

Finite Element Simulation-Based Analysis of Electromagnetic Properties of Biological Tissues on Transmission Performance of Implantable Wireless Charging Systems

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Abstract. Wireless charging technology for implantable medical devices has received significant consideration due to its non-contact property. However, its transmission efficiency and safety are deeply influenced by the electromagnetic characteristics of human body tissues. To quantify this effect, this study utilizes ANSYS Maxwell software to build up a simulation model that includes the coil and human body tissue based on finite element analysis and systematically analyzed the working mechanisms of conductivity, permeability, permittivity and the mechanical structure of the coil on determining the magnetic coupling coefficient. The results have shown that, the conductivity of tissues and the misalignment of coil are the main reasons that leads to the decrease of k , while the influence of permittivity in a magnetic coupling dominant mechanism has a negligible impact. Incorporating ANSYS Simplorer to conduct a circuit-level simulation, this study further evaluates the final transmission efficiency and risks for tissue heating of the system, and certified the appropriate range of working frequency (0.1MHz-10MHz) reconciles both high efficiency transmission and biological safety. This study provides essential evidence of design and data support for optimizing the transmission coil and selecting the frequency for implantable medical devices of wireless power transfer system.

Keywords: Wireless Power Transfer, Magnetic Coupling Coefficient, Implantable Medical Devices, Biological Electromagnetic Properties, Finite Element Analysis.

1. Introduction

Wireless power transfer technology provides an ideal solution to electricity supply for implantable medical devices (like cardiac pacemaker and nerve stimulator) and overcomes the risks of battery-life limitations and infections caused by transdermal charging. The core mechanism is based on near-field magnetic coupling resonance. However, as complex and inhomogeneous medium, the tissues of human body have conductivity, permeability and permittivity that would disturb the distribution of electromagnetic field significantly. It would not only decrease the magnetic coupling coefficient and transmission efficiency, but also cause partial temperature rise due to eddy currents and dielectric loss, leading to safety problems [1].

Although research on magnetic coupling wireless transfer is becoming widespread, the majority focuses on free space or coil optimization in simple medium. At present, there is a lack of systematic and quantification research that aims on investigating how the synergistic impact of a variety of electromagnetic parameters of human body tissue and mechanical structure of transmission coil would affect the transmission performance of the system. Therefore, it is essential to determine the sensitiveness of each parameter on the value of magnetic coupling coefficient and sort out the relationship to the final transmission efficiency. This is pivotal for designing a safe and efficient implantable charging system.

This research aims to quantify the key electromagnetic parameters of human body tissue (conductivity, permeability and permittivity) and the mechanical structure of the coil (alignment and spacing) independently and alternately on the value of k and restrict on the transmission efficiency through circuit simulation systematically using finite element simulation. The structure of the thesis is arranged as follows: Chapter two would elaborate the basic theories of magnetic coupling wireless charging, electromagnetic features of biological tissue and the method of establishing the simulation

model; Chapter three will present and further analyze the simulation results of each parameter and reveal its pattern for influencing the value of k ; Chapter four will make a conclusion of the study and elaborate the limitations and directions for optimizations and propose on future development.

2. Basic Theories and Simulation Method

2.1. The Principle of Magnetic Coupling Wireless Power Transfer and its Efficiency Relations

The core of magnetic coupling wireless power transfer system is the primary coil (Tx) and secondary coil (Rx). Its working principle is based on Faraday's law of electromagnetic induction. The alternating current produces an alternating magnetic field in the primary coil, which passes through the secondary coil and induces electromotive force and current. In this way, electric energy is transferred [2]. The physical quantity that measures the tightness of coil coupling is magnetic coupling coefficient (k), it is defined by:

$$k = \frac{M}{\sqrt{L_p L_s}} \quad (1)$$

Where M is mutual inductance of the primary and secondary coil, L_p and L_s corresponds to the self-inductance of the primary and secondary coil, respectively. For a magnetic coupling resonant WPT system, the maximum theoretical transmission efficiency (η) is closely related to the value of k and the quality factor of the coil (Q). The k value directly determines the "width" of the energy transmission pathway [3]. The quality factor Q is a dimensionless parameter that measures the ratio of energy storage or component energy storage and energy consumption per cycle. The higher of Q , the less of energy loss, the sharper the resonant frequency selection. A simplified expression is:

$$\eta = \frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2} \quad (2)$$

From this equation, the magnetic coupling coefficient (k) is one of the key factors determining the upper limit of transmission efficiency. Any factor that causes a decrease in k would decrease the maximum transmission efficiency of the system directly and significantly. Therefore, the nature of this research investigating the influence of each parameter on k , is to reveal their restriction pattern on the final transmission efficiency of the system.

