

PERFORMANCE EVALUATION OF A WIRELESS CHARGING CONVERTER FOR ACTIVE IMPLANTABLE MEDICAL DEVICES

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Abstract

This paper evaluates the performance of a wireless power transfer (WPT) converter for active implantable medical devices (AIMDs). The efficiency is the key parameter in the design of a WPT converter for charging of AIMDs. The compensation topology of a WPT system has an important role for high efficiency power transfer. Thus, this work analyses a WPT converter using LC/S hybrid compensation topology, for wireless charging of AIMDs, in terms of high efficiency power transfer. In the efficiency analyses, the WPT converter is tested by 3D electromagnetic simulation software. The maximum efficiency is obtained as 72.33% while the output voltage is 4.2 V and the current is 0.45 A. Finally, safety performance of proposed WPT converter is also evaluated based on specific absorption rate (SAR) analysis. The average peak spatial head/torso SAR produced by WPT converter is obtained as 0.0254 W/kg, which is lower than recommended restrictions.

Keywords: Wireless Power Transfer, Active Medical Device, Efficiency Performance, SAR

VÜCUT İÇİNE YERLEŞTİRİLEBİLEN AKTİF MEDİKAL CİHAZLAR İÇİN KABLOSUZ ŞARJ EDEN BİR DÖNÜŞTÜRÜCÜNÜN PERFORMANS DEĞERLENDİRMESİ

Özet

Bu çalışma, vücut içine yerleştirilebilen aktif medikal cihazlar için kablosuz güç transferi (KGT) dönüştürücüsünün performansını değerlendirmektedir. Vücut içine yerleştirilebilen aktif medikal cihazların kablosuz güç transferi dönüştürücüsü tasarımında, verim önemli bir parametredir. Bu yüzden, bu çalışma LC/S hibrit kompensasyon topolojisini kullanan bir KGT dönüştürücüsünü yüksek verimli güç transferi açısından analiz etmektedir. Analiz çalışmasında, KGT dönüştürücüsü 3 boyutlu elektromanyetik simülasyon yazılımı ile test edilmiştir. Maksimum verim, çıkış gerilimi 4,2 V ve akımı 0,45 A durumunda iken %72,33 olarak elde edilmiştir. Son olarak, KGT dönüştürücüsünün emniyet performansı da özgül emilim oranı (SAR) analizi ile değerlendirilmiştir. Sunulan KGT dönüştürücüsü tarafından üretilen ortalama gövde/kafa maksimum SAR değeri 0,0254 W/kg olarak, tavsiye edilen sınırlamaların altında elde edilmiştir.

Anahtar Kelimeler: Kablosuz Güç transferi, Aktif Medikal Cihaz, Verim Performansı, SAR

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1. Introduction

The importance of active implantable medical device (AIMD) increases day by day due to their life saver functions. AIMDs can improve or treat the needed functions of some organs with the use of electrical sources surgically placed into the body [1].

The main problem of AIMDs is the limited life time of their battery. The depletion time of a battery, depending on the role and operation conditions, changes between 5 and 15 years [2], [3]. Then, the battery has to be replaced with another surgery operation, which can cause to risks like infection, rejection, etc. [4]. The use of rechargeable battery allows recharging the battery and this results in extended lifetime for the battery. The

wireless power transfer (WPT) method can be used to recharge the battery from the outside of the body [5]-[7]. The power transfer is provided with coupling coils, transmitter outside of the body and receiver inside of the body [8]-[11]. Therefore, at the outside of the body, a WPT converter providing power delivery to the receiver coil should be designed [12]-[14]. A WPT system for AIMDs should provide high efficiency and safety criteria to be implanted.

The compensation network has important role to provide high efficiency power transfer. The well-known compensation networks, in the literature, are series-series (SS), series-parallel (SP), parallel-parallel (PP) and parallel-series (PS) [15], [16]. PP and PS compensation networks are usually not preferred due to their poor efficiency [17]. In [5], a WPT system with SS and SP compensation network is presented for AIMDs. The power transfer efficiency capability of the WPT system is tested at 300 kHz and 13.54 MHz operation frequencies. SP network gives better efficiency at 300 kHz and SS network is better at 13.56 MHz in terms of efficiency.

