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Optimal Secondary Coil Design for Inductive Powering of the Artificial Accommodation System

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***Abstract*—Age-related ailments like presbyopia and cataract are increasing concerns in the aging society. Both go along with a loss of ability to accommodate. A new approach to restore the patients' ability to accommodate is the Artificial Accommodation System. This micro mechatronic system will be implanted into the capsular bag to replace the human crystalline lens. Depending on the patients' actual need for accommodation, the Artificial Accommodation System autonomously adapts the refractive power of its integrated optical element in a way that the projection on the patients' retina results in a sharp image. As the Artificial Accommodation System is an active implant, its subsystems have to be supplied with electrical energy. Evolving technologies, like energy harvesting, which can potentially be used to power an implant like the Artificial Accommodation System are at the current state of art not sufficient to power the Artificial Accommodation System autonomously [1]. In the near future, therefore an inductive power supply system will be developed which includes an energy storage to power the Artificial Accommodation System autonomously over a period of 24 h and can be recharged wirelessly. This Paper describes a new possibility to optimize the secondary coil design in a solely analytical way, based on a new figure of merit. Within this paper the developed figure of merit is applied to optimize the secondary coil design for the Artificial Accommodation System.**

I. INTRODUCTION

The treatment of age-related ailments like presbyopia and cataract is gaining more and more importance in an aging society. The number of cataract surgeries done per year is about 700.000 in Germany alone. In a standard cataract surgery the clouded human lens is replaced by a rigid, artificial intraocular lens, this causes that the human eye looses the ability to adapt to different distances (i.e. to accommodate). Similar to the case of presbyopia, the patient loses his ability to accommodate and needs vision aids to adapt to different target distances.

The Artificial Accommodation System [2]–[4] will be an alternative to rigid and pseudo-accommodating intraocular lenses. It is an autonomous, micro-mechatronic lens implant which will be implanted like a standard intraocular lens. As it is completely placed inside the capsular bag, it has to fulfill its function without the use of body signals.

The Artificial Accommodation System consists of several subsystems. Amongst others, it contains an integrated optical element whose refraction is adjusted to the patient's actual demand of accommodation. To adapt its refractive power, the optical element is moved by an actuator [5]. The dynamic adaption of refractive power gives the patient the ability to focus on different distances without additional visual aids. The demand of accommodation is measured by an integrated sensor subsystem and is relayed to the integrated control unit. A further subsystem will enable the internal communication between two implants as well as the external communication with a programmer or remote control device. This enables the attending health professional to perform individual patient calibration and diagnostics. All subsystems need electrical energy which is provided by an energy supply system.

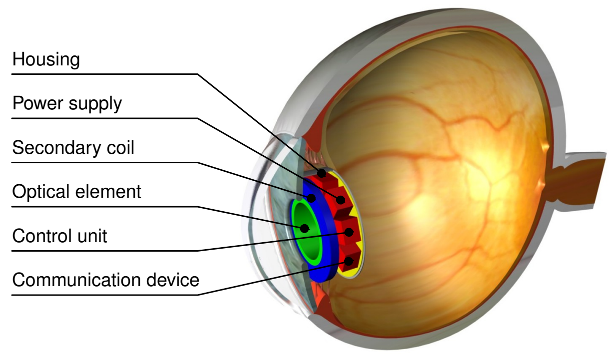

Fig. 1. Location of the Artificial Accommodation System within the eye after implantation.

II. CONSTRAINTS AND REQUIREMENTS

The external geometry of the Artificial Accommodation System can be described as a cylinder with a diameter of 10 mm and an axial length of 4 mm. The rotational axis of the cylindrical geometry coincides with the optical axis of the Artificial Accommodation System and the optical axis of the patient's eye. Inside the Artificial Accommodation System, a cylindrical space of 5 mm in diameter around the optical axis is reserved for the optical element. The annulus around the optical element serves to house all other subsystems including the energy supply system [6].