2.2. The Electromagnetic Characteristics of Biological Tissues and their Effects on Coupling and Efficiency

Biological tissues would show three main features in an electromagnetic field. They would affect the magnetic coupling coefficient (k) under different frequencies and lead to energy loss, thereby changing the efficiency (η) [4]:

(1) Conductivity (σ): Tissues with high conductivity (like muscle and blood) would induce a great eddy current in an alternating magnetic field. These induced currents would produce two main effects: (1) producing a secondary magnetic field that would weaken the initial magnetic field and decreasing k ; (2) Leading to ohmic loss, which transfers the energy of magnetic field directly into heat, thereby decreasing the transmission efficiency. These are the main negative effects that affect the value of k and η .

(2) Permeability (μ_r): The majority of biological tissues have $\mu_r \approx 1$. If μ_r increases, it would divert the pathway of magnetic field lines, leading to a weakened magnetic field reaching at the secondary coil, which decreases the value of k . The magnetic loss tangent is a physical quantity that measures the degree of energy loss of magnetic materials in an alternating magnetic field. It codetermined the electromagnetic performance of the material along with permeability. Simulations that account for the correlation between permeability and magnetic loss tangent can more accurately model material behavior at high frequencies, thereby enhancing the reliability of the calculation results.

(3) Permittivity(ϵ_r): Biological tissues often have high permittivity. In a magnetic coupling dominant WPT system, the displacement current produced by polarizing effect would have a relatively small impact on the distribution of magnetic field distribution. Therefore, its impact on k value can often be negligible, but may slightly change the efficiency of the system under higher frequencies through dielectric loss. The reason why dielectric loss and dielectric constant are considered as the same factor is that they together form the complex dielectric constant in complex form, which completely describes the energy storage and loss behavior of materials in an electric field. The study of dielectric loss is crucial for evaluating the performance of materials in devices such as capacitors, and it can also reveal their microstructure and dynamic processes.

2.3. The Effect on k due to the Mechanical Structure of the Wireless Charging Coil

The mechanical structure of the coil, including its shape, size parameters, and alignment, significantly impacts the coupling coefficient. The radius and number of turns of the coil would determine the range and intensity of the magnetic field distribution. However, when the transmitting and receiving coils are axially or radially offset, the overlapping area of the magnetic fields decreases, resulting in a reduction in the coupling coefficient.

2.4. Setting up the Simulation Model

ANSYS Maxwell eddy current field analysis is employed to construct a geometric model that includes transmitting/receiving coils and human tissues (muscle, subcutaneous tissue) [5]. As shown in Figure 1(a), the transmitting coil (light green) has a segmented dodecagonal spiral structure with a rectangular cross-section of 4mm in height and 1mm in width. It has a starting radius of 20mm, with each turn increasing by 1.2mm in radius, 15 turns, 12 segments, a right-handed rotation, and a layer spacing of 0 mm.

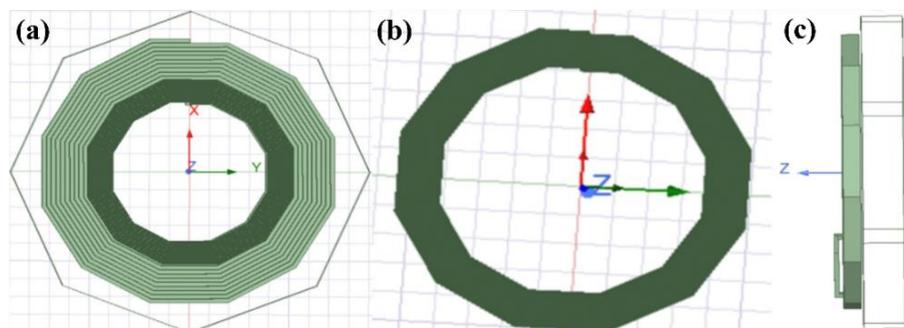


Figure 1. Schematic diagram of the coil structure (a) Primary coil (b) Secondary coil (c) Side view of primary and secondary coils

As shown in Figure. 1(b), the receiving coil (dark green) is a segmented dodecagonal spiral structure with a radius of 0.2mm. It has a starting spiral radius of 20mm, a radius variation of 0.45mm, 15 turns, 12 segments per turn, a right-handed rotation, and a layer spacing of 0mm. Figure. 1(c) shows the simulated side view of the coil device, with the transmitting coil, human muscle (white part) and receiving coil (placed inside the human body) in sequence from left to right. The parameters of human tissues refer to real data, such as the muscle with a dielectric constant of 18000, a dielectric loss of 180, and a conductivity of 0.2-5.5 S/m. The simulation frequency ranges from 1 kHz to 1 GHz, and the control variable method is used to change the parameters, outputting the k value and magnetic field distribution.

The magnetic field intensity obtained from the simulation using the initially designed wireless charging coil is shown in the Figure. 2.