In order to increase power transfer efficiency of a WPT system, the hybrid compensation networks also exist in the literature [18]-[20]. In [18], a hybrid compensation network including additional inductor, capacitor and switch is presented to operate overall charge control mode of the battery. In [19], S/SP compensation network is presented to improve output voltage control capability of the WPT converter. In [20]-[21], double-sided LCC compensation network is presented to charge the electrical vehicle battery. Double-sided LCC compensation network improves the overall charge control modes of the battery and eliminates one inductor of hybrid topologies mentioned earlier. However, double-sided LCC compensation network is not good candidate for AIMDs application due to the number of components at the receiver side. An LCC-C compensation network is presented for pacemaker applications in [22], with series compensation of the receiver side. The design of the WPT system is implemented taken into consideration of real pacemaker device and pig tissues. In [23], an LC/S hybrid compensation network is presented to improve the response of constant current charge control mode. The operation of the compensation network is tested at 85 kHz operation frequency. The constant current operation response of the LC/S topology is better than double-sided LCC compensation network. Besides, fewer component number presents size and cost advantages compared to LCC compensation network.

In this work, power transfer efficiency performance of a WPT converter with LC/S compensation network is evaluated for AIMDs applications. The basic principles and operation of the compensation network is presented. The receiver coil of WPT converter is modeled by 3D magnetic simulation software, taken into account of human tissues and real AIMD dimensions. Then efficiency and safety performance of the converter

is tested by electromagnetic simulation at 300 kHz operation frequency. The efficiency variation as function of different distances between transmitter and receiver coils is also extracted. The maximum efficiency is obtained as 72.33% at 8 mm distance while the output voltage is 4.2 V and the current is 0.45 A. Finally, a safety performance evaluation is also presented based on electromagnetic field (EMF) produced by proposed WPT converter. According to the safety performance analysis, the average peak spatial head/torso specific absorption rate (SAR) produced by WPT converter is 0.0254 W/kg and it is found within the recommended limits.

2. LC/S Hybrid Compensation Network for WPT Converter

The LC/S compensation network topology is shown in the circuit scheme of WPT converter, given in Figure 1. Where L_1 - C_1 - C_5 represent the compensation components for transmitter and receiver sides. L_p and L_s are the coupling coils providing energy transfer to the load. D_{R1} - D_{R4} diodes produce the dc output voltage, C_F is the filter capacitor and R_L represents the load. U_1 is the input power source, V_B is the battery voltage and M is the mutual inductance between coupling coils.

The voltage gain of the converter can be extracted with M model approach as given in [23] and it can be written as follows:

$$G_{LC/S} = \frac{V_B}{V_{in}} = \frac{2\sqrt{2}j\omega M Z_{C1}}{\pi Z_S (Z_r + j\omega L_p)(Z_{C1} + j\omega L_1)} \times R_{ac} \quad (1)$$

Where Z_S is the impedance of the receiver side, Z_r is the reflected impedance from the receiver side. Z_{C1} represents the equivalent impedance of C_1 , L_p and Z_r . These impedances can be defined as follows:

$$Z_S = R_{ac} + \frac{1}{j\omega C_5} + j\omega L_s \quad (2)$$

$$Z_r = \frac{\omega^2 M^2}{Z_s} \quad (3)$$

$$Z_{C1} = \frac{(Z_r + j\omega L_p) \frac{1}{j\omega C_1}}{Z_r + j(\omega L_p - \frac{1}{\omega C_1})} \quad (4)$$

Above, ω is the angular operational frequency, R_{ac} represents the ac equivalent resistance of the rectifier, output filter and resistive load. Thus, R_{ac} can be defined as below:

$$R_{ac} = \frac{8}{\pi^2} R_L \quad (5)$$

The efficiency of WPT converter can be defined as

$$\eta = \frac{P_o}{P_{in}} \quad (6)$$

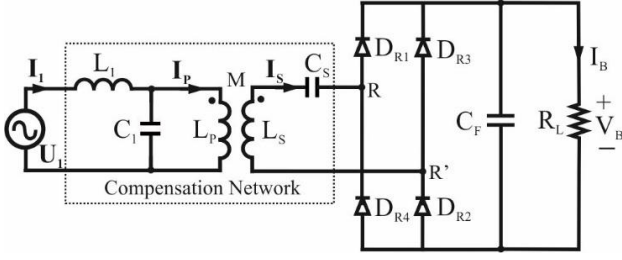


Figure 1. The circuit schematic of WPT converter with LC/S compensation for implantable AIMDs.

