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Parameters Effecting Performance of Wireless Power Transfer System

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Abstract Wireless power transmission (WPT) is the transmission of electrical energy without using any conductor or wire. It is useful to transfer electrical energy to those places where it is hard to transmit energy using conventional wires. This paper investigates the effect of various parameters of the design of magnetically-coupled resonant circuits for non-radiative WPT . Such as coils diameter, number of turns, wire diameter, spacing between turns (pitch), load resistance, and frequency and their influence on the efficiency and power delivered to the load. Results are presented in the form of plots for power transfer efficiency of the system to show the comparison of power and efficiency with distance.

Keywords: Wireless Power Transfer, Magnetic Resonant Coupling, Quality Factor.

العوامل المؤثرة على اداء منظومة نقل للطاقة لاسلكيا

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ملخص نقل الطاقة لاسلكيا هو عبارة عن ارسال الطاقة الكهربية بدون استخدام أي نوع من انواع الموصلات او الاسلاك. وهذا ذو اهمية بالغة عند تحويل او توصيل الطاقة الكهربية للاماكن التي يصعب فيها نقل الكهرباء بطريقة الاسلاك التقليدية . في هذه الورقة تمت دراسة العديد من العوامل المؤثرة على اداء عمل منظومة نقل للطاقة لاسلكيا المصممة على مبدأ رنين الربط المغناطيسي .من هذه العوامل ، قطر الملف، عدد اللفات، قطر السلك المستخدم للملف، المسافة ما بين اللفات، مقاومة الحمل و التردد المستخدم وتأثير هذه العوامل على كفاءة المنظومة و القدرة المعطاة للحمل .قدمت النتائج على صورة رسومات تبين ارتباط التغير في الكفاءة و القدرة الموصلة للحمل مع المسافة.

الكلمات المفتاحية: تحويل القدرة لاسلكيا، ربط الرنين المغناطيسي، معامل الجودة .

Introduction

The initial idea of wireless power transmission (WPT) by magnetic resonance method was introduced by Nikola Tesla in the period 1891 to 1904 [1].Tesla achieved a great progress by designing a resonance transformer that was recognized as Tesla coil and transmitted million volts of electrical energy to a distance of miles and lit lamps and turned on an electric motor. Unfortunately, Tesla's experiments were halted due to lack of financial resources and he failed to finish his plans. Wireless power transmission (WPT) is an efficient way for the transmission of electric power from one point to another through vacuum or atmosphere without the use of wire or any substance. Using this technology, it is possible to supply power to places, which is hard to do using conventional wires. Wireless power transfer can be done via electric field coupling, but electric field coupling provides an inductively loaded electrical dipole that is an open capacitor or dielectric disk. Extraneous objects may provide a relatively strong influence on electric field coupling. Magnetic field coupling may be preferred, since extraneous objects in a magnetic field have the same magnetic properties as empty space. Since magnetic field coupling is a non-radiative power transfer method, it has higher efficiency. However, power transfer range can be increased by applying magnetic coupling with resonance phenomenon applied on. Recently, a highly efficient mid-range wireless power transfer technology using magnetic resonant coupling was proposed by a research group led by Marin Soljacic from MIT in 2007 [2] . It is a system that transfers power between two resonating coils. They used a self-made wireless power device to power a 60-watt bulb from a distance of 2m, with an efficiency of 40–50%. The appearance of this technology breaks the traditional model of electromagnetic induction transmission for which efficiency strictly depended on the coupling coefficient of coils. Wireless power transmission distances were extended from the millimetre to the meter range [3–8]. This represented a breakthrough in wireless power transmission technology. With the development and application of wireless power transmission technology based on magnetic resonance coupling، parameters optimal design and optimal control for the power transmission process have become the focus of research [9–13]. To maximize transmission power or transmission efficiency, [10–12] analysed the influence laws of operating parameters on the transmission performance، optimized load value, coil size, and quality factor of the system. However, with coupling coefficients between coils, as key parameters in system design, no optimal conclusion was drawn. Furthermore, influence laws of operating parameters on the transmission stability were not investigated. On the other hand, although magnetic resonance has significant advantage in transmission distance compared with electromagnetic induction, this technology has intrinsic limitation as the load absorption power is sensitive to variations in the operating parameters, and small differences in operating and resonance frequency will reduce transmission performance significantly. In this paper parameters affecting wireless power transfer system such as coil diameter, number of turns, wire diameter, spacing between turns (pitch), load value and frequency were investigated.

