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EFFICIENT POWER TRANSMISSION SYSTEM USING MESH & REFLECTED IMPEDANCE COUPLING METHODS FOR MEDICAL IMPLANTS

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ABSTRACT

In this paper, the mathematical analysis and optimization of inductive power transmission system with serial to parallel topology for implanted biomedical devices is presented. The mathematical analysis based on the mesh coupling method is used to determine the dissipated power on the implanted remote electronics. In addition, the reflected impedance method is used to calculate and optimized the efficient power transmission without and with the power amplifier resistance. The proposed relative distance separated between the two sides of the inductive link is 6 mm with a coefficient factor 0.09 and the remote load resistance is assumed 300 Ω. The results show that efficiency with low input impedance is 78% and with higher input impedance is 40%. The efficiency is reduced approximately 51% when the power amplifier resistance is used as a series resistance with the transmitted LC-tank. The system optimization can be achieved by tuning the capacitor at the received LC-tank. The mathematical analysis is modeled and simulated in MATLAB.

Keywords: biomedical implanted devices, inductive coupling links, Class-E power amplifier.

1. INTRODUCTION

The wireless inductive coupling is an attractive developing technology for biomedical applications such as implanted micro-system, cochlear implant and brine pacemaker implant. In this method, which use magnetic coupling as the communication environment, which is common with RFID techniques [1-5]. Practically, the RF short-range communication transmits a low power, which is less than a milli watt, radiated RF power signal from the reader coil antenna, which is mostly designed to offer fixed sinusoidal carrier amplitude that provides a stable wireless transfer power. The stability of the RF signal gives a high readability for DC voltage at the implant device in terms of the distances from the reader coil [6, 7]. However, the bio-device system is composed of two coils: one implant has integrated and isolated inside the human body, the other located outside the body and called the reader. To have better power transfer efficiency of inductive coupling link, both sides of the link are tuned at the same resonant frequency f_0. There are four possible resonance circuits as inductive coupling topologies such as serial-to-serial connection circuits, serial to parallel connection, parallel to serial connection and parallel-to-parallel connection [8]. Researchers found that the serial to parallel topology is the suitable connection for biomedical applications. In this topology, the primary circuit is tuned in series resonance to provide a low impedance load for driving the transmitter coil, where the secondary circuit is almost invariably parallel, and uses an LC circuit for better driving of a nonlinear rectifier load. There are several parameters such as input impedance, LC-tank and load resistance to be considered in the design of an inductive coupling link and the generated magnetic fields [9].

The mathematical analysis and simulation are most important to design an ideal inductive coupling links for approximating the received power. Different mathematical analysis methods such as mesh coupling analysis circuit, loose coupling analysis, reflected impedance analysis and network circuit analysis have been investigated for resolving and deriving the equations for calculating the received power of the implant device. These methods are for evaluating the received power by a load R_{Load} at the implant circuit. In addition, the load resistance is varied over a wide range, at different values for optimum received power. There are many mathematical analysis methods, which can be considered for calculating the received power, and magnetic coupling coefficient [10]. In this paper, the mesh coupling method is used to determine the dissipated power on the implanted load resistance, then the reflected impedance method is used to calculate and optimized the efficient power transmission when the input impedance is low and when the power amplifier resistance is used as high input impedance.

2. POWER AMPLIFIER IMPEDANCE ANALYSIS

In general, class-E PA technique is commonly used in wireless power transmission for biomedical and biotelemetry applications. The implant system needs a highly efficient power amplifier to transmit the RF power signal, which modulates according to the control information from the reader, into the implant device. Hence, the class-E is a more suitable PA as an element driver for the transmitter coil, with theoretical 100% efficiency (only ideal switch): the actual efficiency is about 90 ~ 95% [11, 12]. Most of researches analysis the design of class-E- PA for fixed load of 50 Ω or 75 Ω, this load is not the appropriate case of the inductive coupling power which it usually very small and depending of the secondary coil load and coupling link [13]. So, in this work, and as given in our previous work, the optimal load resistance (power amplifier impedance) is (R_P = 41.89 Ω) [14]. The matching network included capacitor (C_{ST}) and inductor (L_{ST}) is used to calculate the parasitic resistance

