

Power optimization techniques for an inductive power transmission system

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Abstract—As the technology is moving towards the world of wireless systems, the concept of inductive power transfer between galvanically isolated coils is becoming significant for low power application. The main advantages are its minimum influence of external atmospheric factors, smooth supply of power to moving systems, least maintenance and ruggedness. In general, the system should be designed in such a way that the received power at the load should not be less than the minimum required power up to a certain distance between coils. This paper proposes the implementation of two different power enhancement techniques for increasing the received power at the load in a two coaxial coil system which is powered by a source having some significant impedance. For these two techniques, analytical model is built and it is followed by simulation and verification by experiment. The first model gives freedom to the user to use it in his own way without changing the design of the circuit; and the second one lets the user design the circuit to obtain more power. By using these two methods; the power as well as the flexibility of the system increase, thereby facilitating the use of inductive power transfer devices.

Index Terms—wireless system; inductive power transfer; moving system; power enhancement; circuit design

I. INTRODUCTION

Wireless power transmission is particularly useful when it is difficult to interconnect wires or it is hazardous or it is impossible to make a wired connection. Throughout all the technological advances in recent years, most electric vehicles [1], medical implants [2], and mobile phones [3] have been continuing to grow and develop by making them more reliable, convenient, effective and comprehensive.

In theory, power can be transferred by different methods such as laser [4], electromagnetic waves [4], electrostatic induction [4] and electromagnetic induction. Laser is a wireless method which transfers power optically. This method converts first the electric power to light for emission. After being received, the laser beam is then transferred back to electric power. Power transfer by electromagnetic waves introduces the use of Radio Frequency in the range of 3 kHz to 300 GHz. In electrostatic induction, power is transferred wirelessly between two electrodes of a capacitor assembly. Table I [5] demonstrates the typical distance of the relevant methods.

Wireless power transmission via inductive links has been around for a long time. It finds a widespread use in modern medicine, and is more precisely in use in implantable electronic devices. We can find high-power transfer which includes battery recharging of electrical vehicles, portable devices such

		Transmitted power	Typical distance
RF	LF	High	< 50 cm
	HF	30-40 W	Up to 2 cm
	UHF	1-3 W	3.5-10 m
	Microwave	1-75 W	Up to 30 m
Laser		High	Long distance
Capacitive		UP to 1-3 W	< 10 mm
Inductive		1 mW-1000 W	< 2 m

TABLE I
 TYPICAL DISTANCE IN DIFFERENT METHODS [5].

as laptop computers and cell phones and a broad range of industrial applications [6].

A very important aspect with respect to energy is the load efficiency and systems are designed to achieve a dc-to-load efficiency above 77% at 6 MHz across a distance of 30 cm by using Class-E amplifiers [7]. Researchers have also gone for different shapes of coils for best performance as for the hexagonal winding array used for wireless battery charging [8]. Use of multiple receivers is also done in order to get more power [9] and it is found out how the system responds in presence of metallic structures [10] as in the case of sensors in removable vehicle seats [11].

But according to the knowledge of the author, very few has considered a system powered by a significant source impedance. Often many systems are powered by source circuits which have different stages of power electronic converters before they feed power to the coils. Due to these pre-stage circuits, sometimes significant source impedance comes into play in the coil system. This impedance, if much greater than the system impedance, consumes much of the power before it even reaches the load. This reduces the efficiency and also causes the load power to decrease to a very low value. This paper discusses two power enhancement methods in case of high source impedance. To take the source impedance into consideration here the circuit has been powered by a signal generator which has an impedance of 50 ohms. For a simple Series-Series (SS) topology [10] the power delivered to the load is given by Fig. 1 using 100 kHz as working frequency and 50 ohms as source impedance. The expression for power at load is given by

$$P_L = \left(\frac{V_{1,rms}}{R_1 + R_r} \right)^2 R_r \left(\frac{R_L}{R_2} \right) \quad (1)$$

