voltage control and frequency control can be produced in several ways. One of the proposed options is controlling from the external system (Silay, Dehollain and Declercq, 2010), and the other one is controlling from the internal circuit (Donaldson, 1985). For simplicity, we used the first one in this paper.

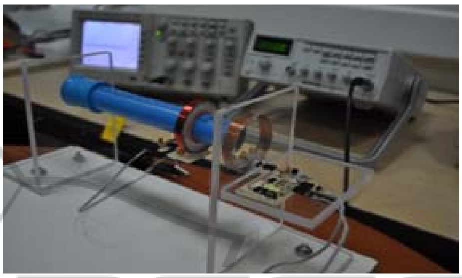

Figure 3: Inductive link prototype for measurements.

4 OVERALL EFFICIENCY OF THE SYSTEM AND EXPERIMENTAL RESULTS

The overall efficiency of the system was empirically established by using two control methods. Amplitude voltage control and frequency control, for a fixed voltage at the load of 5V. The position of the primary coil was fixed, and the distance of the secondary coil was incremented by 2 mm for every measurement, in order to see the difference of efficiency produced by the change of the distance between the coils. The circuit and instruments used are shown in figure 3. All the measures were done with a 100MHz digital oscilloscope and computed in Matlab.

4.1 Measurements with Amplitude Voltage Control

The voltage controller varied the supply voltage of the primary circuit to maintain a constant load voltage at the secondary circuit for each distance, with a constant frequency of the system of 1 MHz. The measurements started 0 mm between the coils, and were increased until 25 mm, with measurements every 2 mm. The input voltage shows an exponential behavior from 5V to 32V with respect to the distance, which means that it is not possible to reach a greater distance between the coils, because it would supply an input voltage greater than the maximum voltage permitted by electronic components.

4.2 Measurements with Frequency Control

The frequency controller varied the frequency of the system from 1.28 MHz to 1.05 MHz in order to maintain a constant load voltage at the secondary circuit for each distance, with a constant supply voltage of 7 V. The measurements started at 0 mm between the coils, and were increased until 35 mm, with measurements every 2 mm.

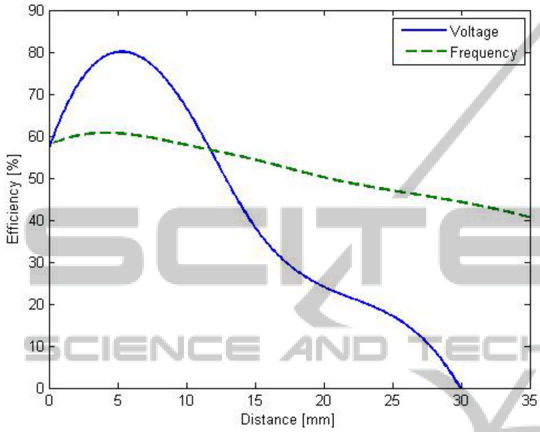

Figure 4: Efficiency of the amplitude voltage control and frequency control at each distance.

It was not possible to maintain a constant output voltage with a value of 5V for a distance between the coils was greater than 35 mm.

4.3 Efficiency of Both Control Systems

The overall efficiency of both control systems was measured in order to compare the two ways of maintaining a constant output voltage at a certain value. Figure 4 shows that the efficiency of the amplitude voltage control is greater at distances between 0 mm and 11.8 mm, and over that distance, the efficiency of the frequency control is greater. The amplitude voltage control has a greater maximum voltage, but is more sensitive to distance changes. On the other hand, the frequency control has fewer variations of efficiency at different distances, but its maximum efficiency value is less than the maximum efficiency of the amplitude voltage value.

5 CONCLUSIONS

An analysis of the efficiency of two control systems used to regulate the DC voltage in an implanted device fed by an inductive power link was presented. Both control systems work outside the body, eliminating the voltage regulator in the implanted circuit (inside the body). These ways of voltage control reduce the power and heat dissipated inside the body. The first control system regulates the power supply voltage and the second adjusts the frequency of the inductive link. Experimental results show that the efficiency of the system is greater when using amplitude voltage control for a range of distance between 0 mm and 11.8 mm. Above that, frequency control is better. A difference of 20% was obtained at the optimal points.

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