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(R_{LT}), which presents a combination of the loss resistance (R_{loss}) and radiation resistance (R_r) for the transmitter coil as shown in Figure-1. The values are found as follows (C_{ST} = 12.35pf), (L_{ST} = 21.68 nH), hence, the parasitic resistance (R_{LT}) can be calculated as given in (1).

$$R_{LT} = \frac{L_{ST}}{C_{ST}R_L} \qquad (1)$$

The total impedance of the matching network given in Figure-1 has a real part and imaginary part as given in (2),

$$Z_{total} = \frac{R_L - \omega^2 R_L C_{ST} L_{ST} + j\omega L_{ST}}{j\omega R_L C_{ST} + 1} \qquad (2)$$

where the real part impedance at operating frequency 13.56 MHz is approximately 41.89Ω and the imaginary part is approximately equal zero.

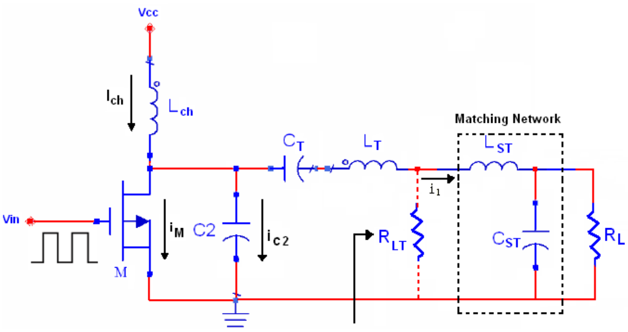

Figure-1. The class-E power amplifier with matching network.

3. THEORETICAL ANALYSIS FOR POWER DISSIPATION

The inductive coupling link for the bio-implantable applications consists of two models such as external and internal models. The external model is located outside the body, whereas the internal model integrated inside the body. Figure 2 (a) shows the schematic diagram of the inductive powering links with the parasitic components. Figure 2 (b) shows the simplified coupling links using two RLC circuits. The external circuit tuned to the series resonance, whereas the internal circuit tuned to the parallel resonance [15]. Both circuits tuned to the same resonant frequency of 13.56 MHz.

The circuit analysis for the inductive circuits is analyzed by mesh coupling analysis and described as follows: M represents the mutual inductance between the transmitter (reader) inductor L_{read} and the receiver inductor L_{impl}. The transmitter coil having lumped elements as parasitic resistor R_{LT} and their associated capacitor, which the series capacitor with the associated capacitor defined as C_T (C_1 and C_{ST}). The receiver coil having lumped elements as parasitic resistor R_{LR} and their associated capacitor, which the parallel capacitor with the associated capacitor defined as C_R (C_{SR} +C_2).

In this section, the mesh equation analysis as the first method for deriving the equations and calculating the received dissipated power by load resistance (R_{Load}) is described. We supposed the reader voltage (V_{reader}) and the implant voltage (V_{impl}) could be calculated in (3) and (4) respectively:

$$V_{reader} = R_P + j\left(\omega L_{reader} - \frac{1}{\omega C_T}\right) * I_1 \pm j\omega M I_2 \qquad (3)$$

$$V_{imp} = \pm j\omega M I_1 + Z_2 I_2 \qquad (4)$$

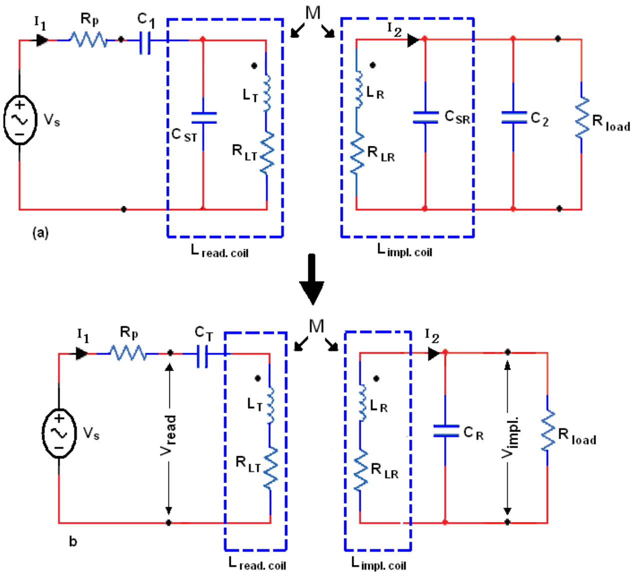

Figure-2. (a) Model of the inductive link with lumped elements (b) Simplified inductive coupling link.

