Optimization of wireless power transmission for two port and three port inductive link

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Abstract: Recent developments have shown that the use of buried electronic devices or body implants has been becoming prevalent. Such low power devices are being powered up through non-contact means utilizing inductive coupling from external powering source. Inductive coupling not only solves the issue of energy availability but helps collecting the sensed data that can be archived or used for subsequent monitoring purposes. This paper analyses the performance of two-port and three-port inductive links in terms of power sent, power received and power transfer efficiency. All the above mentioned parameters have been plotted using analytical approach and obtaining simulation where required. The effect of mutual coupling has been studied in detail for both systems and demonstrated by plotting the power transfer efficiency for different values of the coefficient of coupling (k) using MATLAB. Results show that power transfer efficiency depends highly upon the value of k.

1. Introduction
Technological advancement has bestowed its innovation and novelty upon all the scientific fields. The portability in electronic devices is one of those and it has acquired a distinct significance in today’s world [1]. The constant and unremitting energy availability to these low power devices is a challenge still. Especially in the case of using as a source of energy, batteries that may drain out after specific duration and need to be replaced. In some applications, the replacement of batteries may not be a costly exercise, while in some other applications it may be costly as well as time consuming and may be even impossible due to inaccessibility concerns; hence a constant voltage supply from batteries is becoming more important than ever [2]. Therefore, interfacing and coupling of an energy harvesting system for charging up of batteries in such devices may significantly improve their energy availability besides reducing maintenance and operational cost and relieving concerns of occasional replacements for batteries [3].

Inductive coupling is considered to be an efficient technique for transfer of power wirelessly. The basic working principle for inductive coupling states that the external power source and the implants to be powered are to be placed in the close vicinity to each other [4]. There is no need to expose or connect any of the systems to the other physically. The primary coil is excited by the external power...
source to store the energy. The contiguity and the nearness of coils play a vital role in the generation of low power electrical field that inter-connects them and hence allows the transfer of electricity between the two systems. The energy sharing between the systems becomes possible only if they have the same amount of power.

The most appealing and alluring use of inductive coupling is in the field of biomedical implants where it is not only be used for powering these devices but also for gathering of data in telemetry purposes. Powering refers to deliver the effective amount of energy to the implanted device from the external source in order to operate it and telemetrically insinuate to the transfer of intuited data from the buried devices or implanted device to an peripheral device and vice versa [5]. Fig. 1 below shows an arrangement how an inductive coupling can be used for powering and telemetry purposes.

![Powering and Telemetry system](image)

Fig. 1: Simple model for inductive coupling to be used for powering and telemetry

Inductive coupling makes the biomedical implants possible to operate by powering it according to the requirements and also in monitoring the subject. Due to which these implanted devices help in the real time monitoring of human body providing an exclusive prospect for the timely diagnosis and treatment of many diseases by collecting the data from the internal parts of human body [6].

Initially, the transfer of energy using implanted devices has been quite clumsy and a knotty procedure because the wires as an interfacing medium used to be pierced through the skin. But this method soon proved to be useless as it not only hindered the patient's movements but also had an astounding chance of infection. As explained earlier that a battery also cannot be inserted to power up the implanted device due to its size and draining out reasons. The total size of the implant increases eventually even if the battery is small enough, therefore restraining the possible implant sites. Furthermore, lifetime of the batteries is limited and even the rechargeable batteries have limited number of recharge cycles before becoming completely unusable.

In recent research works, many techniques have been proposed to power up the implanted devices and to collect the data sensed from them. One of the most expedient approaches is the use of energy harvesting method to power up the device using thermal [7], light [8] and piezoelectric sources [9]. Most of these techniques make use of the external environmental resources of temperature, wind, water, sunlight as energy reservoir. But all these sources are not available in the case of biomedical implanted devices. In the case of thermal energy harvesting, the working environment is restricted so in case of unavailability of thermal sources, therefore it requires an advance arrangement for the alternative powering source such as vibrational source in order to complement the process and hence keep the device running. Using solar energy harvesting also suffers from similar problems regarding the limitation of working environment. The use of implanted and external antennae to wirelessly transmit energy to the implant appears to be a suitable alternative. However, parameters such as human safety, power transfer efficiency and simplicity of electronics imply that the operational frequency must be in the frequency range between 1 and 20MHz [10]. Due to this constraint, the size of the implanted antenna, which is closely related to the electromagnetic radiation frequency, becomes
too large to be implanted. But if inductive coupling is used for both powering an telemetry purposes, it proves to be the most efficient method as it has got several preferential advantages including reliable continuity of supply as compared to that from environmental parameters such as temperature, light etc. Being advantageous from many aspects, inductive coupling has some disadvantages too such as

