Investigation the Effect of Misalignment and Distance between the Coils for Wireless Power Transfer in Retinal Implants

Emrullah Aydin[1], Mahmut Emin Celik[1], and M.Timur Aydemir[1]

[1]Electrical Electronics Engineering Department, Faculty of Engineering, Gazi University, Ankara, Turkey
emrullahaydin@gazi.edu.tr, mahmutemincelik@gazi.edu.tr
aydemirmt@gazi.edu.tr

Abstract

Powering retinal implants with a battery contrary to many neuroprosthetic devices is one of the greatest difficulties encountered for both design and implantation phase. Considering there are limitations on space and volume in intraocular region with extra risks for replacement surgeries, inductive coil links, which use near-field resonant inductive coupling with the mutual inductance between primary and secondary coils, attract considerable attention to reliably transfer the necessary power to retinal implants wirelessly. Retinal prosthesis requires continuous power transfer to process real time images into stimulation patterns, so high power transfer efficiency plays a critical role. In this work, we examined the effect of misalignment of the coils and the gap distance between coils on coupling coefficient solving the equations by custom-written MATLAB codes followed by Finite Element Method. It was seen that coil misalignment and distance between coils showed similar impairing effects on coupling coefficient.

1. Introduction

Retinal implants are the devices used to elicit visual sense for visually impaired patients by electrically stimulating neurons remained intact. There are two main parts of a visual prosthesis system. The first unit is in the intraocular region that includes microelectrode array and related electronic circuits whereas other part is outside of the eye and includes processor, camera and external antenna [1,2]. The images taken from the camera mounted on a glass are processed and transferred to a stimulation pattern which is applied to the electrodes simultaneously. Therefore, the system needs to be powered continuously.

Powering visual prosthesis is one of the biggest challenges for high performance systems. So far, different methods are used to supply visual prosthesis. Because there is a quite limited space in the eye, using a battery inside the eye is not even an option. Transferring power wirelessly is an option, many researchers prefer these days. In this near-field power transfer method inductive coils are used [3-8]. The simplest coil link design includes two coils with a gap between them. The first coil supplied with a source generates a magnetic field that links the secondary coil and induces a voltage there to be applied to the load. So, the load is wirelessly supplied through inductive coil link.

In this work, basic equations that describe the operation principles of wireless power transfer (WPT) with inductive coil are given, and design process for a simple system is described. Optimal relationship is determined to provide the necessary power, which is about 56 mW which is the estimated power consumption for a high-density electrode array that includes more than 1000 electrodes. This power is used for operating electronic circuits and neural stimulation on the chip. Once the design is complete the parameters calculated in MATLAB van be used to perform finite element analysis of the system to analyze the effect of misalignment between the coils.

2. Powering Retinal Prosthesis

The idea behind the visual prosthesis concept is bypassing the damaged parts of the visual pathway because of several degenerative retinal diseases, then electrically stimulating nerve cells remaining intact [9]. The most prevalent two degenerative eye diseases are Retinitis Pigmentosa and Age Related Macular Degeneration. They impair photoreceptor layer of the retina and cause blindness in time. It is reported that more than 40 millions of people are affected in the world. Moreover, as a leading cause of blindness in the developed countries Age Related Macular Degeneration will affect more than 4 millions of people in USA until 2020 [10].

With the recent developments in bioengineering, micro technology, packaging and neuroscience and collaborative multidisciplinary studies have provided innovative development of sophisticated microelectronic devices to electrically stimulate retina tissue to regenerate visual sense [11]. These devices are called visual prosthesis and they could be categorized into different classes according to where they are placed such as retina, optic nerve and visual cortex. In this work, we are interested in retinal prosthesis because they are quite advanced devices compared to others.

Retinal prosthesis uses retina tissues to elicit visual sense by stimulating them. There are different targets on them for implantation such as epiretinal, sub retinal and suprachoroidal side. Epiretinal prosthesis aims to stimulate nerve fibers that are outputs of retinal ganglion cells. In the beginning of development phase, different methods are used to supply the devices using cables [12, 13]. Chemical reactions on the surface between electrodes and tissue induce immune system, which causes system failure by increasing total electrode impedance [14]. After chronic implantations with humans, the strategy changes to inductive coil links [15, 16]. EPI-RET-3 uses epiretinal implant approach. It is powered wirelessly without any cable crossing the eye ball [17]. Subretinal implants are placed in an area between retinal pigment epithelium layer and bipolar cell layer near the degenerated photoreceptors. Even though solar cells were used to stimulate neurons in the past, it was seen that they cannot generate enough power, so power is provided by additional supplying electronics.