Where the implant impedance Z_2 can be expressed by:

$$Z_2 = \frac{R_{load}}{1 + \frac{R_{load}(-\omega^2 L_{imp} C_R)}{j\omega L_{imp}}} \qquad (5)$$

Applying to (3) and (4) Cramer s ruler for the matrix can be written as:

$$\begin{bmatrix} V_{reader} \\ V_{implant} \end{bmatrix} = \begin{bmatrix} Z_{reader} & \pm j\omega M \\ \pm j\omega M & Z_{implant} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \qquad (6)$$

At the resonance condition the reactance of the inductor and capacitor are both equal, where

$$j\omega L_{implant} = \frac{1}{j\omega C_R} = 0 \qquad (7)$$

Equation (7) substitute into the equation (5); this yields the implant impedance (Z_2 = R_{load}).

From (6), the currents and voltage can be derived at the load resistance to get the power consumption delivered by load, and the reader current can be driven as:

$$I_1 = \begin{bmatrix} V_{reader} & -j\omega M \\ 0 & R_L \end{bmatrix} = \frac{V_{reader} R_L}{R_{reader} R_L + \omega^2 M^2} \qquad (8)$$

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The implant current can be calculated in (9) as:

$$I_2 = \begin{bmatrix} R_L & V_{reader} \\ -j\omega M & R_L \end{bmatrix} = \frac{V_{reader}R_L}{R_{reader}R_L+\omega^2M^2} \quad (9)$$

Where the implant load power can be given in the expression below:

$$P_{implant} = \left(I_{implant}\right)^2 R_{load} \quad (10)$$

4. EFFICIENT POWER TRANSMISSION OF COUPLING LINK

One of the main drawbacks of an inductive coupling link is the weak coupling resulting inefficient power transmission. The Power Transfer Efficiency (PTE) is one of the important factors to evaluate the performance of an inductive coupling link [16]. In this section, assurance is made to derive analytic formulas to determine PTE Figure-3. The resistance R_{LT} and R_{LR} are equivalent series resistors (parasitic resistors) of inductors L_T and L_R, respectively. R_{load} represents load resistance, $C_R = C_{SR} + C_2$. The efficient power transmission is quantified by using reflected impedance analysis from the transmitter and receiver, (Z_t and Z_r) as given in (11 and 12), and having real and imaginary parts as given in (13) and (14) as shown in Figure-3.

$$Z_t = \frac{v_t}{I_1} = \frac{\omega^2M^2}{Z_2}$$
(11)

$$Z_r = \frac{v_r}{I_2} = j\omega M\frac{I_1}{I_2}$$
(12)

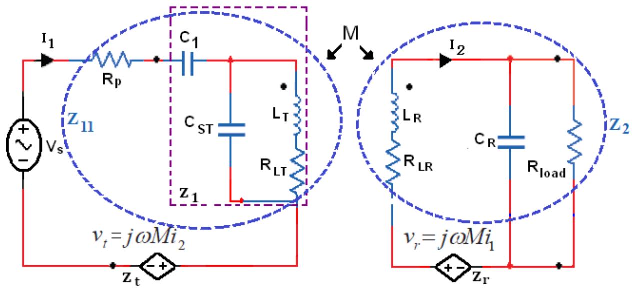

Figure-3. Inductive power link schematic and its equivalent circuit.

$$Z_1 = (R_{LT} + j\omega L_T // \frac{1}{j\omega C_{ST}}) + \frac{1}{j\omega C_1}$$
(13)

$$Z_2 = R_{LR} + j\omega L_R + \frac{1}{j\omega C_R} // R_{load}$$
(14)

The PTE is the ratio of power consumed by the secondary circuits over the total power drained from the power supply source η_T. The power receiver efficiency is the ratio of power consumed by the load R_{load} over the total power consumed at the implanted side η_R and as given in (15) and (16) respectively.

$$\eta_T = \left|\frac{Z_t}{Z_1+Z_t}\right| \leqq \frac{K^2Q_1Q_2R_{load}}{K^2Q_1Q_2R_{load}+Q_2^2R_{LR}}$$
(15)

$$\eta_R = \left|1-\frac{R_{LR}}{Z_2}\right| \leqq \frac{Q_2^2R_{LR}}{Q_2^2R_{LR}+R_{load}}$$
(16)

