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Optimal Physical Coil Separation Condition for Wireless Charging System

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Abstract: ***Now-a-days, wireless transfer of electric power has received much attention in the world arena. As a safe, reliable and convenient technology, Magnetic resonance coupling (MRC) based wireless power transfer (WPT) system shows a remarkable ability to power up in a wide range from mW to kW range. In this paper conventional magnetic field analysis with maximum power transfer theorem has been used to explain the frequency characteristics of the transferred load power. The intensity of magnetic field, induced receiver voltage, physical air gap of coils relating to the dimension of the coils has been examined. The experimental results are well agreed with the theoretical results. The acquired analysis depicts the optimal physical separation condition relating to the size of the charging coils of a WPT system.***

Keywords: Magnetic circuit model; Optimal separation condition; WPT system

I. INTRODUCTION

With the rapid advancement of consumer portable electrical/electronic appliances in recent years, it is expedient to introduce a reliable technology to power up wirelessly, even in short to medium range [1-4]. There are numerous such technologies still existing and magnetic induction based wireless power transfer is one of them. Although, inductive coupling based WPT system is very well-known technology and frequently used, due to poor efficiency, it is practically almost restricted to use now [5-8]. In order to avoid the above situation, MRC based WPT system is introduced in 2007 and till date appealed the world's attention as most effective non-radiative power transfer technique over short to midrange. It is based on the fact that, two objects are inclined to couple strongly if they are operated at same frequency whereas interacted very weakly with the others non-resonated objects.

Even though RIC-WPT system is proved to be better in efficiency, compared to its contemporary technology but so far not adopted worldwide as the best one due to its poor low power delivery capability even at perfectly tuned condition [9-14]. Generally RIC-WPT system comprises of two major parts, RF power electronic circuit at transmitter and at the receiver side and the resonant inductive link. With noteworthy advancement in semiconductor technology, significant contribution is achieved from RF parts where as much improvement is still expected from the resonant inductive link in order to hold the future RIC-WPT system.

There are different models based on circuit theory, magnetic field theory, coupled mode theory, reflected load theory and HF transformer principle are available in order to analyze MRC based WPT system. It is also been noticed that power transfer capability of the system is mostly reliant on the mutual coupling, which is purely a coil design dependent parameter. In general, the mutual coupling depends on, no. of turns in the coils, shape and size of the coils, air gap between the coils, materials used and more importantly the depth of coupling. With implementation of litz wire for designing the transmitter and receiver coil, it will be even more complicated to estimate the mutual inductance and its accuracy in use with different models to analyze different characteristics of MRC based WPT system. Again, coils structure and dimension once designed are remain fixed and can't be changed in order for maximum power transfer. So, magnetic field theory will be considered as most appropriate model to analyze MRC based WPT system with utmost accuracy. In this work magnetic field analysis with equivalent circuit model have been realized incorporating the coil design parameters to characterize the magnetic field strength, mutual coupling, induced voltage and the optimal separation gap between the coils of a resonant inductive link for maximizing the load power. By this proposed method, the ideal position of the receiver coil in MRC based WPT system can be estimated and maximum power transfer to load can be calculated.

II. DESIGNED WPT SYSTEM AND MECHANISM

A high frequency voltage source is supplied as input to the resonant inductive coupled circuit comprising of coils in the transmitter and receiver sides. The experimental setup of this system is visualized in Fig. 1. The inclusion of an external capacitor in the transmitter circuit provides resonance in series to the transmitter coil which makes possible for a maximum amplitude high frequency current from the high frequency voltage.

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Flux generated in the transmitter coil is captured by the mutually coupled receiver coil prompting efficient energy transfer between the inductive links. A compensation capacitor is connected to the receiver coil to enhance the power transfer ability. It also enables resonance in the receiver coil at similar operating.

The regulator circuit eventually processes the voltage at the receiver for further application.