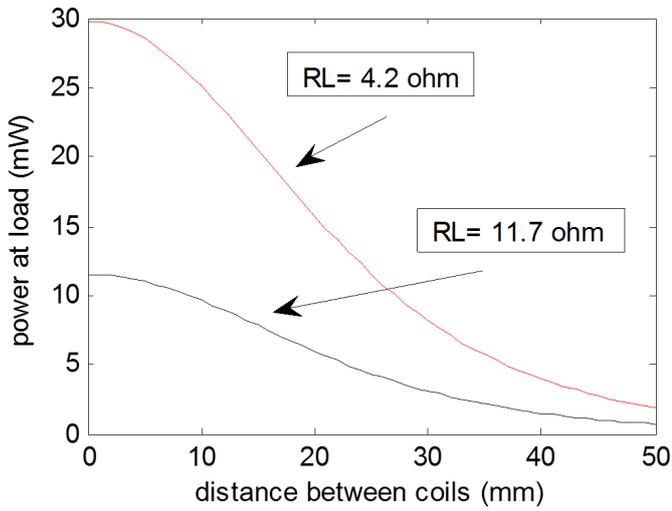


Fig. 1. Power vs. distance.

As it can be observed the simplest system has a falling curve with distance and gives low power at load under significant source impedance. The objective of this paper is to introduce two different techniques that enhance the load power under the same conditions.

II. PARAMETERS

The system that we used here can be best studied in Fig. 2 and also the experimental setup is made up of two such coaxial coils.

The receiving coil is vertically moved to get power at different distances. The coil setup is made to demonstrate the power enhancement techniques that have been formulated in this paper. The coils are manually made and have the following properties.

One of the key factors of this model is to calculate the mutual inductance as a function of distance between the coils. The principle of resonant inductive coupling is used here and under such conditions the mutual inductance is given by [12]

$$M = \frac{\mu_0 \pi N_1 N_2 r_1^2 r_2^2}{2 (d^2 + r_1^2)^{3/2}} \quad (2)$$

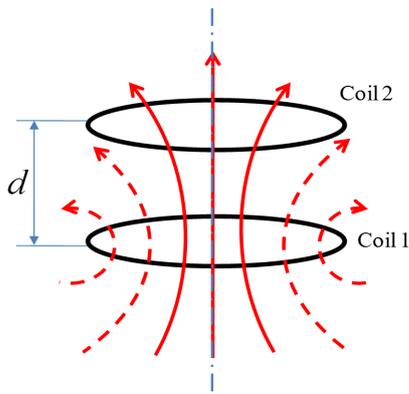


Fig. 2. coaxial coil system.

Properties	Sending coil	Receiving coil
Number of turns	9	9
Radius (mm)	40	32,5
Self-Inductance (μH)	10,384	8,24
Resistance (Ω)	0,12	0,104

TABLE II
COIL PARAMETERS.

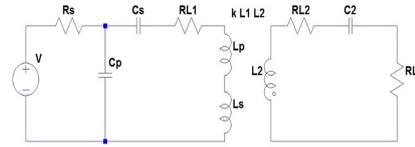


Fig. 3. Impedance matching circuit.

Where N_1 and N_2 are the number of turns in the sending and receiving coils respectively and r_1 and r_2 are the radius of the coils respectively. d is the vertical distance between the coil centres. The system is powered by 10 Volts sinusoidal from the signal generator with a frequency of 100 kHz, not exceeding the self-resonant frequency of the coils. The two working loads 11.7 ohm and 4.2 ohm are chosen arbitrarily.

III. IMPEDANCE MATCHING

A. Analytic and simulation

For maximum power transfer, the load impedance reflected at the primary should be equal to R_s , the source impedance. The circuit is modified using some capacitances at the sending side. The concept that is implemented here is independent of the distance between the coils and the load resistance, therefore giving freedom to the user to use any resistance or distance he wants without changing the circuit design.

Here we add two capacitors, one in parallel with the coil and the other in series as shown in Fig.3. The capacitors are added such that some part of the sending coil self-inductance resonates in series with the series capacitor and the remaining part of the inductance resonates with the parallel capacitor.

