# Analysis of Four Coils by Inductive Powering Links for Powering Bio-implantable Sensor

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***Abstract*** **– The inductive coupling link technique is popularly used for transmitting power in many biomedical applications, where it helps in transferring power to numerous implanted biomedical devices like a wireless pressure sensor system. It has also been noted that the inductive coupling variables significantly affect the coupling efficiency. In this study, the researchers have investigated the inductive coupling link variables for 3 transmitter coils and one receiver coil. They used a resonant frequency of 27 MHz as the operating frequency, based on the Industrial, Scientific and Medical (ISM) band. The experimental results indicated that the Voltage gain (i.e., Vgain) value of the inductive links was dependent on the Coupling Factor (K) existing between every coil and load resistance (i.e., Rload). It was also noted that the value of the Voltage gain increased with an increase in the implanted resistance, based on a constant coupling factor. Furthermore, the simulation results indicated that if the Rload=1000, the Vgain value would be maximal, whereas if Rload = 200Ω, the Vgain value would be minimal and ≈ 5V.**

**These results indicated that the operating system could satisfy all the requirements for powering the implanted sensor biodevices.**

***Keywords*** **– low band frequency (ISM), energy harvesting, in-stent restenosis, four inductive coupling links**

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## 1. Introduction

In the past few years, the inductive link technique has been used in many Implantable Medical Devices (IMDs) like brine implants, pacemakers, retinal implants, cochlear implants and in-stent restenosis coronary artery systems, for transmitting power to the pressure sensors. Additionally, these devices help in recording, measuring and sensing the various physiological signals present in the body [1], [2]. A majority of these devices are implanted in the body for the long term. Hence, owing to the long life-spans of the implanted batteries, occupied area and the resulting chemical effects, the inductive coupling links are regarded as a suitable choice for powering the implanted medical devices for a short-range [3]. Generally, the inductive coupling links are made of two resonating RLC parts [4], wherein Part 1 is operated by the Power amplifier that is placed outside the body and is known as a primary part, external component or in vitro part. On the other hand, Part 2 is integrated and placed within the body and is known as a secondary component, internal part or in vivo part. The secondary part is supplied power inductively with the help of the primary part based on the magnetic flux, wherein it acts as the antenna. However, this technique cannot satisfy the power requirements of the device if the distance between the receiver and transmitter components is large. Furthermore, the researcher designed a device that included two RLC circuits within the transmitter component while one RLC component was included in the receiver component for improving the power transfer efficiency when the two components of the link were tuned to the same resonant frequency [5], [6]. It was noted that the fragile coupling link present between the transmitter and receiver coils led to the ineffective power transfer between the sides [7]. In a majority of the cases, the primary coils were tuned in a series resonant for offering a low impedance load, whereas the secondary circuit was invariably parallel [8]. For transmitting the power to the implanted biodevices at a narrow band, the researchers selected a resonant frequency based on the Industrial, Scientific and Medical (ISM) band, as it could not heat or damage the human tissues [9]. The inductive coupling link variables are as follows: Transmitter coil inductance, i.e., L1, L2, L3; Receiver coil inductance (L4); Mutual inductance (Mij); Resonant frequency (f0); and Coupling factor of Kij (where Kij must range between 0 and 1 i.e., 0< Kij <1). These inductive coupling link variables directly affect the coupling link efficiency. Out of all the above factors, the coupling factor (Kij) is a major parameter that helps in determining the quantity of power that is transmitted to the implanted sensor biodevices [10].

In this study, the researchers have determined and analysed the relationship between Voltage gain (Vgain) and other variables like coupling coefficient (Kij) and load resistance (Rload) for the 3 RLC circuits at the transmitter end and one RLC Circuit at the receiver end. They have assumed the implanted load resistance variables to be 200, 400, 600 and 1000 while the variable coupling factors were presumed to be 0.3, 0.5, 0.7, 0.9.

## 2. Method and Theoretical Model for Inductive Coupling Link

In this study, the researchers implemented a wireless inductive coupling link that used a magnetic flux for transferring power between the transmitter and receiver coils. Figure 1. presents the inductive link that consists of the L1, L2 and L3 coils at the transmitter end and the L4 coil at the receiver end. For improving and maximizing the power transfer efficiency, the researchers tuned the transmitter coils in a series resonance, while the receiver coil was tuned in parallel resonance.