The Artificial Accommodation System with all its subsystems is expected to have an integral power consumption of a maximum of 1 mW of electrical power. One major requirement for the realization of the Artificial Accommodation System is an autonomous, minimum run time of 24 h without recharging or user interaction. This means, if the Artificial Accommodation System is being supplied by an inductive power link, it needs to have an integrated battery with a capacity of a minimum of 24 mWh, supplying the System between recharge times. To comply with the requirements of the patient compliance, the battery has to be recharged in less than one hour. Taking into account the charging efficiency of the battery and all losses inside the charging circuit, a minimum of 50 mW of electrical power has to be transmitted over the inductive link to fully recharge the battery within one hour. Another major requirement for the Artificial Accommodation System is that all voltages have to stay below 40 V.

Because of the limited component space inside the Artificial Accommodation System, the volume of the secondary coil has to be as small as possible. Therefore the secondary coil was chosen to be structured onto the flexible circuit board of the Artificial Accommodation System in form of a planar coil around the optical element (depicted blue in figure 1). The manufacturing process chosen for the printed circuit board [7] allows four signal layers with a variable thickness of the conductive gold layer of up to 20 µm. Depending on the layer stack-up this results in a total thickness of the board of approximately 50 µm. The achievable clearance for a coil with a conductor height of 20 µm is 25 µm.

As a good compromise between transfer efficiency and compliance with international regulations 13.56 MHz has been chosen as the operation frequency for the inductive power link.

After the amount of power to be transferred is known, a first step to realize an inductive power link for the Artificial Accommodation System is the optimization of the layout of the secondary coil of the inductive link. The objective of this paper is to describe an analytical way to optimize critical design parameters of the secondary coil layout depending on the said constraints based on an universal figure of merit.

III. Universal figure of merit for optimal secondary coil layout

The figure of merit to calculate optimal coil parameters can be derived from a simplified schematic of the inductive link which is shown in figure 2. The circuit shows the resonant primary and secondary parts of the link. To attain a high current and therewith a high field strength the primary coil is serially compensated with a capacitance. To keep losses inside the secondary coil low, it is advantageous to keep the current inside the secondary coil low and the voltage above the coil high. This is achieved by introducing a parallel capacitance to tune the secondary circuit to the operating frequency. In figure 2 R_1 and R_2 describe the resistances of the primary and secondary coils L_1 and L_2. C_1 and C_2 are the respective compensation capacitances for the primary and secondary coils to keep them in resonance at the operating frequency. R_L stands for the resistance of the load and

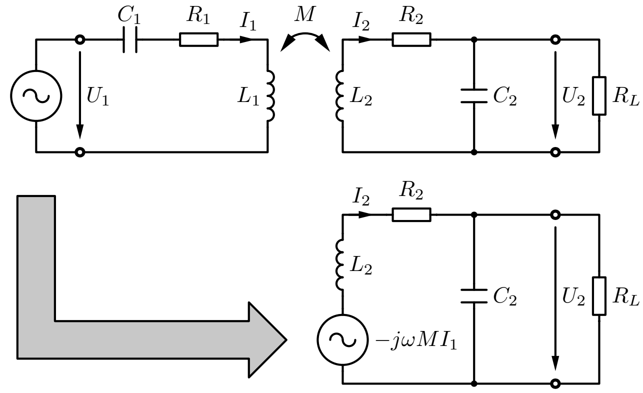

Fig. 2. Equivalent circuit diagram for the inductive power link.

M describes the mutual inductance between L_1 and L_2. By means of a transformation of the primary part into the secondary part, the influence of the primary coil current can be modeled as a voltage in the secondary circuit. In consequence we get the transfer function between secondary output voltage U_2 and primary coil current I_1 as follows:

$$\frac{U_2}{I_1} = \frac{\omega\, M}{\sqrt{(1 + \frac{R_2}{R_L} - \omega^2\, L_2\, C_2)^2 + (\omega\,(\frac{L_2}{R_L} + R_2\, C_2))^2}} \quad (1)$$

with ω as operating frequency, the mutual inductance M, the parasitic resistivity of the secondary coil R_2 and the inductance of the secondary coil L_2.