At resonance, the series capacitor C_s nullifies L_s , and the circuit looks like a parallel resonant circuit with C_p and L_p . It is important to note that we are working with only sending side, so not taking the effects of mutual inductance and the receiving side. From electrical parallel resonance concept we know that at resonance the total impedance of the resonant circuit is $R_{L1} + \frac{(\omega L_p)^2}{R_{L1}}$. Now to match the impedance R_s , it should be,

$$R_s = R_{L1} + \frac{(\omega L_p)^2}{R_{L1}} \quad (3)$$

and from (3) we get,

$$L_p = \frac{\sqrt{R_{L1}(R_s - R_{L1})}}{\omega} \quad (4)$$

Therefore,

$$L_s = L_1 - L_p$$

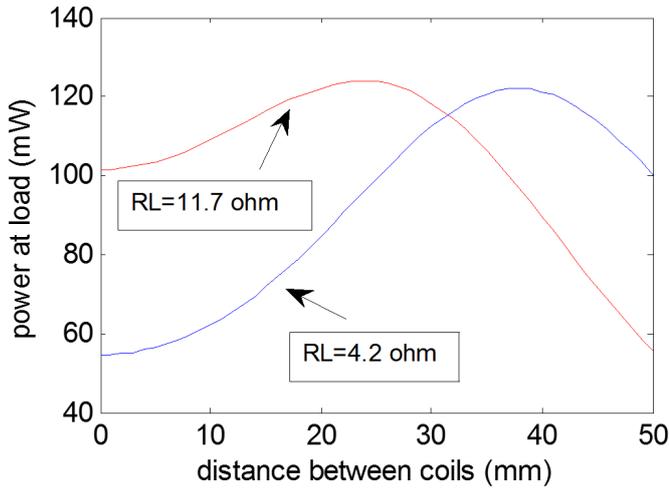


Fig. 4. power vs. distance.

Distance (d) in mm	Sending coil	
	$R_L=11.7\Omega$	$R_L=4.2\Omega$
15	115	72
25	120	95
35	100	119
45	66	109

TABLE III
POWER VS DISTANCE.

$$C_s = \frac{1}{\omega^2 L_s}$$

From parallel resonance,

$$C_p = \frac{L_p}{R_{L1}^2 + (\omega L_p)^2} \quad (5)$$

In our case with $R_s = 50 \Omega$, $L_p = 3.89 \mu\text{H}$, $C_p = 0.65 \mu\text{F}$, $L_s = 6.494 \mu\text{H}$, $C_s = 0.39 \mu\text{F}$. The power at load is calculated and is given by,

$$P_L = \frac{V_{1,rms}^2 R_r}{R_x (R_r + R_{L1})} \left(1 - \frac{R_s}{R_x}\right) \left(\frac{R_L}{R_2}\right) \quad (6)$$

Where, $R_r = \frac{(\omega M)^2}{R_2}$, $R_2 = R_{L1} + R_L$, $R_x = R_s + \frac{R_{L1} + R_r}{A^2 + (\omega C_p R_0)^2}$, $A = 1 - \omega^2 L_p C_p$ and $R_0 = R_{L1} + R_r$. Figure 4 shows the continuous variation of power with respect to distance for two different loads.

It is to be noted that in the actual coil setup the minimum distance that can be taken between the centers of coils is 15 mm due to the thickness of the coils. The simulation has been done using Itspice and the results are as shown in Table III.

The simulation result is close to what is found in analytical results. The coupling factor obtained from the mutual inductance calculation is put in the Itspice circuit to obtain the power curves.

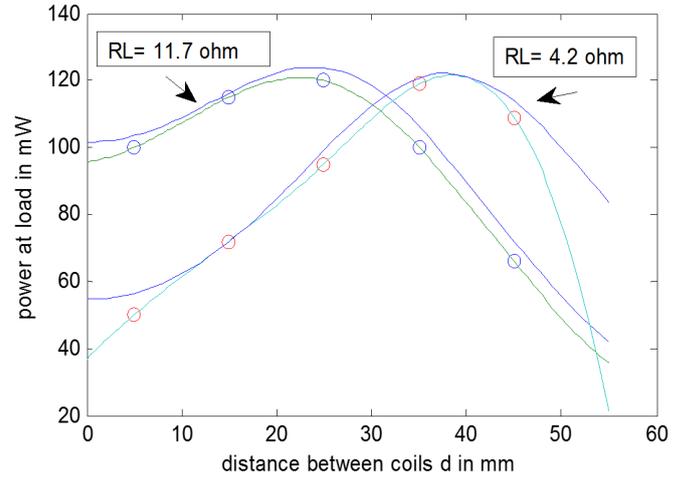


Fig. 5. analytic and experimental.