- More heat generation as compared to other techniques
- Low efficiency
- Emission of harmful magnetic radiations
- More power consumption

A typical research proposes an OP-AMP based inductive coupling circuit to scrutinize the magnetic coupling of two coils that can be used to power up the implanted devices in the microwatt range [11]. The circuit for the powering system is espoused with a transmission coil and a monitoring device and an OP-AMP circuit connected with an inductive sensor. Furthermore, the paper includes some important parameters that need to be taken into consideration while designing an inductive power link. The inductive coupling has been further elaborated in [12] by proposing a system consisting of a reader coil inductively coupled to the sensing circuit, a front end analogue circuit, and a digital signal processing (DSP) unit. The results have been shown in the form of analytical derivations and simulation of a typical telemetric circuit. The simulation is shown to be perfectly matched with the analytical results.

This paper compares two coils and three-coil energy transfer system based upon the phenomenon of inductive coupling in terms of power transfer efficiency. Simulation results show that it is no more a monotonically decreasing function of the distance between the coils if it is tuned to a resonant frequency that can be calculated easily. This is the point where the system shows the maximum performance at a relatively larger operating distance by tuning it to certain required operating frequencies.

The paper is organized such that Section II presents the analysis of telemetry systems containing the subsections (a) and (b) for the modelling and simulation results for two coils and three coils inductive coupling system respectively. Section III presents the discussion and comparisons and section IV concludes with the conclusion.

### 2. Analysis of telemetry system

The power received by the reader side mainly depends upon the separation between the coils or the mutual coupling. Two coils are said to be linked inductively, when the primary coil excited by the external source is able to have a magnetic field induced in the secondary coil, producing a voltage across its terminals as a result.

Mutual coupling, playing a vital role in overall performance of the whole system, primarily depends on the dimensions and positioning of the two coils. Analytically the mutual coupling can be expressed as

\[
M = \frac{\mu_0 N_1 N_2 R_1^2 R_2^2 \pi}{(R_1^2 + x^2)^{3/2}}
\]

(1)

Where M is mutual coupling coefficient

- \(\mu_0\) = permeability of air \((4\pi \times 10^{-7} \text{ H•m}^{-1})\)
- \(N_1\) and \(N_2\) are the turns of primary and secondary coils respectively
- \(R_1\) = radius of the coil in the source loop
- \(R_2\) = radius of the coil in the load loop
- \(x\) = separation between the coil

Assuming \(N_1 = N_2 = 1000\) turns and radius of the coil \(R_1 = 3\text{ mm}\) and \(R_2 = 1\text{ mm}\), varying ‘\(x\)’ between 1mm to 0.1 meter, Equation (1) above is plotted for M as a function of distance as shown in Fig. 2.
It can be observed that mutual inductance $M$ decreases remarkably as the separation between the coils increases. So for higher values of mutual inductance, coils need to be placed near to each other as this determines the value of $K$, the coupling coefficient between the coils given as

$$K = \frac{M}{\sqrt{L_1L_2}}$$

2.1 Modeling and plots for two coils inductive coupling system

As shown in the Fig. 3, the circuit consists of two parts each with a coil separated by a certain distance from the other having a mutual coupling $j\omega M$ between them. One of the coils, connected to the source is the primary coil whereas the other side including load is the secondary coil.

Fig.2: Mutual inductance as a function of distance ‘$x$’

Fig.3: Two coils inductive coupling system
The circuit shown above follows the principle of inductive coupling for transferring the power wirelessly. The currents for each loop can be calculated by applying KVL that comes out to be

\[
\begin{align*}
I_1 &= \begin{bmatrix}
V_s \\
0
\end{bmatrix} - j\omega M \\
Z_{22}
\end{bmatrix} = \frac{V_s Z_{22}}{Z_{11} Z_{22} + \omega^2 M^2} \\
I_2 &= \begin{bmatrix}
Z_{11} \\
V_s \\
0
\end{bmatrix} - j\omega M \\
Z_{22}
\end{bmatrix} = \frac{j\omega M V_s}{Z_{11} Z_{22} + \omega^2 M^2}
\end{align*}
\]

(3)

(4)

The power sent from the source loop equal the source voltage times the current in the source loop that can be expressed mathematically as

\[ P_{sent} = |I_1| V_s \]  