Where P_o is the output power and it can be written as

$$P_o = I_s^2 R_{ac}. \quad (7)$$

Where I_s is the current flowing through the receiver side and it can be defined as below:

$$I_s = \frac{j\omega M I_p}{Z_s}. \quad (8)$$

The input power of the transmitter side is defined by

$$P_{in} = I_1 V_1 \cos \alpha_{in}. \quad (9)$$

Where I_1 is the input current of the transmitter side of WPT converter and it can be defined as follows:

$$I_1 = \frac{V_1}{Z_{in}}. \quad (10)$$

Z_{in} is the input impedance of WPT converter and defined as

$$Z_{in} = Z_{C1} + j\omega L_1. \quad (11)$$

The $\cos \alpha_{in}$ is the phase angle between V_s and I_s . The phase angle can be extracted from the input impedance, as given below:

$$\cos \alpha_{in} = \frac{\text{Re} |Z_{in}|}{|Z_{in}|}. \quad (12)$$

3. Performance Evaluation of WPT Converter for AIMDs

In the performance evaluation of the converter, the change of the output voltage is accepted between 3.8 V and 4.2 V taken into consideration of the most used Lithium-ion battery cells. The performance of the converter is tested with an electromagnetic simulation at 300 kHz operation frequency. The coupling coils of the converter are modeled with 3D electromagnetic field simulation using finite element method (FEM). In order to see operation of the modeled coupling coils, a

transient 3D field-electric common simulation is performed. Then a safety performance evaluation is carried out based on EMF produced by WPT converter. The design of coupling coils, transient simulation results and safety performance analysis are separately presented in the following sections.

3.1. The Coupling Coils

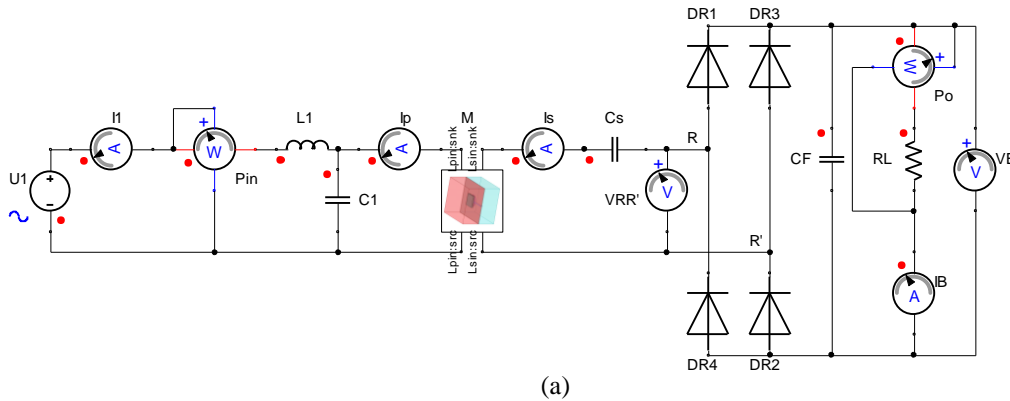
The design of coupling coils had an importance to improve the performance of power transfer efficiency. The coupling coils are designed in planar circular form. The external dimension of the transmitting coil is determined to be little larger than the receiving coil in case of any position alignment failure between coupling coils. A titanium case representing AIMD's shell is modeled and a thin ferrite film is placed between the receiver coil and titanium case in the simulation work, in order to decrease the effects of the induced Eddy current losses on the titanium case. The geometrical properties of the circular coupling coils are listed in Table I. In the determination of self-inductance of the receiver side, the ferrite film and the titanium case are taken into consideration. The transmitter coil is accepted in the air.

Table 1. The geometrical properties of circular coils.

Parameters	Transmitting Coil	Receiving Coil
External Diameter	53.4 mm	45.5 mm
Internal Diameter	18.3 mm	20.04 mm
Turns Number	13	9
Self-Inductance	6.75 μ H	4.66 μ H

3.2. Field-Electric Co-Simulation Analysis and Results

In this part, efficiency analysis of the WPT converter during the charge of the battery is evaluated. The circuit schematic and designed coupling coils are given in Figure 2. The modeled circular coupling coils are operated with 3D field-electric common simulation to obtain their transient response. The design specifications and used components in the simulation are given in Table II. The components of LC/S compensation are determined based on [23]. The input of the converter is fed from a sinusoidal ac source, U_1 . The rectifier diodes with 0.8 V voltage drop are used in the simulation work.