B. Experimental

The experiment is done keeping all the parameters same. The experimental result is shown along with the analytical results in the Fig. 5 for two different load resistances 11.7 ohm and 4.2 ohm.

It is observed from the graph that the analytical model matches with the experimental results. Fig. 6 shows the power increase compared to the simple method.

The significant characteristics of this method is that the sending side design is independent of the receiving side and it is with the user who will choose the load and best working distance and there is no need to change the sending side design for that. If the source impedance is other than 50 ohms, it is needed to match the impedance and going by the formulas discussed, the power and the tuning capacitors can be again calculated.

IV. ADDITION OF PARALLEL CAPACITORS

A. Analytic and simulation

The motivation of this type of circuit will be explained by the circuit shown in Fig. 7. This is the simplest equivalent circuit where R_1 represents all the impedances in sending side including the source impedance and R_r represents the reflected impedance of the receiving side. As told earlier, due to high source impedance, R_1 is more than 50 ohms whereas R_r is of the order of 1 ohm. The idea is to increase R_r so that most of the power is delivered to the receiving side.

Power transferred to the load side $P_t = I^2 R_r$. Now $R_r = (\omega M)^2 / R_2$, where R_2 is the total impedance at the receiving side at resonance. Thus to increase R_r we have to reduce R_2 . For that we add a capacitor across the load and tune it for parallel resonance. The receiving side is as follows:

At resonance, Power delivered to the load = $P_L = P_t - I^2 R_{L2}$
Also $P_t = I^2 R_2$, so $I^2 = P_t / R_2$

$$P_L = P_t (1 - R_{L2} / R_2) \quad (7)$$

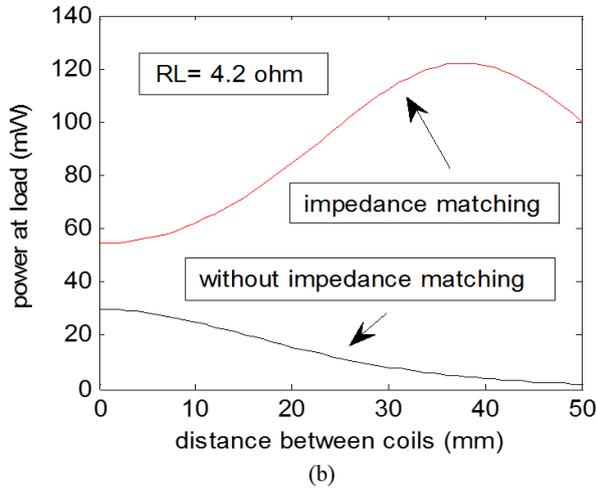
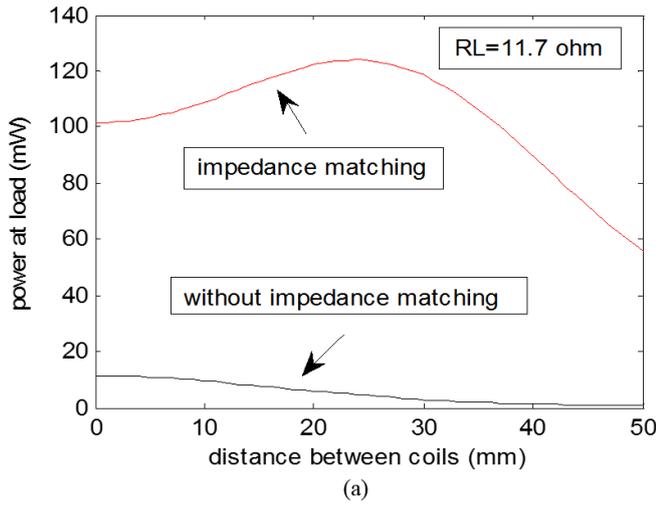


Fig. 6. (a) power at 11.7 ohm (b) power at 4.2 ohm.