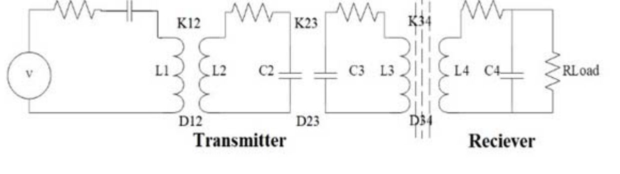


*Figure 1. Structure of Inductive Coupling Circuit*

Physically, it was seen that the coupling factor (Kij) was equal to the fraction of magnetic flux that was generated by L1, which then passed through coil 2, i.e., L2, and then to the third and fourth coils, i.e., L3 and L4. Also, the mutual inductance (Mij) was the reciprocal property of 2 coils, i.e., M12, M23 and M34, respectively. On the other hand, the coupling coefficient (Kij) ranged from 0 to 1, which indicates the electrical coupling level between the different inductor pairs.

$$K_{ij} = \frac{M_{ij}}{\sqrt{L_i L_j}} \tag{1}$$

This was seen to be the primary factor that determined the maximal distance (Dij) which helped in accurately operating the implant and determining the amount of power that could be transmitted to the implanted biomedical devices. The researchers calculated the inductive parameters depending on the shape of the different coils, i.e., the transmitter end coils were rectangular, while the coils at the receiver end were helical [11]

$$L = \frac{1.27\mu N_{square}^2 d_{avg}}{2}\left[ln\left(\frac{2.07}{\emptyset} + 0.18\emptyset + 0.13\emptyset^2\right)\right] \tag{2}$$

$$L_{helical\ coil} = \frac{\mu\pi r^2 N_{stent}^2 T}{l_{stent}} \tag{3}$$

Furthermore, the parasitic resistance values, i.e., RL1, RL2, RL3 and RL4 for the L1, L2, L3 and L4 coils that were calculated using Eqs. (4-7) were small as shown in Table 1. These values could be used for inductive powering based on various factors like the type of coils, resistive load and coupling links

$$R_{1,2,3} = R_{dc}\frac{t_c}{\sigma\left(1-e^{-\frac{t_c}{\sigma}}\right)} \tag{4}$$

$$R_{dc} = \rho\frac{l_c}{\omega.t_c} \tag{5}$$

$$l_c = 4N_{square}d_{out} - 4Nw - \left(2N_{rectangular\ coil} + 1\right)^2(s+w) \tag{6}$$

$$R_4 = \frac{R_{load}}{1+\omega_0^2 R_{load}^2 C_4^2} \tag{7}$$

The capacitance for circuit can be calculated from equations (8-11)[8].

$$C_1 = C_{amplifier}\left[\frac{5.447}{Q_{amplifier}}\right]\left[1 + \frac{1.42}{Q_{amplifier} - 2.08}\right] \tag{8}$$

$$C_2 = \frac{1.3924}{L_2\omega_s^2} \tag{9}$$

$$C_3 = \frac{1.8225}{L_3\omega_s^2} \tag{10}$$

$$C_4 = \frac{R_{load} + \sqrt{R_{load}^2 - 4\omega^2 L_4^2}}{2\omega^2 R_{load} L_4} \tag{11}$$

Wherein Rload indicates the implanted resistance, which is > 2ΩL4

For estimating the Voltage gain (Vgain) between Coils 1 and 2, Coils 2 and 3, and Coils 3 and 4, the researchers determined the Quality Factor (Qn) for every coil. This was dependent on the Resonant Frequency (f0), coil inductance, and parasitic resistance for the pair of coils, as shown in Eqs (2, 3) and (8-11).

$$Q_n = \frac{\omega L_n}{R_n} \qquad (12)$$

Wherein; n =No. of coils; parasitic resistance. The Vgain value was estimated using Eq. 13.

$$v_{gain\ 12} = k_{12}\sqrt{\frac{L_2}{L_1}}\ Q2 \qquad (13)$$

$$v_{gain\ 23} = k_{23}\sqrt{\frac{L_3}{L_2}}\ Q3 \qquad (14)$$

$$v_{gain\ 34} = k_{34}\sqrt{\frac{L_4}{L_3}}\ Q_p \qquad (15)$$

$$Q_p = \frac{(Q_4 R_4)\ //\ R_{load}}{\omega_0 L_4} \qquad (16)$$

*Table 1. Presents the values of the various parameters used in this inductive coupling system*

| Parameter | Symbol | Value |
|---|---|---|
| Coil Inductance 1,2,3 | L1, L2, L3 | 44.80µH |
| Coil Inductance 4 | L4 | 0.355 µH |
| Parasitic Resistance 1,2,3 | R1, R2, R3 | 14.98 Ω |
| Capacitance 1 | C1 | 0.80 PF |
| Capacitance 2 | C2 | 0.557 PF |
| Capacitance 3 | C3 | 0.557 PF |
| Capacitance 4 | C4 | 97.41 PF |
| Resonance Frequency | F0 | 27MHz |

## 3. Result and Discussion

Many researchers have realized the significance of developing effective IMDs since these devices can directly impact the safety and the lives of the users. The inductive coupling link is regarded as the most effective technique that helps in transmitting power to the battery-less, implanted devices [12]. In this study, the researchers have used a series-to-parallel inductive coupling topology, where they tuned 3 primary coils (reader) in a series resonance for decreasing the impedance load and operating the transmitter coils. They improved the link efficiency by tuning both the receiver and transmitter RLC circuits so that the inductive link showed a similar resonance frequency of 27 MHz.