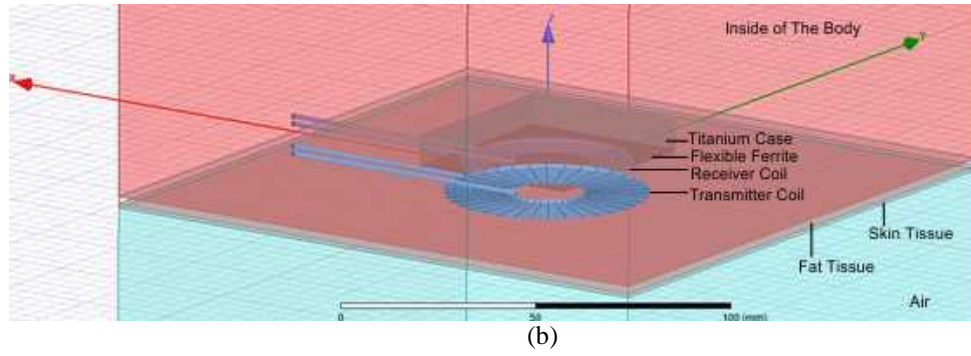
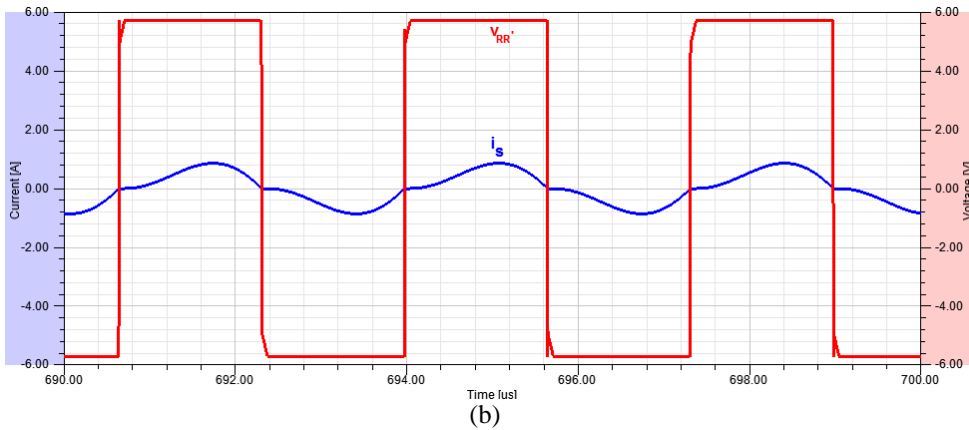
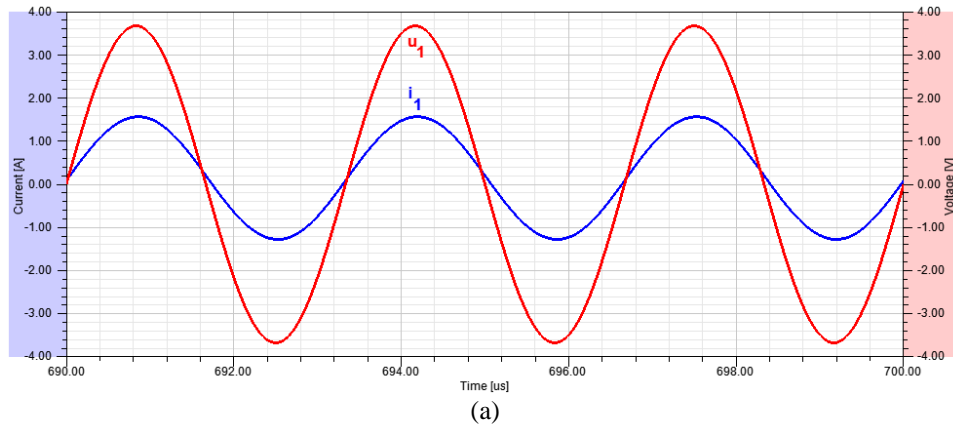


Figure 2. (a) The circuit schematic of the simulated WPT converter. (b) The circular coupling coils modeled 3D electromagnetic field simulation.

Table 2. Design specifications and used components in the simulation work.