(5)

Whereas the received power for the load/reader loop is given by

\[ P_{received} = |I_2|^2 R_l \]  

(6)

For the parameters used in the circuit in Fig. 3, the power transfer efficiency, \( \eta \), (as a ratio of power received to the power sent) is as shown in Equation (7).

\[ P_{eff} = \frac{P_{received}}{P_{sent}} \times 100 \]  

(7)

Substituting the values of each parametric value, final expression for the power transfer efficiency comes out as shown in Equation (9).

\[ P_{eff} = \frac{|I_2|^2 R_l}{|I_1| V_s R_l} \times 100 \]  

\[ P_{eff} = \frac{|I_2|^2 R_l}{|Z_{22}| |Z_{22} Z_{11} + \omega^2 M^2|} \times 100 \]  

(8)

(9)

Equations (5) and (6) are simulated for the component values of circuit shown in Fig. 3 and the resulting plots are shown in Fig. 4. It can be observed that power received reaches maximum at a frequency of 10 kHz approximately. Maximum power can be transferred if the circuit is tuned to this frequency in order to make this circuit to perform more efficiently.

Fig. 4: Power sent, power received as a function of Frequency

Similarly, as shown in which is shown in Fig. 5, equation (9) can be plotted to show the power transfer efficiency for a fixed resistive load, \( R_l = 15 \Omega \). It can be seen in the plot that the power transfer...
efficiency reaches the maximum value at the same value of resonant frequency. Both power transfer efficiency and resonant frequency can be enhanced by changing the value of $k'$ and load resistance.

2.1.1 Effect of load variations
An increase in the value of load resistance reduces the impedance of secondary coil because they are inversely proportional to each other according to Equation (10). This decrease in impedance increases the power transfer efficiency subsequently. To check the effect of load variations on the power transfer efficiency, Equation (9) is plotted keeping all the parameters constant except the value of $R_L$ varying it from $0\Omega$ to $1000 \Omega$ (Fig. 6). Results show that the power transfer efficiency increases almost linearly with a higher slope until it reaches the maximum at $R_L=110 \Omega$ and then start decreasing. In Fig. 7, the load resistance and frequency both are made variable and the plots show that power transfer efficiency increases with $R_L$ until $100 \Omega$ where it achieves the maximum. After that it becomes constant and only the resonant frequency keeps increasing, even if the load is varied after that.

$$Z = (R_L j \omega L_1) \left( \frac{\omega^2 M^2}{\frac{1}{R_L} + j \left( \frac{\omega}{\omega L_1} \right)^2} \right)$$  \hspace{1cm} (10)

Fig. 5: Power Transfer Efficiency as a function of frequency

Fig. 6: Power transfer efficiency as a function of $R_L$
2.1.2 Effect of changing coefficient of coupling ‘$K$’

As explained earlier in the literature, that the value of coupling coefficient plays an important role in determining the efficiency of an inductively coupled circuit. According to Equation (1) the mutual coupling depends upon the separation distance between the coils. Fig. 2 shows that an increase in the distance between the coils reduces the mutual inductance visibly that eventually reduces the mutual coupling. Fig 7 illustrates the effect of changing value of mutual coupling between the coils and it can be noticed here that the circuit achieves higher power transfer efficiency for a larger value of ‘$K$’. If the coils are placed near to each other, it makes the input impedance independent of frequency changes but it increases the power transfer efficiency effectively. We can conclude that when the distance between the coupled coils is smaller, the value of M is higher and hence the value of ‘$K$’, so the higher power transfer efficiency is achieved.

Fig. 6: The power transfer efficiency as a function of frequency with different value of $R_L$

Fig. 7: Power transfer efficiency as a function of frequency for different values of ‘$K$’
2.1.3 Effect of added capacitance
If a capacitor is added in the circuit as shown in Fig. 2 with dotted lines, it increases the power transfer efficiency immensely because of the fact explained in Equation (10). As the impedance is inversely proportional to the value of capacitance and resistance so an insertion of capacitance reduces the impedance that increases the power transfer efficiency. The capacitive transducers are preferred over the resistive transducers because of their enhanced immunity to the temperature changes. The effect of addition of a capacitor is shown in Fig. 8, where it can be observed that the efficiency has increased up to 95% for $C = 1 \mathring{F}$ but the bandwidth has reduced as well. So it demands to tune the circuit carefully because of this shorter bandwidth.