Then total coupling link efficiency is $\eta_{link} = \eta_T * \eta_R$ where total link efficiency η_{link} reach its maximum if Z_1, and Z_2 has only real part left where the imaginary part is approximately zero; the quality factors (Q) of the transmitter and receiver coils are Q_1 and Q_2 respectively, and calculated as given in (17) and (18).

$$Q_1 = \frac{\omega_0 L_T}{R_{LT}} \quad (17)$$

$$Q_2 = \frac{\omega_0 L_R}{R_{LR}} \quad (18)$$

Both coils tuned at the same resonance frequency as given in (19)

$$\omega = \omega_0 = \frac{1}{(L_T C_1)^{\frac{1}{2}}} = \frac{1}{(L_R C_R)^{\frac{1}{2}}} \quad (19)$$

The coupling coefficient value is (0 < K < 1) depending on the coils radius. The shape of the inductive inductors is as a two single-layer circular spiral coil with transmitter coil radius (r_T) and receiver coil radius (r_R) respectively [17]. Hence, the coupling coefficient (K) at distance between coils 6 mm is 0.09 and calculated as given in (20).

$$K = \frac{r_T^2 \times r_R^2}{\sqrt{r_T r_R}\left(\sqrt{r_T^2+z^2}\right)^3} \quad (20)$$

The implanted load resistance R_{load}, calculated according to [14, 15], as expressed in (21).

$$R_{load} \geq 2\omega L_R \quad (21)$$

where $\omega = 2\pi f$, hence R_{load} should be more than 175 Ω. The total efficiency is produced of η_T and η_R as illustrated in (22).

$$\eta_{total} = \eta_T\eta_R = \frac{K^2Q_1Q_2^3R_{LR}R_{load}}{(K^2Q_1Q_2^3R_{LR}R_{load}+K^2Q_1Q_2R_{load}^2+Q_2^4R_{LR}^2+2Q_2^2R_{LR}R_{load}+R_{load}^2)}$$
(22)

The efficiency given in (22) represents the total efficiency without considering the power amplifier resistance. Therefore, the

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input impedance is low and has several ohms. The inductive coupling circuit driven with an efficient transcutaneous power amplifier and this makes the external impedance increase. This makes reducing the power delivered to the implanted circuit. Therefore, the power amplifier must carefully design with optimum load resistance (R_P) by using matching network, where the lumped elements for the external coil can be quantify also [14]. Equation (23) observes the external impedance included the power amplifier resistance.

$$Z_{11} = [(R_{LT} + j\omega L_T // \frac{1}{j\omega C_{ST}}) + \frac{1}{j\omega C_1}] + R_P \quad (23)$$

The total efficiency given in (24)

$$\eta_T = \left|\frac{Z_t}{Z_{11}+Z_t}\right| \quad (24)$$

The PTE equation based on these factors given in Figure-3 is becoming;

$$\eta_{link} = \frac{P_O}{P_S} = \frac{K^2 Q_1 Q_2^3 R_{load} R_{LR}}{\left[K^2 Q_1 Q_2 R_{load} + \left(1+\frac{R_P}{R_{LT}}\right)(R_{load}+Q_2^2 R_{LR})\right]\times(R_{load}+Q_2^2 R_{LR})} \quad (25)$$

Equations (22) and (25) modeled and simulated in MATLAB as shown in Fig 4 and 5 respectively, and based on the values given in Table-1, the power transfer efficiency for lower input impedance is higher than the efficiency with higher input impedance.

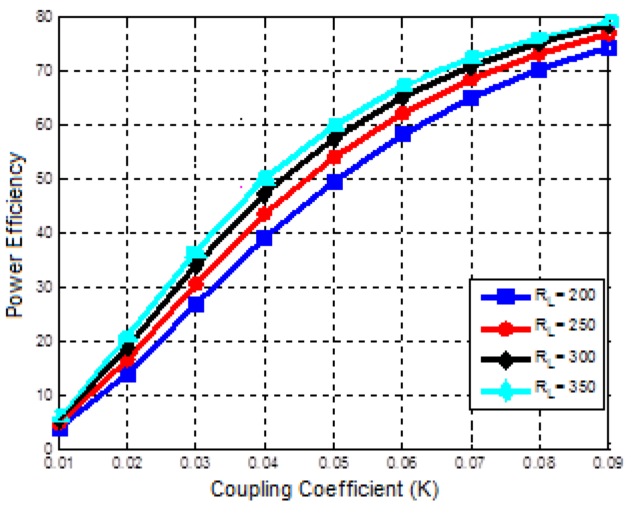

Figure-4. Power efficiency links with low input impedance and various load resistances.