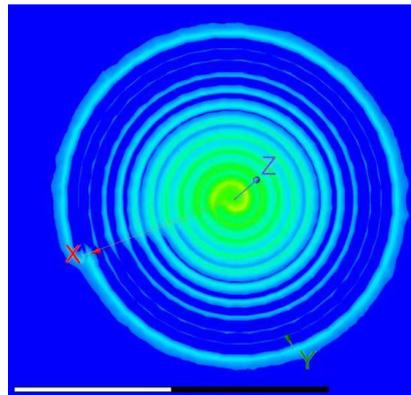


Figure 2. Magnetic Field Contour Map of the Spiral Coil

According to Ampère's right-hand grip rule, the magnetic fields generated by adjacent coils are in opposite directions, causing the outer magnetic field to cancel part of the inner magnetic field. The magnetic field at the outermost circle, having no outer coil to cancel it, is actually stronger than in some inner regions. However, overall, the magnetic field strength produced by the coils is still insufficient. Through simulations, it was found that using the aforementioned wireless charging coil configuration—i.e., increasing the starting radius dimensions of the wireless charging transmitting and receiving coils—can avoid the cancellation of magnetic fields from coils on both sides due to directional differences, thereby enhancing the magnetic field strength in the central region. The Figure. 4 is called a magnetic flux density cloud map, which visually shows the spatial distribution of magnetic field strength through color gradients; the vector diagram on the left Figure. 3 uses arrows to simultaneously present the magnitude and direction of the magnetic field.

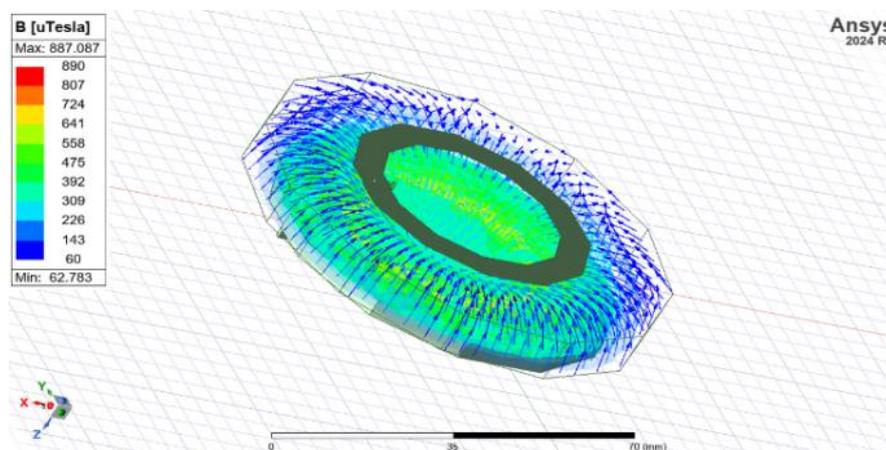


Figure 3. Optimized coil design of Magnetic field vector diagram

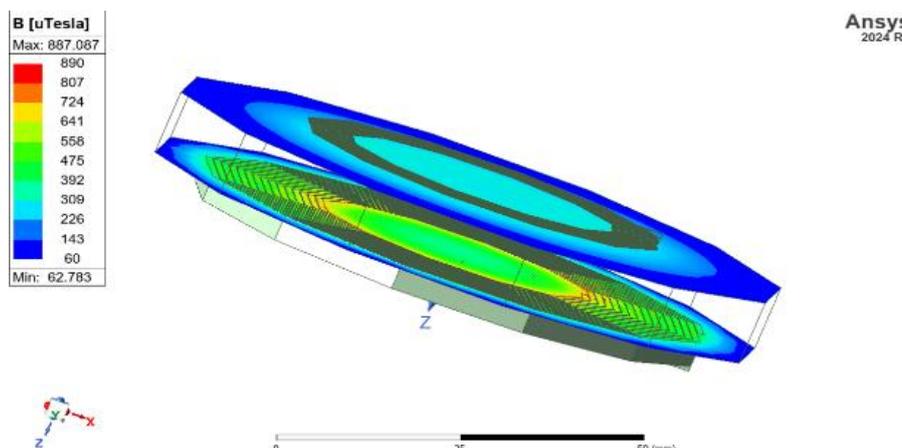


Figure 4. Optimized coil design of Magnetic field cloud map

3. Simulation Results and Data Analysis

This study simulated the effects of human body media with varying conductivity and permeability (including magnetic loss tangent) on the coupling coefficient at 1 MHz. It also investigated the effect of permittivity (including dielectric loss) on k across different frequencies [6].

3.1. The Effect of Mechanical Structure of the Coil on k

The coil alignment (slide) and spacing (gap) have a significant impact on the k value [7]. At 150kHz, when the slide is 0cm and the gap is 10cm, the k value reaches a maximum of 0.288; when the slide increases to 40cm, the k value drops to -0.005; when the gap increases from 10cm to 20cm, the k value decreases from 0.288 to 0.079 (Figure. 5). This is because an increase in spacing or misalignment reduces the overlapping area of the coil magnetic fields, leading to a decrease in the magnetic flux passing through the secondary coil and weakened coupling [8].