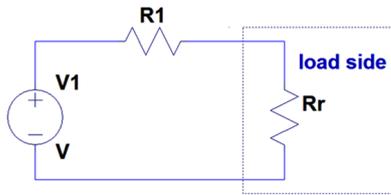


Fig. 7. equivalent circuit.

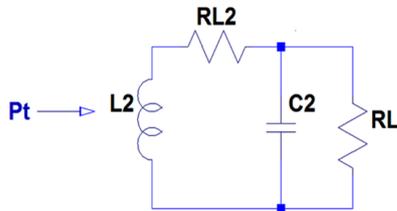


Fig. 8. receiving side circuit.

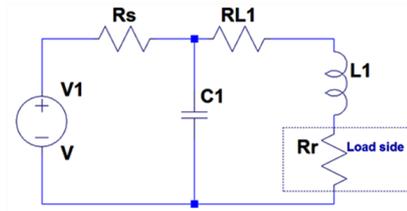


Fig. 9. equivalent circuit.

The total impedance at the receiving side is given by,

$$Z_2 = R_{L2} + j\omega L_2 + \left(R_{L1} \parallel \frac{1}{j\omega C_2} \right) \quad (8)$$

At resonance imaginary part is zero and by calculation we get,

$$C_2 = \frac{R_L^2 \pm \sqrt{R_L^4 - (2\omega R_L L_2)^2}}{2L_2(\omega R_L)^2} \quad (9)$$

For real values of C_2 , $R_L > 2\omega L_2$
In our case $2\omega L_2 = 10.3$ ohm

So R_L needs to be greater than 10.3 ohm to get parallel resonant working tuned capacitor C_2 . At resonance, $Z_2=R_2$, and

$$R_2 = R_{L2} + \frac{R_L}{1 + (\omega C_2 R_L)^2} \quad (10)$$

Now since $R_r=(\omega M)^2/R_2$, to increase R_r , we need to decrease R_2 which implies we need to increase C_2 . So we take the '+' value of C_2 . Thus, with suitable choice of capacitor, R_2 is reduced and the load power is obtained as $P_L = P_t(1R_{L2}/R_2)$. Another capacitor is added in parallel in the sending side to serve the same purpose and the total circuit looks like Fig. 9.

Here $Z_1 = R_s + (R_{L1} + R_r + j\omega L_1) \parallel 1/j\omega C_1$
 $R_0=R_{L1}+R_r$, say

At resonance $Z_1= R_x$, and the value of C_1 is given by

$$C_1 = \frac{L_1}{R_0^2 + (\omega L_1)^2} \quad (11)$$

And

$$R_x = R_s + \frac{R_{L1} + R_r}{A^2 + (\omega C_1 R_0)^2} \quad (12)$$

Where; $A = 1 - \omega^2 L_1 C_1$ Power transferred to the receiving side = Power transferred to $R_r = I_r^2 R_r = P_t$ Equating the resistive power losses and by calculation power is given by,

$$P_L = \frac{V_{1,rms}^2 R_r}{R_x(R_r + R_{L1})} \left(1 - \frac{R_s}{R_x} \right) \left(1 - \frac{R_{L2}}{R_2} \right) \quad (13)$$

It is found that the load resistance needs to be greater than 10.3 ohm to get parallel resonance in the receiving side. So we cannot use the data of 4.2 ohms to compare with this method, instead 11.7 ohm can be used. It is to be noted that C_2 depends