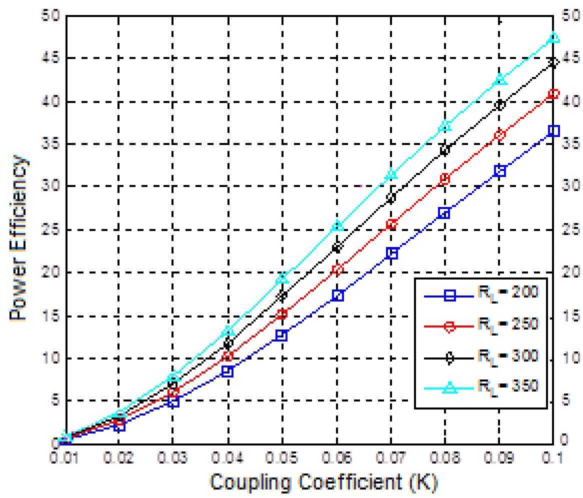

Figure-5. Power efficiency links to P/AM resistance as an input impedance and various load resistances.

5. OPTIMIZATION OF MAXIMUM POWER EFFICIENCY

The purpose of the mathematical analysis given in sections (3 and 4) is to facilitate the process of the inductive coupling links optimization. Referring to Figure-3, the optimization attained for impedance Z_1 and Z_2 without considering the power amplifier resistance. The power efficiency takes place at the resonant frequency ω_o on the implanted coil

$$\omega_{o.imp}^2 = \frac{1}{L_R C_R} - \left(\frac{1}{C_R R_{load}}\right)^2 \quad (26)$$

From Equation (26) is noted that the resonant frequency depends on L_R, C_R and R_{load}. Hence, if the implanted load resistance changes, the coupling system will be out of resonance. Thus, the implanted remote will not receive maximum transmitted power. The capacitor C_R can be adjusted to get optimum resonance as given in (27)

$$C_R = \frac{R_L \pm \sqrt{R_L^2 - 4L_R^2\omega_o^2}}{2L_R R_{load}\omega_o^2} \quad (27)$$

with the condition given in (21), and the mutual inductance between coils given in (28). The coupling factor K maximizes the power transmission between the two coils and identified as k_{crit}.

$$M = K\sqrt{L_T L_R} \quad (28)$$

The maximum power transmission occurs when the load reflected in the transmitter and mutual inductance has the same value as the impedance of the transmitter coil in resonance Z_1 as follow:

$$P_{max} = \frac{M^2}{L_R + \frac{R_{load}}{R_{load} C_R + 1} + R_{LR}} \quad (29)$$

Then, the k_{crit} is calculated as given in (30)

$$k_{crit} = \sqrt{R_{LT} C_T \left(\frac{1}{C_R R_L} + \frac{R_{LR}}{L_R}\right)} \quad (30)$$

The k_{crit} can be in lower value if the distance between coils is ingresses; and there is a misalignment between coils. The distance between inductive links can be increased if both coils have high quality factor, and this can be achieved if the parasitic resistors R_{LT} and R_{LR} have low values. On the other hand, if the load resistance R_{load} is high. In this section, the aim is to optimize the power transmission efficiency which is given in (25) without considering the power amplifier resistance as follows:

$$\eta_p = \frac{|I_2|^2 R_{load}}{R_{eg}[I_1] V_s} \quad (31)$$

Then, for better power transmission efficiency the capacitor C_R must be tuned at the needed value, which depends on the load and should have an optimum operation point and calculated as follows:

$$C_R = \frac{L_R R_{LT}}{R_{LT} R_{LT} + K^2 L_R L_T R_{LT} \omega^2 + L_R^2 R_T \omega^2} \quad (32)$$