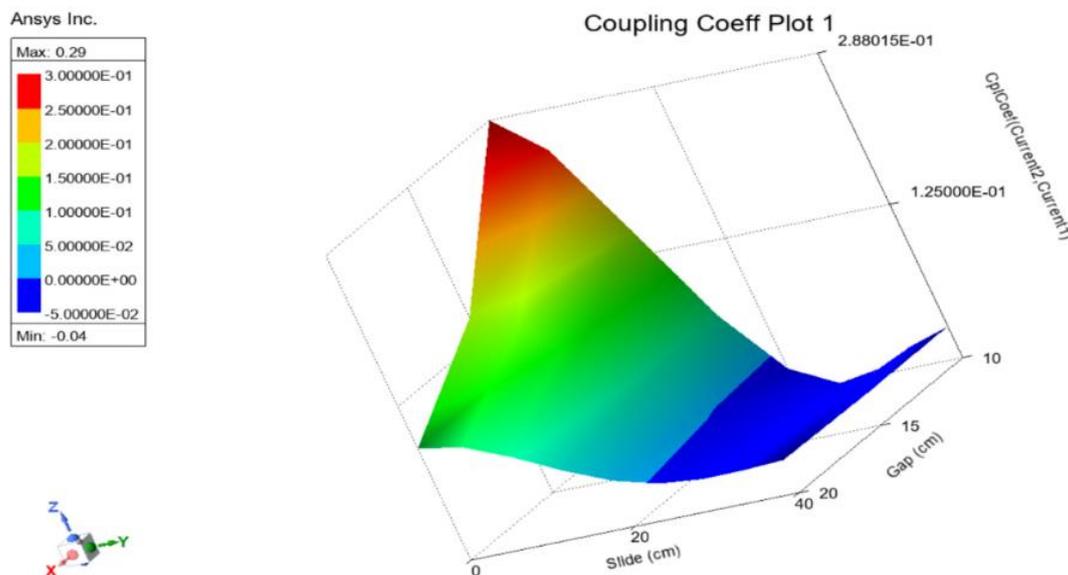


Figure 5. Influence of Coil Mechanical Alignment and Coil Spacing on Coupling Coefficient

3.2. Influence of Electromagnetic Parameters of Human Tissues (Dielectric Materials) on Coupling Coefficient

3.2.1. Influence of Conductivity (σ)

The conductivity has the most significant impact on the k value. At 1MHz, when σ increases from 0.01S/m to 10000S/m, the k value decreases from 0.323 to -0.078 (Figure. 6) (this negative value may cause polarity reversal). Tissues with high conductivity (such as muscles) can generate strong eddy currents, which shield the magnetic field and weaken the coil coupling. Moreover, the higher the frequency, the more obvious the eddy current loss, and the faster the k value decreases.

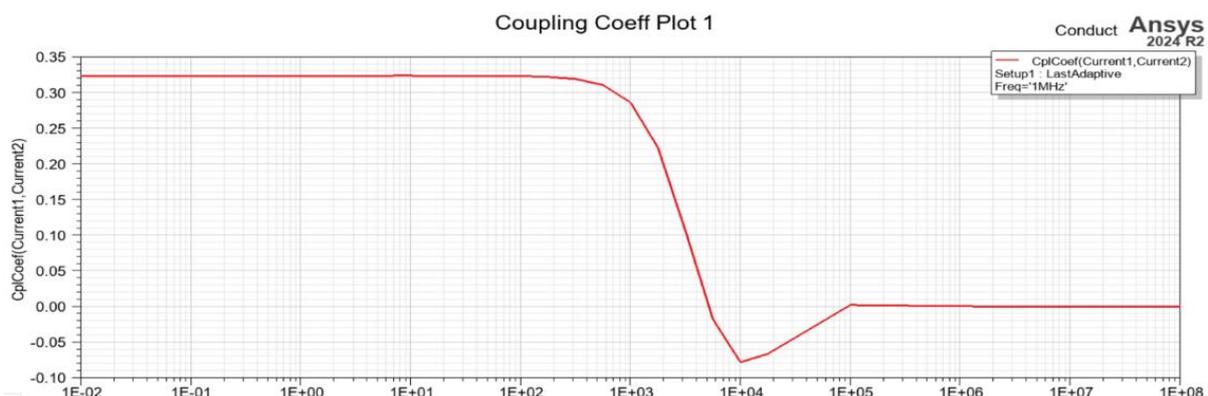


Figure 6. Influence of Conductivity on Coupling Coefficient

3.2.2. Effect of Permittivity (ϵ) and Dielectric Loss ($\tan\delta_\epsilon$)

When the dielectric loss is 0, as ϵ increases from 1 to 100,000, the k value remains stable between 0.316 and 0.323 without significant changes; even when the dielectric loss increases to 100, the k value still shows no notable fluctuations (Figure. 7). This is because wireless charging primarily relies on magnetic coupling, and dielectric parameters mainly affect capacitive losses, having a weak impact on magnetic field coupling. Only at high frequencies (>1GHz) does the dielectric loss have a slight influence, but the magnitude is negligible.