Possible methodologies for WPT system: By using WPT power can be transmitted using one of the most common technologies such as:

1-Inductive coupling: Two devices are said to be mutually inductively coupled when they are configured such that change in current though one wire induces a voltage across the ends of the other wire by electromagnetic induction. This is due to the mutual inductance such as in transformer. In the case of Inductive coupling the range is very small also the interaction is one-one only and finally efficiency of transmission is very small.

2-Resonant inductive coupling: Resonant inductive coupling is the combination of both inductive and resonance coupling. Using the concept of resonance it makes the two objects to interact with each other very strongly. Inductance induces current in the circuit with a capacitor is connected in parallel to the coil, energy will be shifting back and forth between magnetic field surrounding the coil and electric field around the capacitor. Here the radiation loss will be negligible, the efficiency is high (around 70.3%), and the range of transmission is high and one to many mode of transfer is possible.

3-Electromagnetic wave: Electromagnetic wave power transfer is suitable for long range, it is also called as Solar power satellite William C.Brown, the leading authority on wireless power transmission technology, has loaned this demonstration unit**.**

4- Laser Technology: The LASER technology is another efficient way of wireless power transmission. It uses the same possibility as microwave wireless transmission but here energy emission is of high frequency. The other great advantage of LASER power transmission is the small sized aperture collection efficiency of the antenna. LASER transmission does not get dispersed for long distance but it gets attenuation when it propagates though atmosphere and requires existence of an uninterruptible line-of-sight and a complicated tracking system in the case of mobile objects.

Resonant inductive coupling: Wireless power transfer is similar but not same as traditional magnetic induction, such as is used in power transformers, where conductive coils transmit power to each other wirelessly, over very short distances. Wireless charging is the transmission of electrical energy from a power source to an electrical load without physical conductors. It works on the principle of mutual induction between the two, transmitter and receiver coils as in Fig.1 (a). But the major drawback with this technique is that a large amount of this power transmitted is lost in air if the range between the two coils increases. Any conducting material in its vicinity draws power which must not occur.

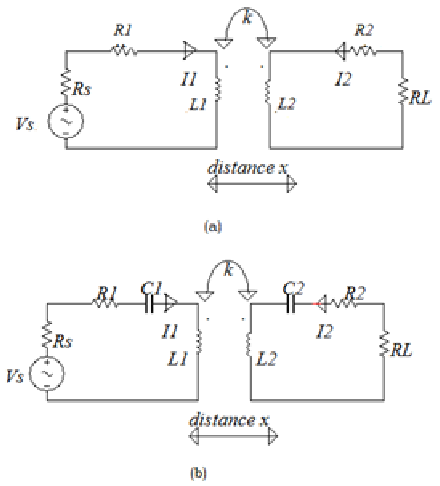

Fig.1: Inductive coupling (a) Resonance inductive coupling (b) of WPT.

So, in order to prevent these draw backs the transmitter and the receiver are made to couple through resonance. The power transfer becomes efficient if we use resonant inductive coupling. Resonant inductive coupling is the near field wireless transmission of electrical energy between two coils that are tuned to resonate at the same frequency. Resonant transfer works by making a coil ring with an oscillating current this generates an oscillating magnetic field. Because the coil is highly resonant, any energy placed in the coil dies away relatively slowly over very many cycles; but if a second coil is brought near it, the coil can pick up most of the energy before it is lost, even if it is some distance away [14]**.** At resonance, the stored electric energy and stored magnetic energy are equal. Circuits consisting of inductors and capacitors have a certain resonant frequency at which the stored energy is released. The quality factor (Q-factor) is a dimensionless quantity that measures the amount of energy stored in the reactive components to the power lost due to resistance. A higher Q-factor means that less power is lost at resonance. A simple wireless power transmission system consists of a transmitter and a receiver coils as shown in Fig.1 (b). The transmitter is represented by the source v_s. and its internal resistor *Rs*, the capacitor C_1 and the inductor L_1. While C_2 and L_2 are the capacitor and the inductor that achieve the resonance to transfer the power to the load resistor R_L. The resistances R_1 , R_2 are the small resistances of the coils themselves . Due to the inductance value of each coil, capacitor values are chosen to achieve the resonance condition $XL=X_C$, through the resonance frequency equation [15].