The researchers used the Pspice OrCad software tool for simulating the proposed system. Figure 2. presents the relationship between the Voltage gain (Vgain) and Coupling factor (Kij) for Coils 1 and 2 when the coupling factor value was variable (K12 = 0.3, 0.5, 0.7 and 0.9, respectively). The simulation results indicated that the Vgain value at K12=0.9 was smaller compared to its value when K12= 0.5; while it was higher than its value when K12 = 0.3. This was based on the reflected magnetic flux occurring between the 4 coils. This was believed to increase if the distance between Coils 1 and 2 was higher but within the limited range; however, the Vgain value would decrease if K12 = 0.3. A similar scenario was noted for Coils 2 and 3 when the K12 value between Coils 1 and 2 was fixed at 0.5, as described in Figure 3. On the other hand, the Vgain value between Coils 3 and 4 would be higher if k= 0.9, instead of a different K34 value when the load resistance value was fixed at 400Ω, as presented in Figure 4.

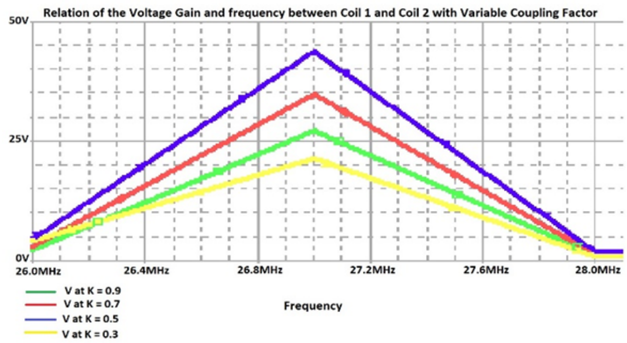


*Figure 2. Shows the relation between voltage gain and coupling factor for first coil and second coil*

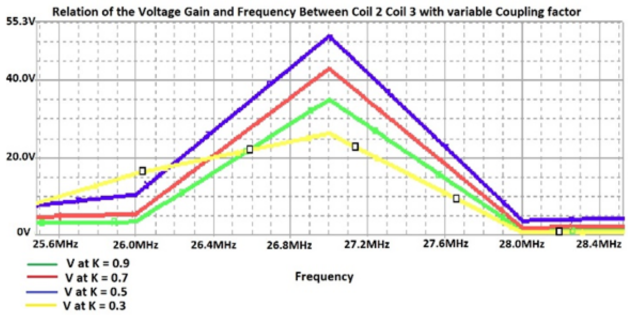


*Figure 3. Shows the relation between voltage gain and coupling factor for third coil and fourth coil*

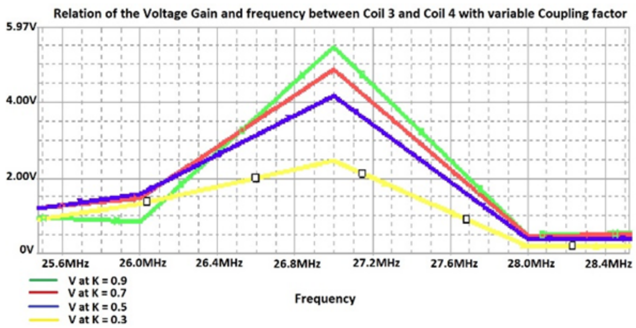


*Figure 4. Shows the relation between voltage gain and coupling factor for third coil and fourth coil*

For validating the model, the researchers used the MATLAB software and highlighted the relationship between the variation in the coupling factor values between the different coils, as it increased the variation in the distance between the coils. Figure 5. describes the variation between the coupling factors, i.e., K12 with K23 at 0.5 and K34 at 0.5. It was noted that the efficiency was low if K12 = 0.9, compared to the efficiency if K12 = 0.5. This explained the data presented in Figure 2. Based on a similar scenario, it was noted that for K23, the efficiency decreased when the Coils 2 and 3 were closer to each other, as presented in Figure 6.