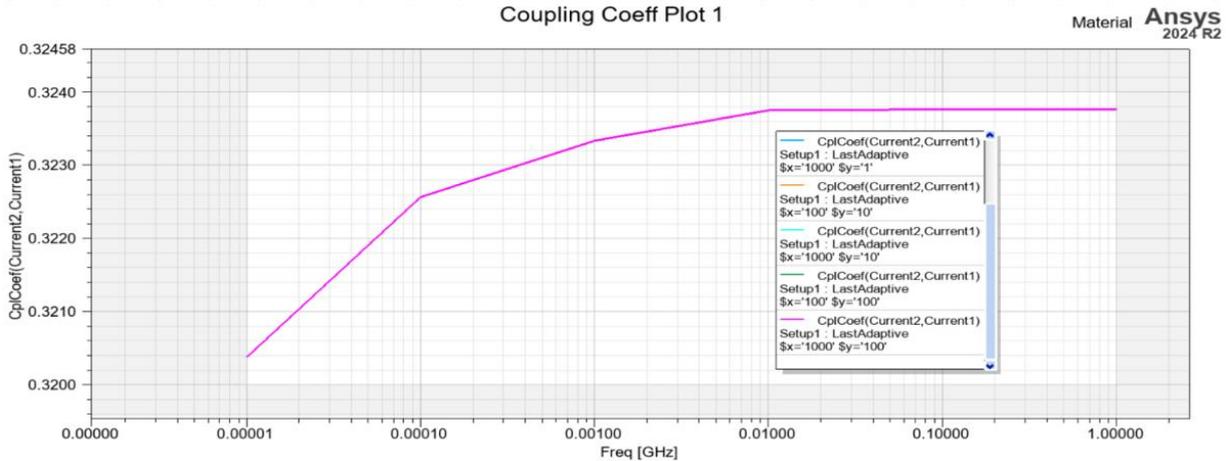


Figure 7. Variation of Coupling Coefficient with Frequency when Muscle is Used as the Medium

3.2.3. Influence of Magnetic Permeability (μ) and Magnetic Loss ($\tan\delta_m$)

Human tissues are non-magnetic materials ($\mu_r \approx 1$). When μ increases from 1 to 10,000, the k value decreases from 0.323 to 0.042 at 1MHz (Figure. 8). At $f=1$ MHz, with magnetic permeability increasing from 1 to 10 and magnetic loss being 0, the coupling coefficient decreases from 0.323 to 0.105. At $f=1$ MHz, with magnetic loss increasing from 1 to 10 and magnetic permeability being 1, the coupling coefficient decreases from 0.323 to 0.067. At $f=1$ MHz, when magnetic permeability increases from 1 to 10 and magnetic loss increases from 0 to 10 simultaneously, the coupling coefficient decreases from 0.323 to only 0.0428. Based on comprehensive data, magnetic loss has a greater impact than magnetic permeability at 1MHz.

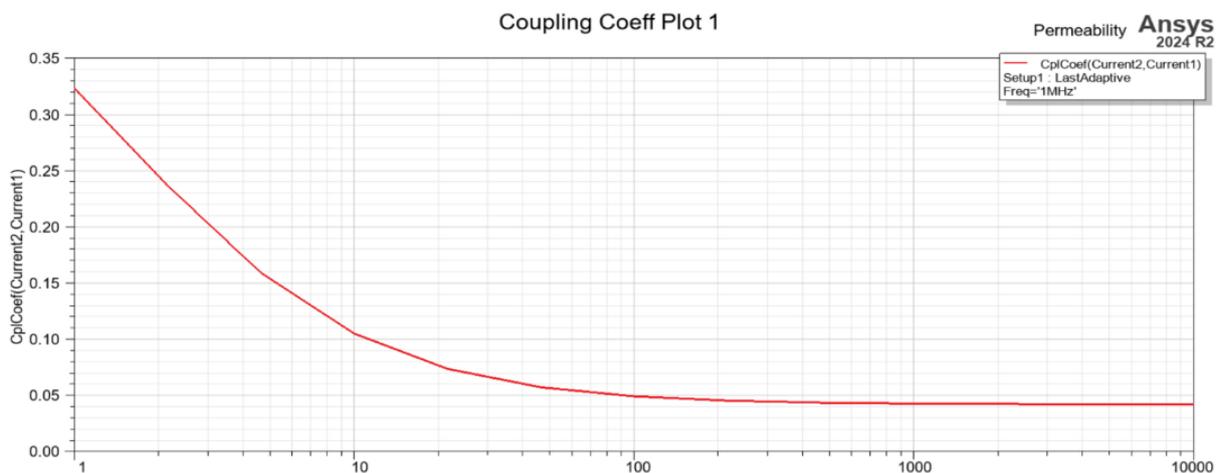


Figure 8. The coupling coefficient varies with the change of magnetic permeability at 1 MHz.