![Graph showing power transfer efficiency as a function of frequency with a capacitor added.](image)

Fig. 8: The power transfer efficiency as a function of frequency in the presence of capacitor
The dip in the middle is because of the smaller value of capacitance and it can be removed easily by using a capacitor with higher value but the higher value of capacitance will cause some more convergence in the bandwidth of resonant frequency.

2.2 Modelling and plots for three coils inductive coupling system
Figure 9 shows a three coils inductive coil energy transferring system. It consists of a source loop containing the primary coil, a Hub loop containing a coil that is acting as a hub to link the other two inductively and a load loop containing the secondary coil. Two coupling coefficients have been used to couple three coils that can be mathematically termed as $j\omega M_1$ and $j\omega M_2$. For transferring the power to the load loop, it has to go through three coils i.e. primary to the secondary.
Current for each loop can be calculated by applying KVL as done for the two coils system. Assuming the impedance of source loop as $Z_{11}$, hub loop as $Z_{22}$ and load loop as $Z_{33}$, the currents for each loop can be expressed by following equations.

\[
I_1 = \frac{V_s(Z_{12}Z_{23} + \omega^2 M_2^2)}{Z_{11}(Z_{12}Z_{23} + \omega^2 M_2^2) + \omega^2 M_1^2 Z_{23}}
\]

\[
I_2 = \frac{V_s(Z_{21}Z_{13} + \omega^2 M_1^2)}{Z_{22}(Z_{21}Z_{13} + \omega^2 M_1^2) + \omega^2 M_2^2 Z_{13}}
\]

\[
I_3 = \frac{V_s(Z_{32}Z_{21} + \omega^2 M_2^2)}{Z_{33}(Z_{32}Z_{21} + \omega^2 M_2^2) + \omega^2 M_1^2 Z_{21}}
\]

Similarly, the power sent and power received by the load loop can be expressed as follows:

\[
P_{\text{sent}} = |I_1|^2 V_s
\]

\[
P_{\text{received}} = |I_3|^2 R_i
\]

The power transfer efficiency is given by Equation (7) where substituting the values for power sent and power received we get the following expression.

\[
P_{\text{eff}} = \frac{V_s^2}{(Z_{22}Z_{33} + \omega^2 M_2^2)^2}
\]
Equations (14) and (15) are simulated for the component values as shown in Fig. 9 and the resulting plots are shown in Fig. 10 where it can be observed that power received reaches maximum at resonance frequency of $10^3$ Hz approx. this means that at this value of frequency, maximum power is being transferred so for the efficient operation and maximum efficiency the circuit needs to be tuned to this value if the same component values are used.

Fig. 11: Power transfer efficiency as a function of frequency

Fig. 11 shows a plot for power transfer efficiency as a function of frequency which has been plotted using Equation (16). It can be observed that the system shows maximum power transfer efficiency at the resonant frequency of 10 kHz. So it can be concluded that for the component values used for the simulation, this circuit needs to be tuned to the resonant frequency for the maximum power transfer efficiency. It must be kept in mind that the value of $'K'$ and load resistance has the same effects on the performance of circuit as well similar for the two coils inductive system.
3. Discussion and comparison

Equations for currents, power sent, power received and power transfer efficiency for two coils as well as three coils inductive coupling system have been derived using analytical approach. All these equations have been plotted for fixed values of components shown in Fig. 3 and Fig. 9 for both the circuits using MATLAB. The effect of load variations and coupling coefficient ‘K’ is studied for fixed as well as variable frequency. The plots obtained as a result show an evident dependency of the performance of whole system on all these factors. Specially, it depends upon the mutual coupling which refers to the separation between the coils. The smaller the gap between the coils, the more efficient the circuit performs. The power transfer reaches a maximum value at a certain frequency which can be referred to as a resonant frequency for that system and it should be tuned to that frequency to get the maximum output.

4. Conclusion

Inductive coupling can be employed to power up the biomedical implants and buried devices normally in the very low voltage requirement. The source for generation can be the human body itself where energy will be harvested using thermal and piezoelectric transducers. This paper has presented the modelling results for an inductively coupled system using two coils and three coils for wireless transfer of power over small gaps. The effect of mutual coupling and load variations, upon the power transfer efficiency of the system has been studied in detail and illustrated with analytical plots using MATLAB. Results show that the coils placed in close vicinity to each other with a smaller gap separation, perform better for transferring the power. A resonant frequency for both the systems has been obtained at which the maximum power transfer takes place. If the circuit is regulated to this value, then the power transfer efficiency is no more a decreasing function of the changes in frequency, distance and load.

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