Ciavatta et al developed a subretinal system including 3500 micro photodiodes in 3 mm^2 area and tested the system with 10 human patients [18]. Results showed that light stimulated micro-photodiodes do not generate enough current for retinal stimulation. When photodiodes were powered with cables for next generation, it did not provide the power expected [19].

Real coils have resistance and capacitance contrary to ideal inductive links with no resistance and capacitance. If it is required to model coils with circuit elements, one simple approach is a resistor in series with an inductor which is enough for lower frequencies compared to natural resonant which could be tuned by adding one capacitor which enables the circuits operate at resonance. Considering a simple inductive coil link model, governing equations are presented in Table 1 for series-series (SS) compensated WPT system [20, 21].

Table 1. Governing equations for inductive coil link parameters

	Parameter	Equation
Capacitance and Current Calculations	Receiver coil capacitance	$C_2 = \frac{1}{\omega_0 L_2}$
	Current in primary coil	$I_1 = \frac{V_1}{Z_T}$
Power Calculations	Equivalent impedance	$Z_T = \left(R_1 + j\left(L_1\omega - \frac{1}{C_1\omega}\right)\right) + \frac{\omega^2 M^2}{\left(R_2 + R_L + j\left(L_2\omega - \frac{1}{C_2\omega}\right)\right)}$
	Maximum power transferred	$P_{MAX} = \frac{\omega M^2 Q_2 I_1^2}{L_2}$
Inductance Calculations	Self-inductance	$L = \frac{1.27\mu_0 N^2 d_{ort}}{2}\left[\ln\left(\frac{2.07}{p}\right) + 0.18p + 0.13p^2\right]$ $d_{ave} = \frac{d_i + d_d}{2}$ $p = \frac{d_d - d_i}{d_d + d_i}$
	Magnetic field equation for mutual inductance	$\vec{B} = \frac{\mu_0 I}{4\pi}\int \frac{d\vec{l} \times \vec{r}}{r^3} = \frac{\mu_0 I}{4\pi}\int \frac{d\vec{l} \times \hat{r}}{r^2}$
	Flux	$\phi_{ij} = N \cdot M_{ij} \cdot I$
	Mutual inductance	$M = \sum_{i=1}^{N_1}\sum_{j=1}^{N2} M_{ij}$

In Table 1 ω_0, V_1, R_L, R_1-R_2, Q_2, μ_0, d_{ave}, p represent the resonant frequency, input voltage, load resistance, transmitter-receiver winding resistances, quality factor of receiver winding, permeability of air, the average value of coil diameter and the fill factor coefficient of winding respectively.

3. Inductive Coil Link Design

In inductive coil links, the current generated in primary part generates another current in the secondary part of the inductively coupled system. The coupling factor of the windings is an indicator of what portion of the flux is transferred between the two sides and ranges between 0 and 1. The quality factor presents coil property as a function of coil shape, geometry and electrical properties of the material. Each coil has its own quality factor depending on its L and R values. As a close situation to the expected condition when an implant placed into the eye, the distance between coils, diameters of receiver and transmitter coils are determined as 2 cm, 3 cm and 2 cm respectively. The model includes two rectangular shaped coils. Graphical presentation of these coils are presented in Fig 1. The figure was prepared to include possible misalignments of windings.

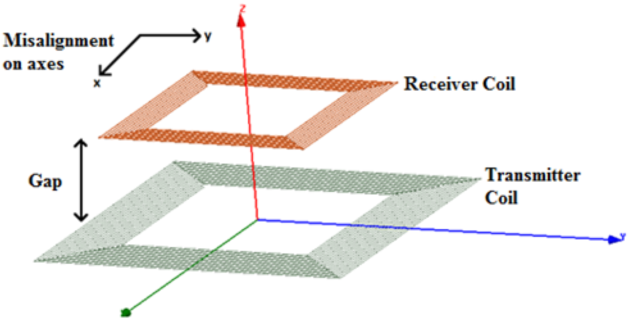

Fig. 1. The model of primary and secondary coils with a gap

A MATLAB code was written to calculate the optimal design parameters by using the equation given in Table 1 for a simple inductive coil link model. The target power is 56 mW. The calculated parameters are given in Table 2.