Applying Kirchhoff's law of voltage on each loop (the transmitter and the receiver) is the start of the analysis. For inductive coupling the equations are [16]:

$V_s = (R_s + R_1 + i\omega L_1 + 1/i\omega C_1)I_1 + i\omega M_{12} I_2$ (1)

$0 = i\omega M_{21} I_1 + (R_2 + R_L + i\omega L_2 + 1/i\omega C_2)I_2$ (2)

Where ω=2πf, I_1 and I_2 are the loops currents and $M_{12} = M_{21} = M$ is the mutual inductance between the transmitter and the receiver.

For perfectly aligned coils the mutual inductance of two parallel single-turn coils separated a distance x, can be calculated as:

$$M = \mu_0 \sqrt{r_1 r_2} \left[\left(\frac{2}{k} - k\right) K(k) - \frac{2}{k} E(k)\right] \quad (3)$$

Where $k = \left(\frac{4r_1 r_2}{(r_1+r_2)^2 + x^2}\right)^{1/2}$ (4)

and $K(k)$ and $E(k)$ are the complete elliptical integrals of the first and second kind, respectively [17]. For resonance inductive coupling the equations are:

$\omega L = 1/\omega C,\ \omega = 1/\sqrt{LC}$ (5)

$V_s = (R_s + R_1)I_1 + i\omega M_{12} I_2$ (6)

$0 = i\omega M_{21} I_1 + (R_2 + R_L)I_2$ (7)

$$\begin{bmatrix} V_S \\ 0 \end{bmatrix} = \begin{bmatrix} (R_s + R_1) & i\omega M_{12} \\ i\omega M_{21} & (R_2 + R_L) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (8)$$

Solving this set of equations the output power P_L,input power P_{in}, internal source resistance power P_s and the efficiency can be calculated as:

$P_L = I_2^2 \times R_L$, $P_{in} = I_1^2 \times R_1$, $P_s = I_1^2 \times R_s$ (9)

Efficiency η

$$\eta = \frac{P_L}{P_L + P_{in} + P_s} 100\% \quad (10)$$

Results and discussion: Initially, a basic tow identical-coils of radius 25 cm, 30 turn, winding diameter 0.2258 cm and pitch equal to winding diameter was simulated using a matlab program .The variations of the efficiency and the power delivered to 100 Ohm load resistance with distance between the coils were investigated. A single power source of internal resistance 50 Ohm, amplitude 50V and resonance frequency of 100 KHz was considered for this case. The results of this design which considered as a reference case for comparisons sake are shown in Fig.2. From the figure it can be seen that the maximum power transferred to the load is 12.3 watts at separations distance between coils of 30.66 cm and the efficiency is 49%.The load power and the efficiency decreases as the separation distance between coils increases due to the decreasing of the coupling factor k between coils at the transmitting and receiving points. Quality factor-Q of 690 was recorded for this design.

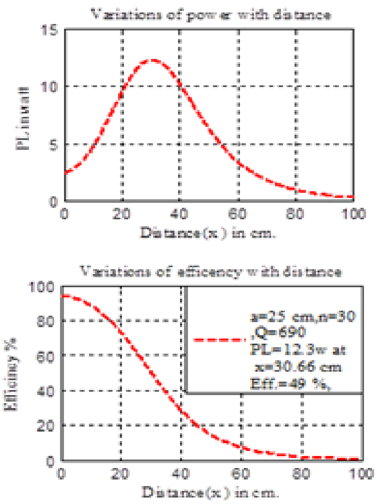

Fig.2: Variations of load power and efficiency with distance.

1-Effect of coil diameter: The plots in Fig.3 illustrates that as the diameter of the coils increases the maximum power delivered to the load and the efficiency remains constant at nearly 12.3 watt and 49% respectively. But the distance at which this power and efficiency values occurs increases due to the increase of the mutual inductance and hence the cupling factor between the tow coils.The Q-factor also increases with coil diameter .