3.3. Building an SS Compensation Circuit in Simplorer to Calculate the Final Transmission Efficiency

3.3.1. Working Frequency

Using a frequency of 0.1 MHz for the simulated circuit enables a good balance between the improvement of the quality factor (Q) and the suppression of electrical losses [9].

The dielectric constant and dielectric loss of human muscle are both large at low frequencies. Input the table of dielectric loss and dielectric constant varying with frequency into the system, establish a new material "muscle" as the medium, and perform simulation to obtain the above curve of coupling coefficient varying with frequency. According to Figure. 9, the k value increases with the increase of frequency, but it approaches the maximum value in the frequency range from 100 kHz to 1 MHz.

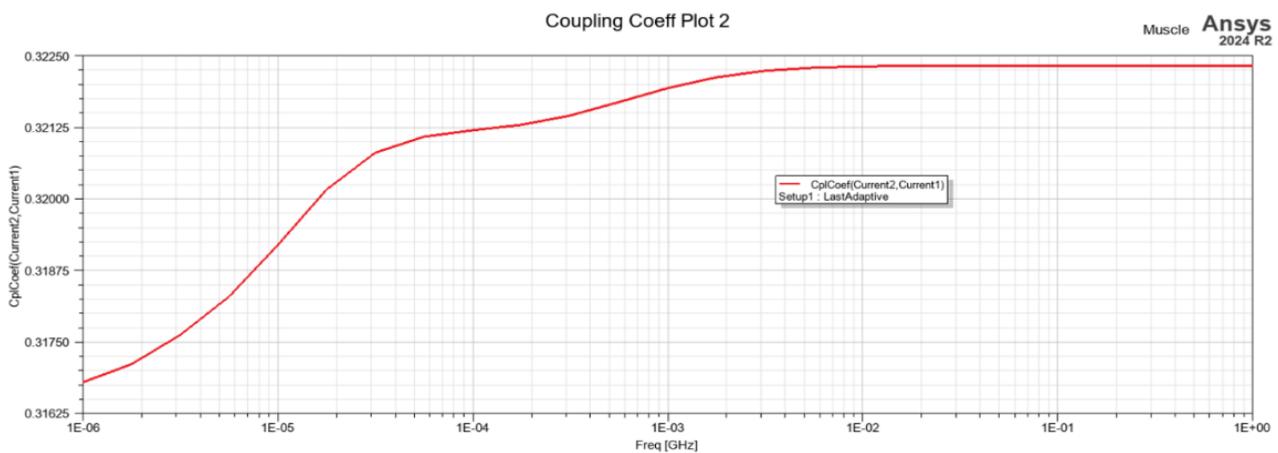


Figure 9. Variation of the coupling coefficient with frequency when the intermediate medium is muscle tissue

Using the RGLC data of the model provided by Maxwell simulation output, L will slightly decrease with the increase of frequency, while R will slightly increase. The Figure. 10 is obtained by calculating the data with Excel.

As can be seen from Figure. 10, the efficiency can also increase as the frequency rises. The fundamental reason is that the quality factor Q of both the transmitting and receiving coils will increase with the increase in frequency. The efficiency also approaches its maximum value around 0.1 MHz and 1 MHz. Therefore, 0.1 MHz and 1 MHz are the acceptable minimum frequencies.

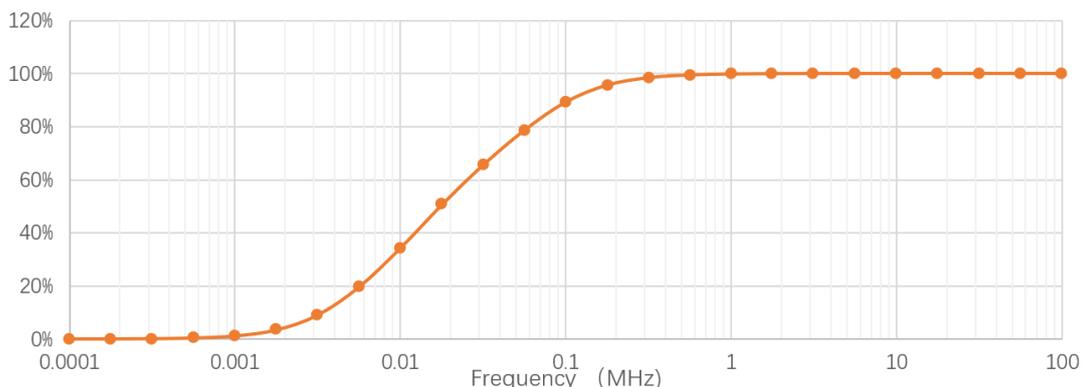


Figure 10. Variation of charging efficiency with frequency for air-core charging coils

The final selection of the operating frequency needs to consider both the energy transfer efficiency of the coils and the efficiency of power electronic switching devices. Modern power switching electronic switching devices generally operate in the range of tens of kilohertz to 10 MHz, and their efficiency decreases as the operating frequency increases. Therefore, a comprehensive consideration requires balancing within the range of 0.1 MHz to 10 MHz [10].