The coupling factor k is a measure for the amount of the magnetic flux of a primary coil penetrating a winding of a secondary coil. A coupling coefficient of 1 means that the field of the primary coil fully penetrates the secondary coil and vice versa. The coils are tightly coupled. A coupling coefficient of 0 consequently describes a situation where primary and secondary coils are practically not influenced by each other. The coupling coefficient of two coils is defined as follows [8]:

$$k = \frac{M}{\sqrt{L_1 \cdot L_2}} \quad (2)$$

With this definition of k, equation (1) can be rewritten in the following form:

$$\frac{U_2}{I_1} = \frac{\omega \cdot k\,\sqrt{L_1 \cdot L_2}}{\sqrt{(1 + \frac{R_2}{R_L} - \omega^2\, L_2\, C_2)^2 + (\omega\,(\frac{L_2}{R_L} + R_2\, C_2))^2}} \quad (3)$$

The ration between U_2 and I_1 described by equation 3 still depends on properties of the primary coil. To get a figure of merit which only depends on parameters of the secondary coil, without loss of generality, the geometry of the secondary coil and the coil alignment is kept constant ($k = \mathrm{konst}$ and $L_1 = \mathrm{konst}$) during optimization.

In case of resonance the inductive reactance and the capacitive reactance of the secondary coil L_2 and their corresponding compensation capacitance C_2 are inverse.

$$jX_L - jX_C = 0 \rightarrow j\omega\, L = \frac{1}{j\omega\, C} \quad (4)$$

This assumption is independent from the resonance in the primary circuit which only serves to increase the primary coil current.

If the secondary circuit is fully in resonance at the operating frequency, the figure of merit to calculate optimal geometrical parameters for the secondary coil can be written as follows:

$$\frac{U_2}{k\, I_1\, \sqrt{L_1}} = \frac{\omega \cdot \sqrt{L_2}}{\sqrt{(\frac{R_2}{R_L})^2 + (\frac{\omega\, L_2}{R_L} + \frac{R_2}{\omega\, L_2})^2}} \tag{5}$$

The described ratio in equation (5) now only depends on properties of the secondary coil and the equivalent resistance of the connected load. So it is possible to optimize the secondary coil on basis of equation (5).

Based on the said manufacturing process, the secondary coil of the link has a planar spiral shape. The self inductance of this spiral coil can be calculated by means of formula (6) [9]. With this formula the self inductance is determined with a deviation smaller than 5 % [9] from the exact value.

$$L_2 \approx \frac{1}{2}\mu_0 N^2 d_{avg}\left[\ln\left(\frac{2.46}{\varrho}\right) + 0.2\varrho^2\right], \tag{6}$$

where μ_0 is the permeability of vacuum, N is the number of turns of the coil, $d_{avg} = (d_{out} + d_{in})/2$ is the mean diameter of the coil and ϱ is the ratio between width of the single turns and the diameter of the coil. ϱ is defined as follows:

$$\varrho = \frac{d_{out} - d_{in}}{d_{out} + d_{in}} \tag{7}$$

Because of the skin-effect, the reduced depth of penetration of the current inside the conductor has to be calculated to get correct results. The resulting resistance can be derived from the following approximation [10]:

$$R_2 = \pi \cdot N \cdot \rho \cdot d_{avg} \cdot \left(\frac{1}{h \cdot w} + \sqrt{\frac{\omega\mu}{8\rho}}\,\frac{1}{h + w}\right) \tag{8}$$

The parasitic resistance of the coil at high frequencies follows from the number of turns N, the specific conductivity of the conductor ρ, the operating frequency ω, the permeability $\mu = \mu_0 \cdot \mu_r$ of the enclosing medium around the coil and the geometric parameters of the coil itself, namely the mean diameter d_{avg} as well as the height h and width w of the conductor.

In the following section the results of the optimization of the secondary coil planned to be used within the Artificial Accommodation System is described.