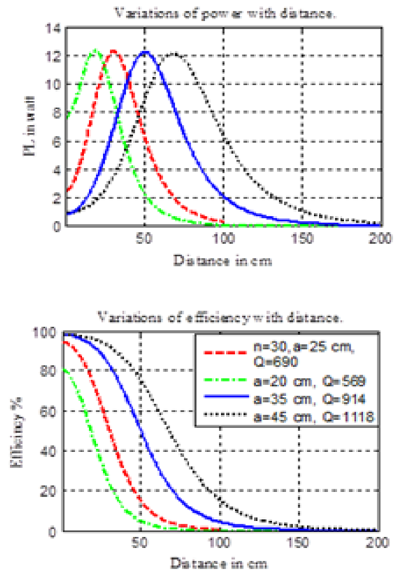

Fig.3: Variations of load power and efficiency with distance for different coil diameters.

2-Effect of turn's number: Four different numbers of turns 30,40,50,60 for the coils were considered. Their effect on power delivered to the load and efficiency shown in Fig.4. As the number of turn's increases the maximum power delivered to the load and the efficiency also remains constant at nearly 12.3 watt and 49% respectively as in the previous case for different coil diameters. But the distance at which this power and efficiency values occurs increases due to the same resons mentioned above . The Q-factor does't change that much with number of turns .

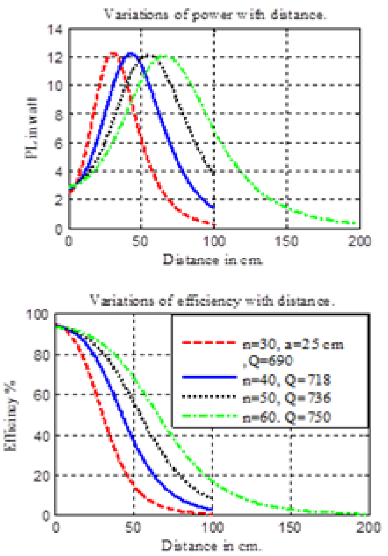

Fig.4: Variations of load power and efficiency with distance for different number of turns.

3-Effect of pitch: The variations of power transferred to the load and the efficiency with distance between the coils for different spacing between turns (pitch) that is equals to wire diameter (dw), (2dw) and (3dw) shown in Fig.5. All other parameters remain fixed as in the reference case dashed red line in the figure. There is no affect seems to be on the properties under investigations efficiency, power delivered to the load and Q-factor.

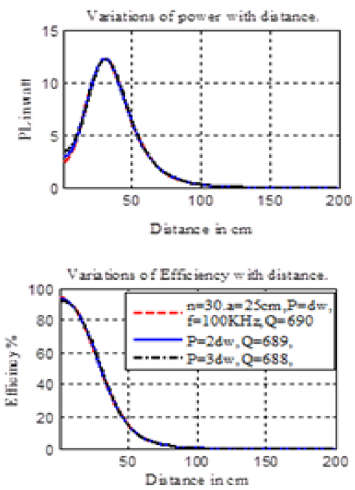

Fig.5: Variations of load power and efficiency with distance for different pitches.

4-Effect of wire diameter: The variations of power transferred to the load and the efficiency with distance between the coils for different wire diameters (dw) that is equals to 0.2258 cm, 0.3 cm and 0.5 cm shown in Fig.6. All other parameters remain fixed as in the reference case dashed red line in the figure. There is no affect seems to be on the properties under investigations efficiency, power delivered to the load but the Q-factor increases as the wire diameter increases.

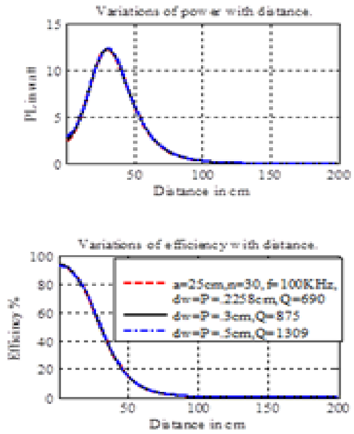

Fig.6: Variations of load power and efficiency with distance for different wire diameters.