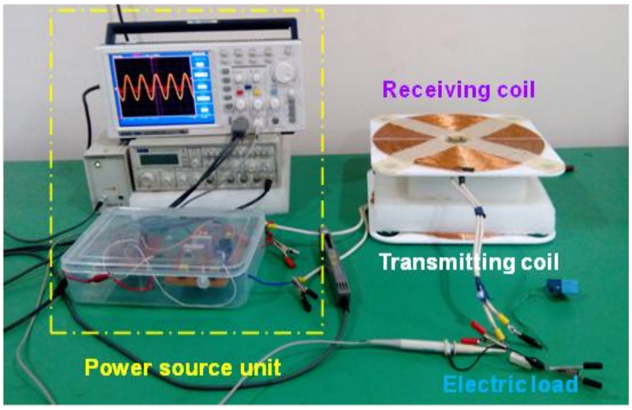

Fig. 1: Designed setup for maximum power transfer in resonant coupled system [11].

III. THEORETICAL CIRCUIT MODEL

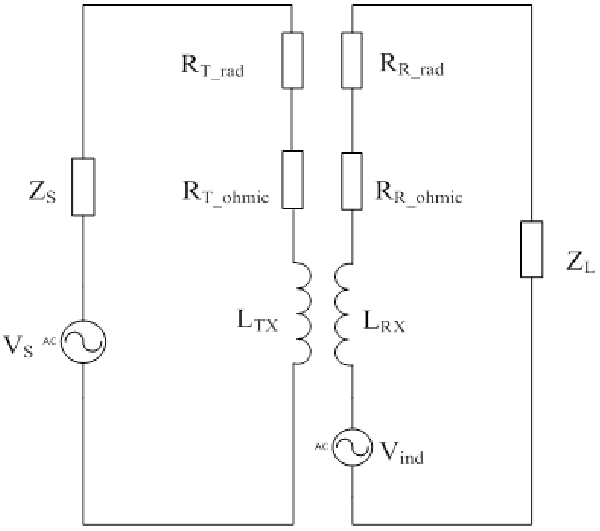

Fig. 2: Equivalent circuit representation of RIC-WPT system

The electromagnetic phenomena based resonant inductive link system is theoritically represented in Fig. 2. for in depth performance appraisal. From the transmitting unit, magnetic field is stored in near field instead of spatial radiation. Hence, losses associated with the transmitter coil will only be depicted from coils's ohmic resistance since radiation losses can be neglected. It can be assumed that the flow of current through the coil is consistent considering the coil to be handled as electrically small since the coil wire length, l<0.1λ. The charging coils of the inductive link are sumbolized with their lumped equivant elements as L_{TX} & L_{RX} respectively. The linkage of magnetic flux between the charging coils is identified by coupling coefficient k and mutual inductance M. Supported by the fact, radiation losses indicated through resistances as R_{T_rad} and R_{R_rad} are negligible and overall coil losses are characterised through resistances represented as R_{T_ohmic} and R_{R_ohmic}.

The source impedances Z_S is supposed to be connected in series, enabling the transmitter coil to resonate at a particular frequency (ω_0). Hence

$$Z_S = \frac{1}{j\omega_0 C_{TX}} \qquad (1)$$

Where $C_{TX} = \dfrac{1}{\omega^2 L_{TX}}$

So, the real input power to the transmitter coil under resonance condition is given as

$$P_{TX} = I_{TX}^2 \cdot R_{TX} \qquad (2)$$

It is apparent that, power transfer to the load will be maximum, when the load impedance (Z_L) is conjugately matched with receiver coil impedance [15]. Hence,

$$Z_L = R_{RX} - j\omega L_{RX} \qquad (3)$$

Consequently, the real power calculated across the load (P_L) is as follows

$$P_L = \frac{V_L^2}{\mathrm{Re}\left[Z_L\right]} \qquad (4)$$

Where V_L is the voltage across the load and calculated by considering the receiver side circuit as a voltage divider circuit as

$$V_L = \frac{V_{IND} \cdot Z_L}{Z_L + R_{RX}} \qquad (5)$$

Following the above equation, the power transferred to the load expressed in term of induced voltage is given by

$$P_L = \frac{V_{IND}^2}{4 \cdot R_{RX}} \qquad (6)$$

According to Faraday's law of electromagnetic induction, the receiver coil having an effective area of A_{RX} receives an induced voltage calculated as

$$V_{ind} = -\frac{\partial \phi}{\partial t} = -\frac{\partial}{\partial t} \oint \vec{B}.\vec{ds} \qquad (7)$$