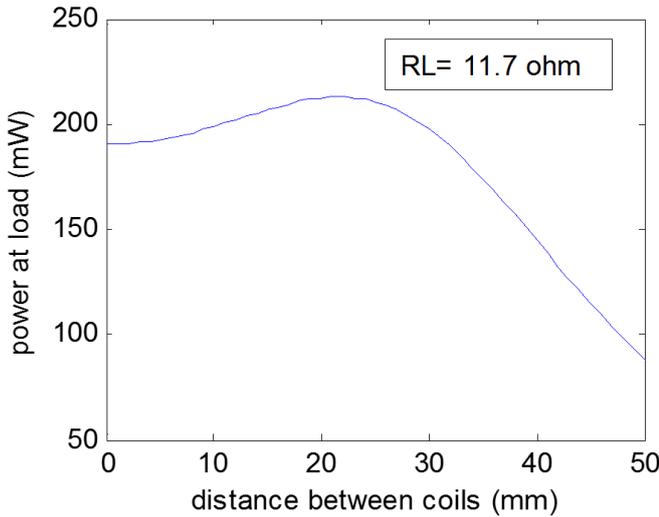


Fig. 10. power vs distance.

Distance d in mm	Capacitances used	Power in mW
15	$C_1 = 0.23 \mu\text{F}$, $C_2 = 0.225 \mu\text{F}$	205
25	$C_1 = 0.239 \mu\text{F}$, $C_2 = 0.225 \mu\text{F}$	209
35	$C_1 = 0.2424 \mu\text{F}$, $C_2 = 0.225 \mu\text{F}$	174
45	$C_1 = 0.2434 \mu\text{F}$, $C_2 = 0.225 \mu\text{F}$	110

TABLE IV
POWER VS DISTANCE.

on the load and C_1 depends both on load and distance between coils. So it can only be used when we have a fixed distance and a fixed load.

The relation between power and distance at a fixed load of 11.7 ohm is shown in Fig. 10. Here since the load is fixed, C_2 will remain constant but every time the distance changes C_1 changes and it is difficult to implement this behavior with changing distance in real circuit. This power curve is particularly useful to find out the best operating distance at a fixed load and then fix that particular distance.

It is evident from the curve that the power has increased by quite some factor than previous values and maximum power is given somewhere around 25 mm. Keeping all the other parameters same the simulation is done in Itspice for 11.7 Ω . Each time the distance changes, the corresponding tuning capacitance changes.

The results match with the analytical values. The next section goes for the experimental values.

B. Experimental

The experiment is done keeping all the parameter same. The experimental result is shown along with the analytical results in the Fig. 11 for the load resistance 11.7 ohm.

It is evident from the curve that the analytical model matches with that of the experiment. The next section will deal with the comparison of two methods.

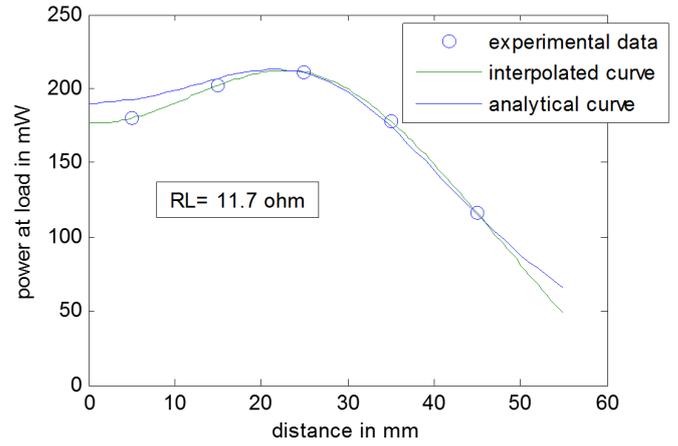


Fig. 11. analytic and experimental.