5-Effect of frequency: Three different frequencies 100 KHz, 0.5 MHz and 1 MHz were considered. Their effect on power delivered to the load and efficiency shown in Fig.7. There is a noticeable increment of the distance at which efficiency and the maximum power transferred to the load occurs with the change of frequency as compared with other parameters. This is an indication for that to transfer power for long distance the frequency should be increased. The Q-factor is highly increased as the frequency increases.

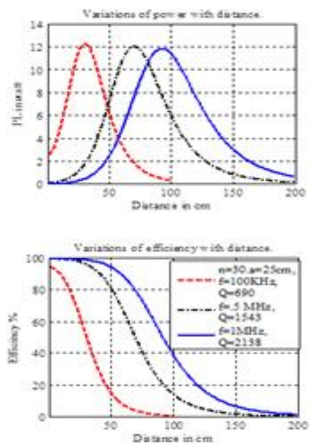

Fig.7: Variations of load power and efficiency with distance for different frequencies.

6-Transferred power and efficiency vs. .frequency: The plots in Fig.8 illustrate the variations of efficiency and power transferred to the load with frequency. The maximum power value delivered to the load is 12.3 watt at frequency of 100 KHz which is the resonant frequency of the desgin .The efficiency is 49% . These values are as same as that recorded in the case of the initial desgin since all other parameters such as coils specifications and separation distance etc. are the same.The power decreased as the frequency increased above the resonant frequency while the efficiency increased until six times of resonant frequency and then remain constant.

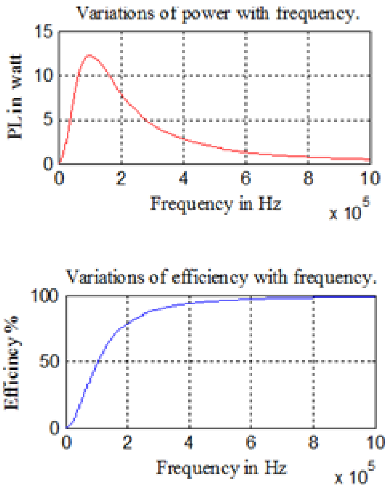

Fig.8: Variations of load power and efficiency with frequency.

7-Transferred power and efficiency vs. RL: The variations of power transferred to the load and the efficiency with the load resistance *RL* is depicted in Fig.9. Their values remain at the same figure of 12.3 watt and 49% respectively as in the previous cases and occurred at *RL* of 100 Ohm which is the load resistance of the desgin. For small values of *RL* the efficiency reaches up to 86% and decreased with increasing the value of *RL*, while the transferred power increases to reach its maximum value at *RL* equals to 100 Ohm and decreases for higher values of *RL*.

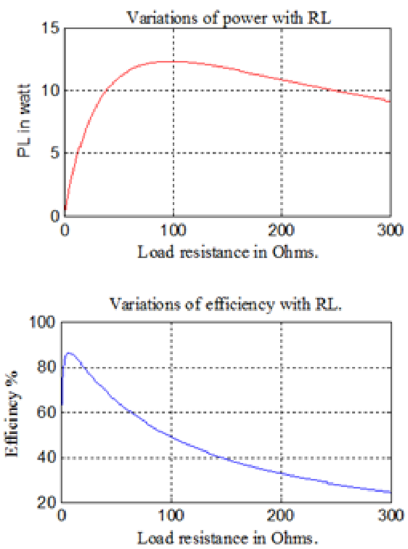

Fig.9: Variations of load power and efficiency with load resistance *RL*.

Conclusion: The effects of various parameters of wireless power transfer WPT system such as coil size, distance between coils and the frequency on its performance were investigated. The mutual inductance and hence the coupling factor between any two coils depends on their shape, their location and the distance between them. Most of these parameters found to have pronounced effect on the distance at which the maximum of the power transferred to the load and the efficiency of the system occurs but not on their maximum values .The resonance frequency has enormous effect among other parameters. In such wireless power transfer WPT system the total power that is supplied by the ideal source does not reach to the load because of the power loss in resistances in the system. The dominant loss occurs in the internal source resistance. This loss occurs whenever a source delivers power to a load, whether through wires or through a wireless power transfer method. Approximately half of the remaining power is delivered to the load resistance.

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