3.3.2. Parameters

Export the coil parameters from Maxwell eddy current simulation (using the parameters of human muscle tissue at 0.1 MHz for the coils), such as the primary coil $L_1 \approx 13.82 \mu\text{H}$, secondary coil $L_2 \approx 17.55 \mu\text{H}$, equivalent resistances $R_1 \approx 0.167 \Omega$ and $R_2 \approx 0.367 \Omega$. Then, obtain the compensation capacitances $C_1 \approx 0.183 \mu\text{F}$ and $C_2 \approx 0.144 \mu\text{F}$ according to the resonance formula $C = 1/(\omega^2 L)$, where $\omega = 2\pi f$ and $f = 0.1 \text{ MHz}$.

3.3.3. Setting up the Circuit Model

Construct an SS series compensation circuit, which can compensate for the coil reactance through the series capacitors at the transmitting and receiving ends, making the system work in a resonant state. This reduces the operating current of the circuit, thereby reducing reactive power, lowering the magnetic loss and copper loss of the coil, and ultimately improving the power transmission efficiency.

Create a new project in Simplorer, add a voltage source, C_1 , L_1 , and R_1 to form the primary series circuit, and add L_2 , C_2 , and load R_2 to form the secondary series circuit. Connect the two coils through a mutual inductance module, and input the mutual inductance value $M \approx 5.02 \mu\text{H}$ obtained from the simulation.

As shown in Figure. 11, the topology on the left side is for the transmitting coil terminal, and the one on the right side is for the receiving coil terminal. It is confirmed that the currents on both sides flow into the transmitting coil and the receiving coil respectively; therefore, the magnetic fields generated by mutual inductance between the coils will be superimposed on each other. A power meter is included in the circuit solely to test the transient power of the two coils before and after compensation, and it has no impact on the circuit itself.

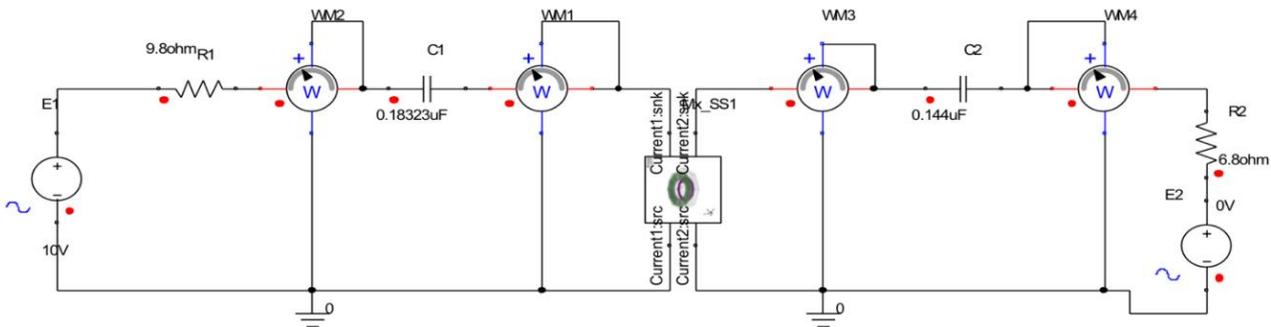


Figure 11. Simplorer Time Domain Simulation Circuit

3.3.4. Calculating Efficiency

According to the circuit on the left, the KVL equation can be derived as follows:

$$U = I_1 (R_1 + j\omega L_1 + j\omega C_1) + I_2 j\omega M \quad (3)$$

According to the circuit on the right, the KVL equation can be derived as follows:

$$0 = I_1 + j\omega M + I_2 (R_2 + j\omega C_2 + j\omega L_2) \quad (4)$$

Condition of resonant in series:

$$1/(j\omega C_1) + j\omega L_1 = 0 \quad (5)$$

$$1/(j\omega C_2) + j\omega L_2 = 0 \quad (6)$$

Simplify to obtain equation for primary circuit:

$$U = I_1 R_1 + I_2 j\omega M \quad (7)$$

Simplify to obtain equation for secondary circuit:

$$0 = I_1 j\omega M + I_2 R_2 \quad (8)$$

Obtaining expression for I_2 :

$$I_2 = -(j\omega M / R_2)I_1 \quad (9)$$

Input Power:

$$P_{in} = UI_1 = (R_1 + \omega^2 M^2 / R_2)I_1^2 \quad (10)$$

Output Power:

$$P_{out} = R_2 I_2^2 = (\omega^2 M^2 / R_2)I_1^2 \quad (11)$$

Definition of coupling coefficient:

$$k = M / \sqrt{L_p L_s} \quad (12)$$

Definition of quality factor:

$$Q_1 = \omega L_1 / R_1 \quad (13)$$

$$Q_2 = \omega L_2 / R_2 \quad (14)$$

From definition of M and k:

$$M^2 = k^2 L_1 L_2 \quad (15)$$

Rearrange to obtain for efficiency expression of the circuit:

$$\eta = P_{out} / P_{in} = (k^2 Q_1 Q_2) / (1 + k^2 Q_1 Q_2) \quad (16)$$

It should be noted that R1 represents the resistance value of the main coil, while R2 includes both the resistance value of the coil and the resistance value of the load.

3.3.5. Simulation verification

Set the simulation duration to 150 μ s, with a step size of 0.02 μ s. Add a power meter and current measurement module, import the eddy current simulation data from the Maxwell model, analyze the total power and useful power of the time-domain circuit. By comparing Figure. 12, the peak values of both in the steady state (the input peak is 1.2085, the output peak is 1.0244) allow us to calculate the transmission efficiency to be 84.77%, which has a slight deviation from the predicted value (calculated through the efficiency formula) of 89.30%.

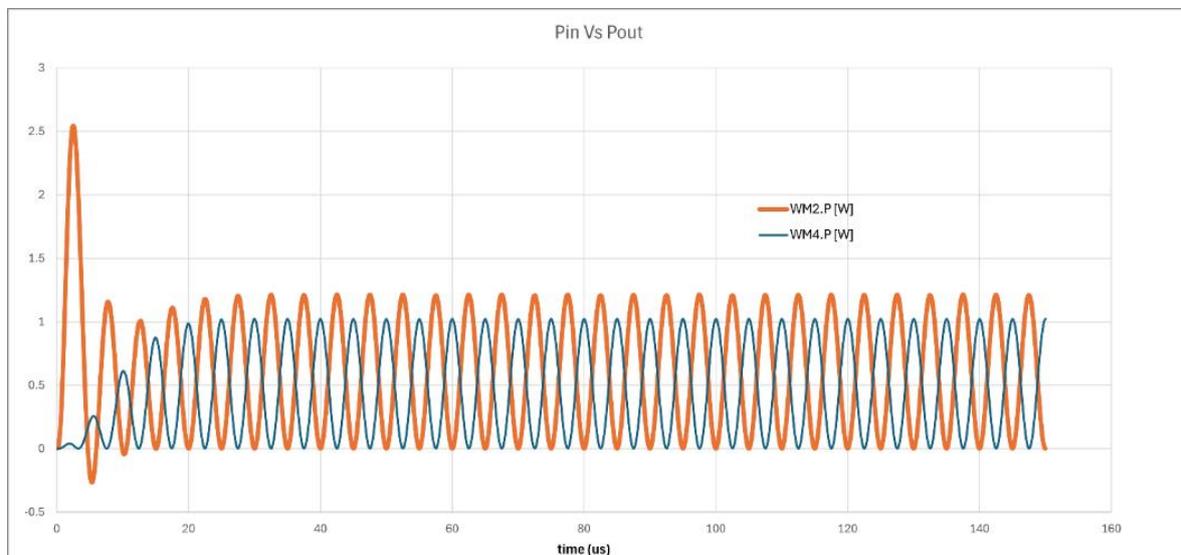


Figure 12. Output of total power and useful power in the time domain

4. Conclusion

This study systematically employed finite element and circuit analysis methods to reveal how the electromagnetic properties of biological tissues and the mechanical structure of the coil jointly affect the transmission efficiency of implantable wireless power transmission systems. The study clearly indicates that the eddy current shielding effect from the conductivity of the tissues is the main factor causing the reduction of the magnetic coupling coefficient and limiting the efficiency, and its influence is much greater than that of the dielectric constant (in the magnetic field-dominated coupling, the influence of the dielectric constant can be ignored). It is notable that the magnetic loss is more detrimental to the coupling performance than the increase in magnetic permeability, providing new insights for evaluating magnetic biocompatibility materials. Additionally, the alignment and spacing of the coil as external factors have a much greater impact on the coupling efficiency than most tissue parameters, highlighting the crucial importance of a stable implantation position. Considering the transmission efficiency, power equipment performance, and biological safety, this study determined that the optimal working frequency range is from 0.1 MHz to 10 MHz. This conclusion deepens the understanding of the magnetic coupling phenomenon in biological environments and provides key theoretical foundations and design guidelines for the design of coil for implantable devices, frequency selection, and safety assessment in the future. Although these achievements have been made, there are also some limitations, such as the use of a simplified human tissue model and static conditions. Future research will involve multi-tissue models, dynamic displacement analysis, and in vitro verification to improve its clinical relevance and reliability.

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