$I_o=0.45$ A, $V_B=3.8$ V - 4.2 V	
$f_{sw}=300$ kHz, $U_1=2.59$ V _{RMS} ,	
$k=0.46$	
L_P	6.75 μ H
L_S	4.66 μ H
M	2.57 μ H
L_1	6.75 μ H
C_1	83.36 nF
C_S	60 nF
C_o	10 μ F

The simulated voltage and current waveforms of the WPT converter are given in Figure3. Figure 3 (a) and (b) show the current and voltage waveforms of the input source and the rectifier. As shown in the simulated results, the voltage and the current of the input source and the rectifier are in same phase. Thus, WPT converter operates at resonant frequency and transfers the maximum power to the load. Figure 3(c) gives rectified current and the voltage waveforms that will charge the battery.



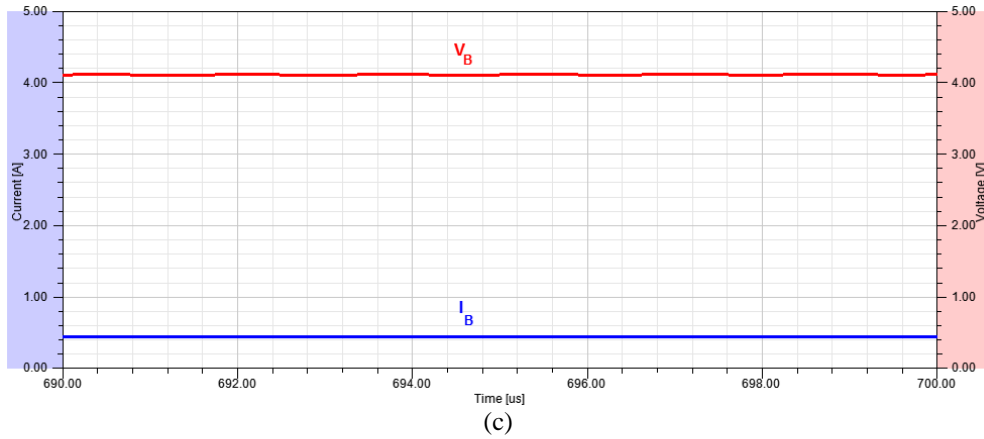


Figure 3. Simulated results. (a) The voltage and current waveforms of the input source (i_1 and u_1). (b) The current waveform of receiving coil and the input voltage waveform of the rectifier (i_S and v_{RR}). (c) The rectified voltage and current waveforms of the WPT converter (V_B and I_B).

The maximum efficiency of the WPT converter is extracted as 72.33%, while the output voltage is 4.2 V and the load current is 450 mA. The variation of the efficiency for different distances is also extracted and the obtained results are given in Figure 4. As shown in Figure 4, efficiency values are decreased while the distance between coupling coils are increasing, as expected. The efficiency is very low after 30 mm distance. The mutual inductance value between the transmitter and the receiver coils also decreases with the increase of the distance, as shown in Figure 5. Therefore, WPT converter with LC/S compensation can be used for active medical devices implanting until 30 mm depth into the body.

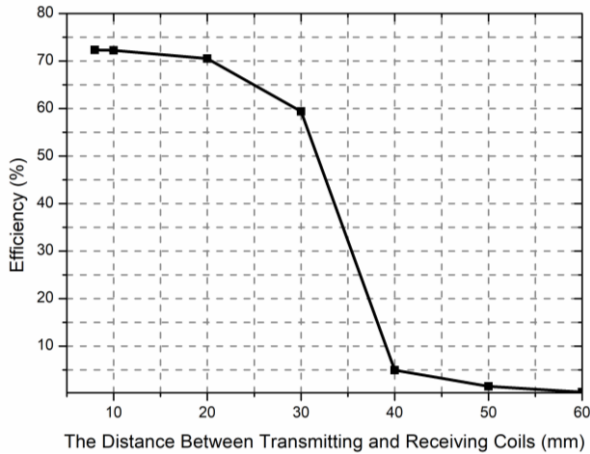


Figure 4. The efficiency variation of WPT converter based on distance variation between two coupling coils.
 $V_B=4.2$ V, $I_B=450$ mA.