Table 2. The values of the parameters of coils

	Transmitter Coil	Receiver Coil
Number of turns (N_1,N_2)	20	10
Self-inductances (µH)	16.84	3.28
Wire cross-sections (mm^2)	2.82*10-9	7.85*10-9
Coil dimensions (mm)	30x30	20x20
Mutual inductance (nH)	982	
Gap (mm)	10	
Coupling coefficient (k)	0.132	

3. Simulation Results

The parameters calculated for the system to transfer 56 mW to the load, retinal implant were used to simulate its operation. In the simulations the transmitter coil is fixed, receiver coil position is varied on x and y axes from 0 to 6 mm by 2 mm steps and the gap distance is varied from 10 to 20 mm by 2 mm steps.

Fig. 2 shows a sketch for magnetic field vector distributions for a fixed and perfectly aligned receiver coil position.

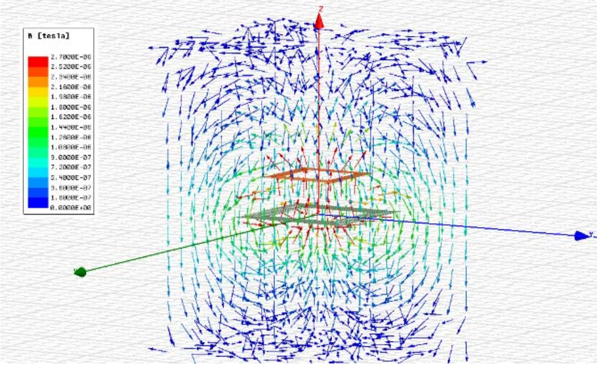

Fig. 2. The magnetic field vector

The results obtained from MATLAB codes are compared to other analysis results conducted with Maxwell® using Finite Element Method. It is seen that first solutions are compatible with the results of Finite Element Method.

Fig. 3 shows the variation of coupling coefficient for different gap distances. As expected the coupling coefficient decreases as the distance between the coils increases. The coupling coefficient gets its highest value as 0.133 when the gap distance is 10 mm.

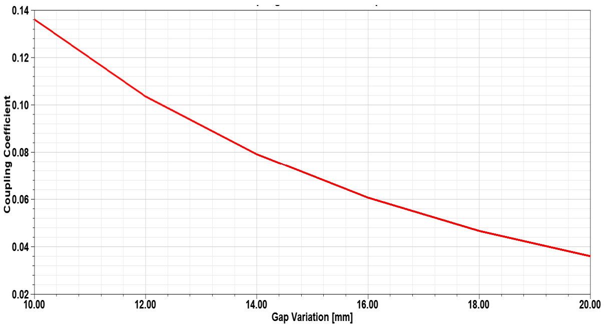

Fig. 3. The variation of coupling coefficient with the gap distance between the coils

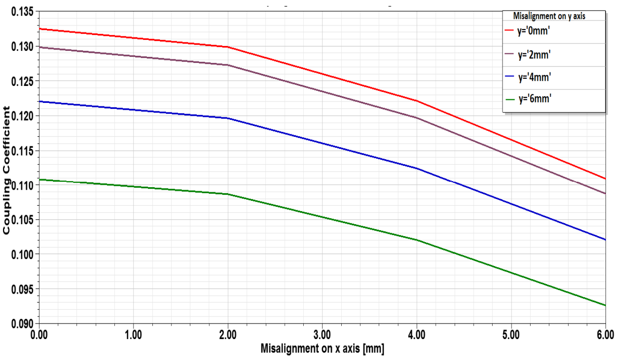

Fig. 4. The variation of coupling coefficient with the gap distance between the coils

Fig. 4 shows the variation of the coupling coefficient against the misalignment on *x* axis for various misalignment values at *y* axis. These results were obtained by FEA analysis where the gap between the coils was kept constant at 10 mm. Taking into consideration that receiver coil which was implanted on the eyeball could move with respect to the transmitter coil that is fixed out of the skin. Fig 4 shows that coupling coefficient decline faster after a misalignment of 2 mm.

4. Conclusions

Wireless power transfer is a promising technology for retinal implants. Considering the spatial limits and infection risks, WPT design is very critical. In this work an initial design process is presented. The coil design of a 56 mW system is described. Design equations were solved in a MATLAB code to find the optimum parameters. These parameters were then used in Maxwell for FEA of the model to see the flux variation and effect of misalignments on coupling coil due to eyeball rotation and motion. It was shown that one-pair coil link design is a good candidate for situations with relatively constant coils.

7. References

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