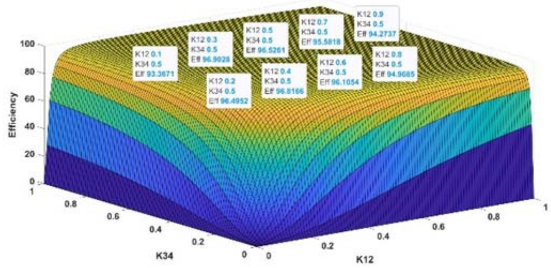


*Figure 5. Variation of efficiency with Coupling factor K12 at K23 =0.5*

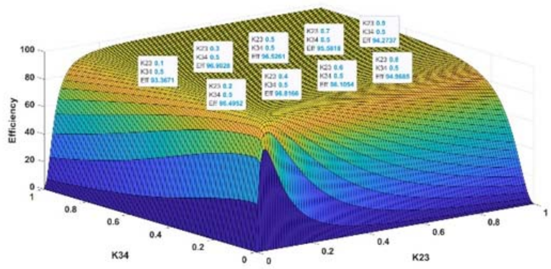


*Figure 6. Variation of efficiency with Coupling factor K23 at K12 =0.5*

Figure 7. highlights the relationship between Vgain, constant coupling factor value (k12=0.5, k23=0.5, k34= 0.5), and the load resistance, i.e., Rload= (200, 400, 600, 1000). The results indicated that the Vgain value was maximal if the load resistance value was maximised (Rload = 1000), while it was the lowest if the load resistance value was the least (Rload = 200).

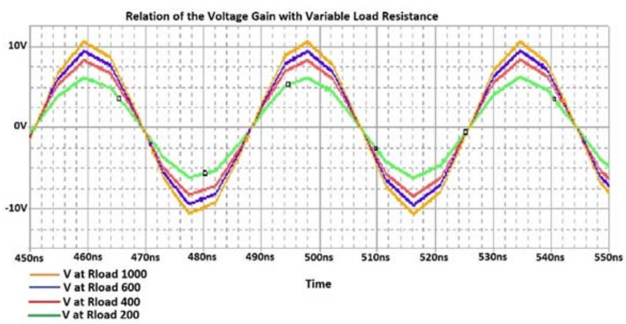


*Figure 7. Shows the relationship between voltage gain with constant coupling factor*

Figures 2.-4. indicated that the inductive links at maximal Vgain value behaved like a passband filter when the central frequency was maintained at 27 MHz. Figure 8. and Figure 9. indicated the input and output sinusoidal signals with a fixed coupling factor, i.e., K34= 0.5 and constant load resistance, i.e., Rload = 400. Thus, the output signal that was transmitted to the IMDs was decreased in comparison to the output signal generated from the primary coil. It was noted that the output signal also transferred power and also satisfied the power requirements for different components of the implanted biosensor.

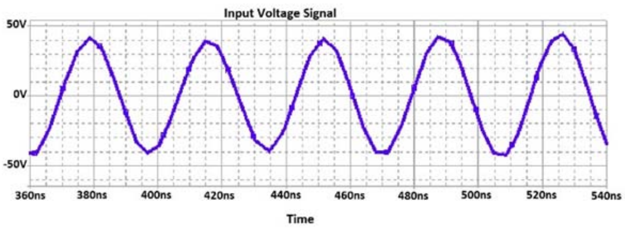


*Figure 8. Shows the input sinusoidal signal to the first transmitter coil*

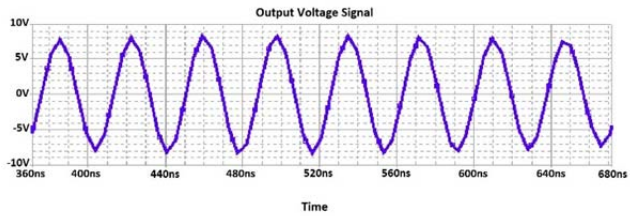


*Figure 9. Shows the output sinusoidal signal from the load resistance*

## 4. Conclusion

In this study, the researcher simulated the design of the inductive coupling link for the wireless power transmission using the Pspice Orcad software. They highlighted the relationship between different parameters like Voltage gain, coupling factor and load resistance. The mathematical module and simulation results indicated that at a constant load value, i.e., Rload and varying coupling factor (Kij) values, the coupling link behaved like a passband filter at the selected central frequency of 27 MHz. The Vgain value increased with an increase in the load resistance at a constant coupling factor. Table 1. presents the values of all parameters used in the system, which could satisfy the requirements of the IMDs and also transmitted power to the internal component.

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