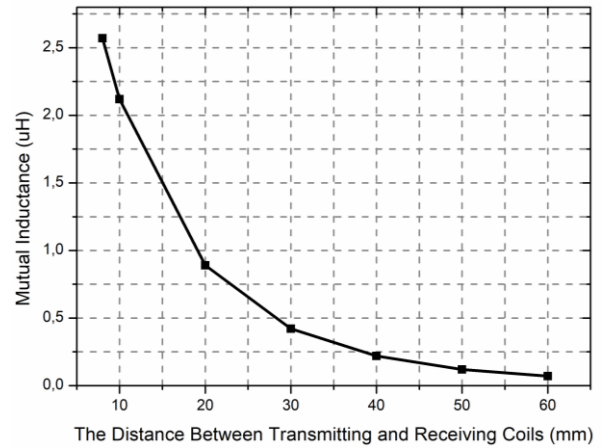


Figure 5. The mutual inductance variation of WPT converter based on distance variation between two coupling coils.

3.3. Safety Evaluations

After efficiency evaluations of WPT converter, the reliability of the system is analyzed based on SAR. In the safety analysis, Commission on Non-Ionizing Radiation Protection (ICNIRP) and the Institute of Electrical and Electronics Engineers (IEEE) presenting basic limits for SAR effects are taken into consideration [24], [25]. The simulated currents, 1.12 A through transmitting coil and 0.6 A through receiving coil, are used for the simulations of SAR analysis.

In order to evaluate the safety performance of WPT converter, an upper body 3D model including head and torso, exist in 3D simulation software, is used. The distance between the receiving and the transmitting coils is accepted as 8 mm. The analysis results of average SAR for 10 g human tissues is given in Figure 6. The produced SAR by WPT converter and its comparison with recommended limits are given in Table III. According to analysis results, for 10 g human tissue, average peak spatial SAR produced by WPT converter is 0.0254 W/kg and this value is much lower than the 2 W/kg recommended by ICNRP and IEEE.

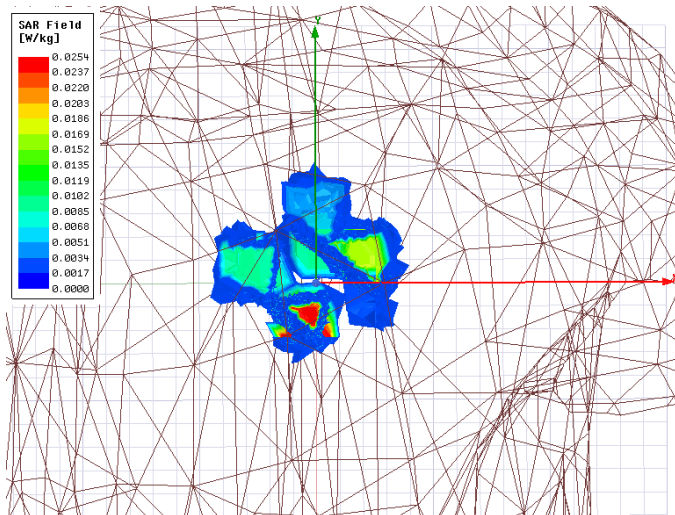


Figure 6. The SAR analysis, in the human tissues, obtained by upper body 3D FEM.

Table 3. The localized head/torso SAR produced by WPT converter and recommended SAR limits.

The Localized Head/Torso SAR Values		
Basic Restrictions		Produced by WPT converter
ICNRP	IEEE	3D FEM Simulation
2 W/kg	2 W/kg	0.0254 W/kg
100 kHz-6 GHz	100 kHz-6 GHz	300 kHz

In the operation of the presented WPT converter, induced Eddy currents on the AIMD's shell reduces the induced voltage across the receiving coil. Therefore, the required energy transferred from the transmitting coil should be increased in order to provide the charge of the battery. However, increased energy from the transmitting coil can cause to damage human tissues. A thin ferrite film can help to reduce the Eddy current losses on the AIMD's shell [22]. If ferrite film is not enough for magnetic shielding, precise implant position of receiving coil can be determined as presented in [26], in the real clinical applications of the presented WPT converter.

4. Conclusion

In this work, a WPT converter with LC/S compensation is presented for AIMDs. The performance of the converter is evaluated based on power transfer efficiency. Transmitting and receiving coils are magnetically modeled and an electric-field common simulation is carried out to obtain transient response of the converter. The simulation results shows the power transfer capability of the WPT converter. The power transfer is provided with approximately zero phase angle between voltage and current of the input source and the rectifier. The maximum efficiency is obtained as 72.33 % at full load condition. The decrease of the efficiency, with the increase of distance, is validated by simulation work. According to safety performance of the WPT converter, average peak spatial SAR produced by

the WPT converter is obtained as 0.0254 W/kg and within the limits recommended by ICNRP and IEEE.

5. Acknowledgment

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