6. RESULTS AND DISCUSSIONS

The inductive coupling link is the common method used in biomedical applications. This method used to transfer power and data to the implanted batter less devices. One of the main disadvantages of this method is the weak coupling. To overcome this disadvantage and increases efficiency, many factors should be considered such as the lumped elements of the coils, load resistance (implanted remote electronics), coils shape and the driven input impedance. Most of the studies obtained the mathematical model and analysis under condition that the input impedance is low and they get better efficiency. Since, power amplifier drives the coupling link, and this resulting increasing the input impedance casing reducing the total efficiency. Therefore, in this study, we present a mathematical analysis to calculate the optimal input impedance with and without power amplifier. The power dissipated on the implanted devices quantified by using the mesh-coupling method. The reflected impedance method is used to calculate the power transmission between the inductive link in two cases; when the input impedance is high and when the input impedance is low. The optimization of the power transmission is presented. The mathematical analyses have been flanked by exhaustive simulation studies carried out using MATLAB. The class-E power amplifier is designed to give high efficiency and having an optimum load resistance 41.89 Ω, and the parasitic resistor for the coil is 2.15 Ω as shown in Fiq 1. The total impedance for the matching network used for the power amplifier where the real part impedance is the optimum class-E power amplifier which equal 41.89 Ω and the imaginary part is approximately equal zero. In section (3), the mathematical analysis based on the mesh coupling method is used to determine the power dissipated on the implanted devices. Figure-2 (a and b) shows the model of the inductive link with lumped elements and simplified inductive coupling link. Figure-3 shows the Inductive power link schematic and its equivalent circuit, where the high and low input impedances were observed as Z_1 and Z_{11}.

Referring to (21) the implanted device should have a resistance more than 175 Ω, and we assumed to be (200 Ω to 350 Ω) with 50 Ω as a different step. The coupling coefficient is depending on the distances between the coils, and for the implanted micro-system application, which integrated in the body at depth 6 mm the coupling factor is 0.09. Where the implanted resistance is 300 Ω as given in equation (20). Figure4 shows the Power efficiency links with low input impedance (2.15 Ω) and various load resistances (200 Ω to 350 Ω). For the coupling factor 0.09 with the chosen resistance 300 Ω, the power efficiency is 78%, and for 200 Ω the efficiency is 73%.

Figure-5 shows the Power efficiency links with high input impedance (41.89 Ω) with presents the power amplifier impedance and various load resistances (200 Ω to 350 Ω). For implanted resistance 300 Ω the power efficiency is approximately 40 %, for implanted resistance 200 Ω the efficiency is 36%. From the results above, the inductivecoupling links need to be optimized. Section 5 presents the mathematical analysis to optimize the power transmission efficiency by tuning the capacitor C_R at the needed value where, the implanted inductor L_R and its parasitic resistance R_{LR} are fixed, which is depending on the load, should have an optimum operation point, and calculated as given in equation (32). From the results above, the power transfer efficiency is reduced by 51% when the power amplifier resistor used as inductive input impedance.

Table-1. Parameters and values for the proposed inductive coupling design.

Description	Symbol	Value
Reader coil inductance	L_T	5.48µH
Implanted coil inductance	L_R	2µH
Readercoil resistance	R_{LT}	2.15 Ω
Implanted coil resistance	R_{LR}	1.8 Ω

Reader coil capacitance	C_T	32.12 PF
Implanted coil capacitance	C_R	32.12 PF
Reader quality factor	Q_1	190
Implanted quality factor	Q_2	53
Coupling coefficients	K	0.09
Relative coils distance	D	6 mm

7. CONCLUSION

In this paper, the mathematical analysis of the inductive coupling link for wireless transmission based on serial to parallel resonance circuits is modulated and optimized using MATLAB. The aim of this analysis is to facilitate and understanding the fine details of the inductive coupling links, which helping designers to optimize the coupling link for best performance. Two methods were used in the mathematical analysis. The first method is the mesh coupling analysis to determine the dissipated power on the load resistance (implanted device). The second method is the reflected impedance analysis to optimize the power transmission of the inductive power coupling. The values given in Table-1 are used in our analysis; the analysis was done when the input impedance of the system is high and low, respectively. The developed mathematical model and the simulation results show that the power transmission increased by reducing the input impedance and vice-versa. The power efficiency is 78% when the impedance input is low, and 40% when the impedance is high (power amplifier resistance) hence, the power efficiency with high input impedance is reduced approximately 51% than it when the input impedance is low. The circuit optimization can be achieved by tuning the capacitor of the implanted RLC circuit where the implanted inductance and resistance are usually fixed.

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