Where, B is the rate of magnetic flux variation. The induced receiver voltage can be represented in the phasor form as

$$V_{ind} = -j\omega \mu_0 A_{RX} H \qquad (8)$$

It is assumed, the charging coils are setup on Z=0 plane in perfect alignment with Z-axis. Considering spiral configuration for both transmitter and receiver coils having ($N_1 = N_2 = N$) number of turns each, the consequent magnetic field strength observed at the receiver, imparted by the transmitter coil current $I_{TX,}$ contains only Z- component. Using Biot-Savart law this magnetic field strength can be computed as:

$$H_z = \frac{I_{TX}}{4\pi}\sum_{i=1}^{n}\frac{a_i^{\,2}}{2\left(a_i^{\,2}+D^2\right)^{\frac{3}{2}}} \qquad (9)$$

The solution evidently manifests dependencies of the magnetic field strength on the distance of separation between the coils as well as the transmitter coil dimensions. The receiver coil having radius b achieves an induced voltage across it as computed by

$$V_{ind} = -j\omega\mu_0 H_z \bullet \sum_{j=1}^{k}\pi b_j^{\,2} \qquad (10)$$

Using equation (9), differentiation of the magnetic field intensity in regard to the coil dimension dependent distance, the explicative separation gap value can be calculated as:

$$\begin{cases} \dfrac{dH_Z}{da} = 0 \\ a = \sqrt{2}D \end{cases} \qquad (11)$$

Equation (9) evidently shows maximum value for magnetic field strength at D=a/√2 instead of D=0. Resonant inductive coupling is the explanation of this deviation and factually highlights that maximum field strength is achieved at a particular separation gap in correspondence to the coil dimension, rather than when almost intact. Therefore, separation gap between the charging coils as well as size of the coils should be accounted for, not only as design specifications but also as performance evaluation metric.

IV. RESULTS AND DISCUSSIONS

The illustrations sketch dependencies of the transferred load power to design specifications such as, magnetic field strength, load power, mutual coupling together with the induced receiver coil voltage attributable to the transmitter coil. Fig.3 shows the variation of magnetic field intensity in regard to separation gap between the charging coils along with coil dimension. For a particular coil separation distance dependent on coil dimension, maximum field strength can be found. Analyzing further, the presence of an optimal separation distance can also be observed at specific coil dimensions where maximum magnetic field intensity can be achieved. Deviations beyond the particular coil separation value show drastic reduction in the magnetic field strength. For testing purposes, maximum concentration of magnetic field strength is observed for a separation distance of 8 cm between the coils, when the coil having radius of 11 cm is considered.

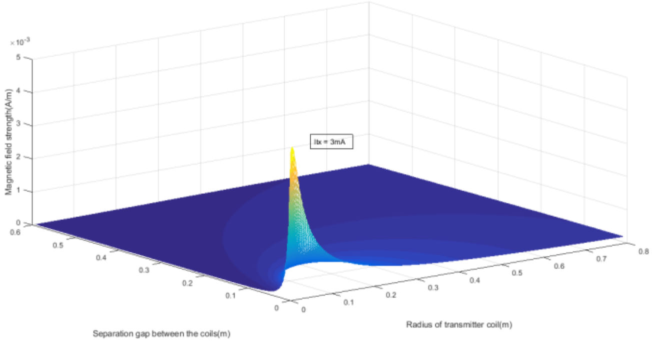

Fig. 3: Effect on Magnetic Field strength with variation of transmitter coil radius and separation gap between the coils

The existence of optimal separation distance is further emphasized by observing the receiver coil induced voltage related to coil dimension and separation between the coils. Fig. 4 illustrates the acquired individualities. Similar observations are also reported for the case of magnetic coupling impacted by changes in coil separation distance and radius of transmitter coil as shown in fig. 5.