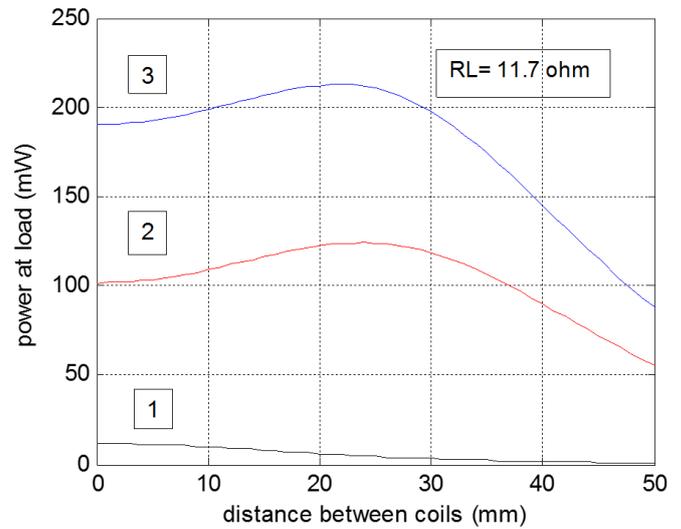


Fig. 12. comparison curve: (1) without power improvement methods, (2) impedance matching and (3) addition of parallel capacitors.

V. COMPARISON OF METHODS

A. Comparison

It is clear from the curves that there is significant increase in power with the application of these methods. Although they have their own advantages and disadvantages. The comparison curve is shown in Fig. 12.

The maximum power is obtained with the addition of parallel capacitor followed by impedance matching. However, although the maximum power is obtained by parallel capacitor method, the main disadvantage is that the tuning capacitors depend on the load and distance between coils. C_2 depends on the load and C_1 on the load and distance. So to use this, the load and the distance should be fixed, whereas in the impedance matching method there is no need to change the design of the capacitors as they do not depend on load or distance. The user needs not change the circuit and can use in accordance with the power curve to get the desired load and

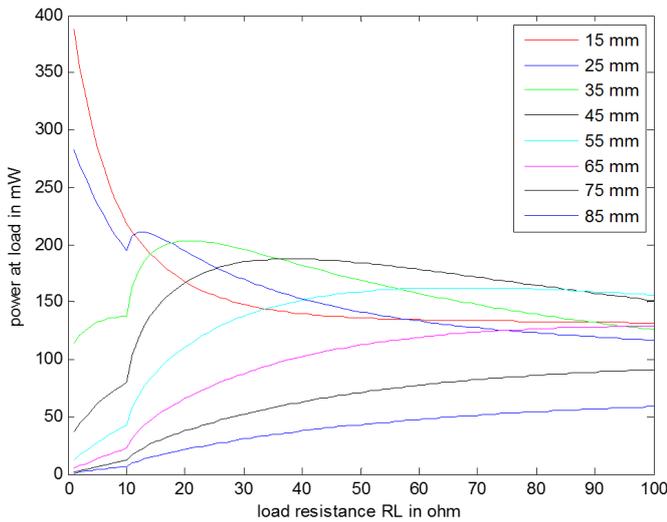


Fig. 14. power vs. load.

distance between coils.

B. Design approach

For the method with parallel capacitors it is important to design the system properly. For maximizing power transfer, a particular design approach can be followed in this case. If the user specifies the distance and not the load, it is very useful to find out the load at which power becomes maximum. First it should be looked how the curve changes with resistance at fixed distance in Fig. 14.

It is found that for every fixed distance there is a load at which power becomes maximum, except for 15 mm and 25 mm. Also the power does not drop below 50 mW even at 100 ohm resistance and 85 mm distance between coils. Therefore first we find the load at which the power becomes maximum and then fix that load and distance and design the corresponding capacitances.

There is one important feature to be noted in all these curves that it gives good amount of power at greater distance and at higher load. If we compare with the first case without any power improvement methods, it is found that in that cases the power gradually falls with increasing distance and at, say 65 mm, the power is very small.

In this case at 65 mm, it is giving more 120 mW of power at 100 ohm load, even at 85 mm distance between coils it is giving 60 mW of power at 100 ohm load. If we extend the concept further, it can be suggested that this method is particularly useful when the load resistance is very high. Fig. 15 shows the power variation at 65 mm and 85 mm when the load varies up to 1000 ohm.