IV. Figure of Merit Applied to the Secondary Coil Design of the Artificial Accommodation System

As described previously the constraints for the design of a secondary coil inside the Artificial Accommodation System are mostly space requirements. The volume to place components inside the implant is very limited. So the outer diameter of the coil is limited to 9.8 mm by the inner diameter of the housing of the implant. The inner diameter of the coil is specified by the outer diameter of the optics which will be 5 mm. The thickness of the coil is predefined by the substrate of the flexible circuit board and therewith is around 50 µm.

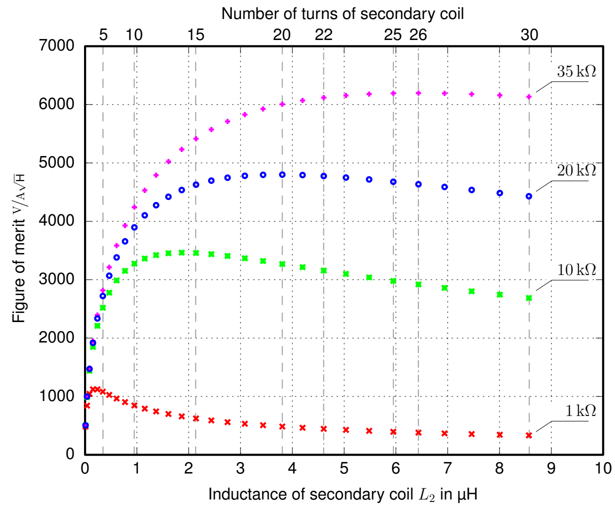

Fig. 3. Figure of merit for different coil geometries at various load resistances.

The goal of the following optimization is to find the optimum number of turns N for the secondary coil depending on the equivalent load resistance. The load resistance can easily be calculated from the power required inside the Artificial Accommodation System, which is 50 mW, and the highest voltage tolerated inside the implant (40 V) and therewith equals 35 kΩ. If the maximum voltage tolerable inside the implant is lower, the equivalent load resistance decreases while the same amount of power is transferred. To find the optimal number of turns, the figure of merit $U_2/(k\,\sqrt{L_1}\,I_1)$ described by equation 5 is shown in figure 3.

As depicted in figure 3 the maximum amplification at 35 kΩ is at $N = 26$ windings. If the output voltage is decreasing, which results in a lower equivalent load resistance, the optimum number of turns of the secondary coil are decreasing, too. To show this effect the trend of the figure of merit with load resistances of 20 kΩ, 10 kΩ and 1 kΩ are shown in figure 3, too.

The properties of the optimal secondary coil for the Artificial Accommodation System are listed in table I. As depicted in figure 3, at an optimum load resistance of 35 kΩ, a slight decrease of the number of turns, for example to 22, results in just a small decrease in the figure of merit. This can be exploited to increase the production yield of the coils during manufacturing without significant losses in transfer efficiency.

V. Conclusion

After a short introduction into the Artificial Accommodation System, the presented contribution examines the possibility of an analytical optimization of the design of a secondary coil for an inductive power supply. Therefore a new figure of merit to optimize the inductive link is demonstrated. The figure of merit allows an optimization of the secondary coil design. All influences of the primary circuit and geometrical properties of the link are omitted. One prerequisite for this to work is, that the secondary part

TABLE I
PROPERTIES OF THE OPTIMAL SECONDARY COIL FOR TRANSMISSION OF 50 MW INTO THE ARTIFICIAL ACCOMMODATION SYSTEM.

Optimal secondary coil	
Outer diameter:	9.8 mm
Inner diameter:	5 mm
Height:	40 µm
Conductor height:	20 µm
Conductor clearance:	25 µm
Windings:	26
Inductance:	6.43 µH
Resistance:	10.53 Ω
Quality factor:	52

is in resonance at the operating frequency of the link. In a last step the new figure of merit was used to optimize the geometrical parameters of the secondary coil for the inductive power link of the Artificial Accommodation System. It could be shown that under given constraints, a coil with 26 turns is optimal for the Artificial Accommodation System. Although the optimization was exemplified on basis of the Artificial Accommodation System, it can be used to optimize the secondary coil design of any resonant inductive power link.

ACKNOWLEDGMENT

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