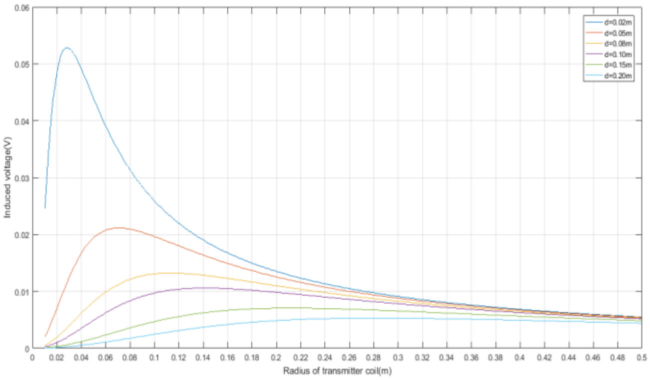

Fig. 4: Open circuit induced voltage variation at the receiver coil with respect to radius of transmitter coil under different separation distance between the coils

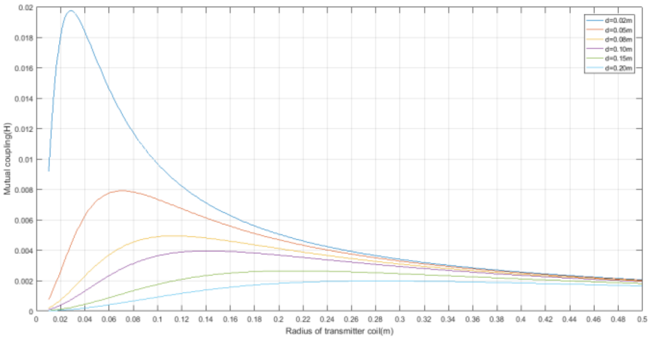

Fig. 5: Variation of Mutual Coupling with respect to transmitter coil radius and coil separation distance

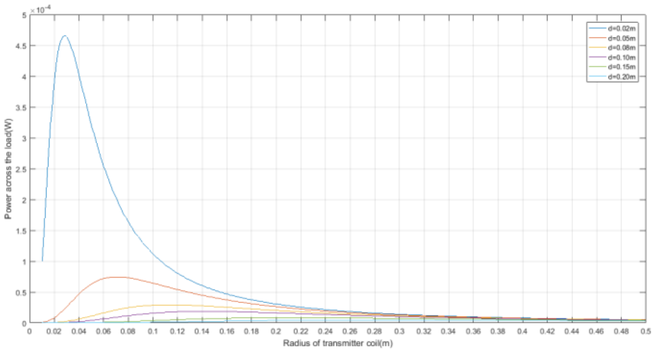

Fig. 6: Effect of coil dimension and coil separation on power transferred to the load

The peak value of the received power is attained when there is maximum induced voltage. At the optimum coil separation distance maximum induced voltage is achieved which can be deduced from the maximum strength of the induced magnetic field. Fig. 6 illustrates this behavior.

Experimental investigation has been performed to demonstrate the simulation efficacy. The simulated results presented in Fig. 6 are compared with the experimental observations [11], illustrated in Fig. 7. This establishes the relation between coil dimensions and the separation gap between them with the load power as well as the induced voltage at the receiver coil. Supported by mathematical derivation, maximum load power is achieved for the test case of 11cm coil radii when separation between the coils is 8 cm. Likewise, validation of the condition for optimal coil separation gap is performed for values of 4 cm and 6 cm. Thus, it can be indicated that, maximum power transfer can be maintained by appropriate selection of receiver coil position in a WPT system rather than modifying other design parameters.

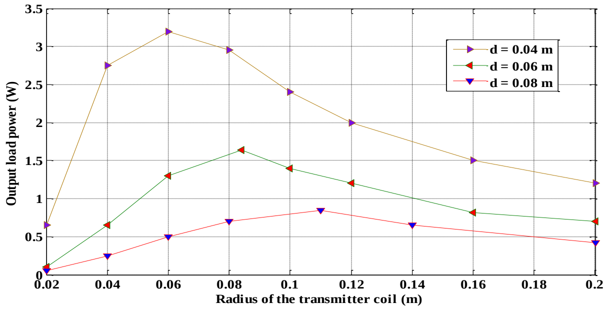

Fig. 7: Experimental output power characteristics corresponding to coil dimension and physical separation.

V. CONCLUSION

In this work, an optimal physical coil separation condition has been outlined for a WPT system. The magnetic field analysis has been done through mathematical as well as equivalent circuit model. It is noticed that there exist an optimal distance with respect to the dimension of the coil at which power transfer is maximum. The corroborated experimental and theoretical results provide the design guidelines for an effective WPT system for powering electronic as well as electrical appliances.

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