It is observed from the curve that power is more than 40 mW at 65 mm distance even at 1000 ohm and it is more than 30 mW at 85 mm distance for the same resistance. Suppose if there is some sensor node which needs at least 30 mW to work, we have a wide range of distance and load, the load can

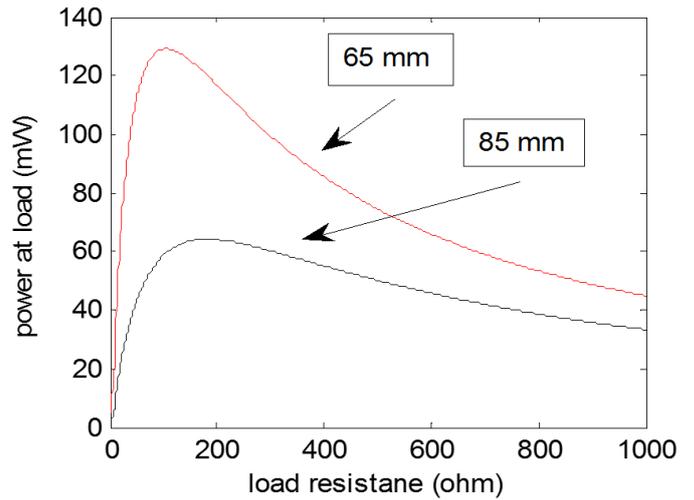


Fig. 15. power vs. load.

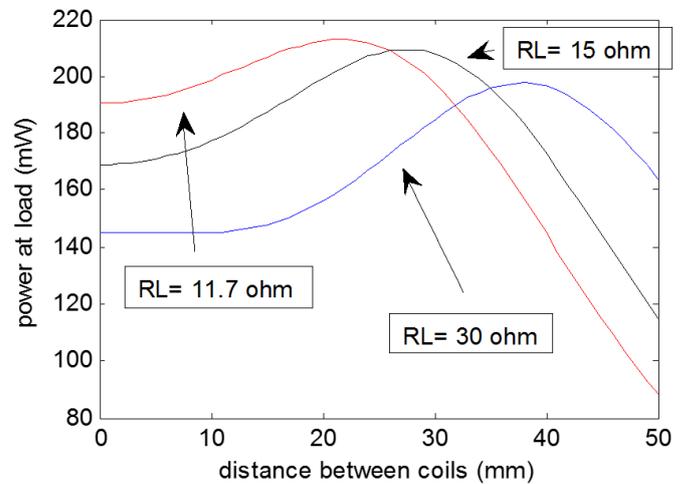


Fig. 16. power vs. distance.

vary up to 1000 ohm and the distance can vary up to 85 mm, giving more flexibility to the system.

There can be another approach if the user specifies the load. Then it is needed to find the best distance at which it gives maximum power. The following curve shows the change of power with distance at three fixed loads.

VI. CONCLUSION

The objective was to increase the received power at the load by using the two propositions made earlier. Whatever circuit we build we cannot avoid source impedance and in this project we found out ways to minimize the effect of source impedance and decrease the power shared by that impedance, thereby maximizing the transferred power.

The proposition which gives the best power is adding parallel capacitors both at the sending and receiving sides. It is very useful if the distance between coils and the load resistance are fixed. As discussed earlier, if either of the distance between coils or load is fixed we can find the best possible situation

where the load power is maximum and design the circuit accordingly. The only disadvantage is for designing the tuning capacitors the distance between coils, or to be exact the mutual inductance and the load resistance have to be fixed.

The impedance matching method is the best when the receiving side is required to be independent to the sending side. For each load there is a particular distance where the power is maximum, the user just needs to find that load distance pair where the maximum power is achieved. There is no need to tune the capacitors at the sending side, as it is independent with the receiving side. Suppose the user wants to run a sensor node which has a resistance of 20 ohms. He has to find the power curve at 20 ohms and find the best distance. Now if he wants to change the load to 5 ohm, he has to again adjust the distance to get maximum power. In a word, the user designs the circuit in his own way without affecting the sending side.

Other than these three methods, for more power the coils can be improved by increasing the number of turns and the quality factor. Also the diameter of the wire and the diameter of the coils can be changed to increase transferred power. The coil can be best optimized for best power. On the other hand, the source impedance can be made low by using different suitable circuits, discussed in various literatures. The best thing is to find out the required power and design the circuits and the coils accordingly. Discussing other different techniques is outside the scope of this paper and it concludes here with these two different power optimization techniques.

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