Characteristics Study of Wireless Power Transfer with Series-Series Inductive Magnetic Coupled Principle

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ABSTRACT

The wireless power transfer system using series-series inductive coupled magnetic resonance is studied in this work. The research is conducted using two separated circular coil facing each other serving as transmitter and reciver coil respectively. The effect of distance variation between two coils as well as loading variation to power efficiency and other electrical properties such as current, voltage, active power, and efficiency are observed. The coil's number of turn, transmitter input voltage, coil's attitude, and electrical frequency of the system are kept constant. The results show that the inter-coil distance value affect the overall performance of wireless power transfer system and match the theoretical prediction.

1. Introduction

The rapid developments in communications and semiconductor technology today has produced a variety of portable electronic devices in industry, healthcare, and commercial. However, these tools still have to be connected to a power source manually through wire when they need to be charged. This surely reduces the mobility of the equipment. The use of wire on medical equipments implanted in the human body is also quite disturbing and risky, like an artificial cardiac pacemaker. Sources of energy flowing through the wires that penetrate the skin will increase probability of patient's infection. Then the wireless power transfer technology is expected to overcome this problem.

Wireless power transfer methods have been developed today. Wireless power transfer mechanisms have different characteristics of distance and efficiency.

In far-field techniques, the power is transmitted by beams of electromagnetic radiation, like microwaves or laser beams. This method successfully supplies power on UHF RFID without battery at a distance of about 10 m [1, 2]. The difficulty of this method is the choice limitation between a wide range of areas and high efficiency. The examples of studies of RF and microwave systems that use high-gain antennas successfully transfer power for more than 1 kilometer with efficiencies above 90% [3, 4]. However, this system requires advanced tracking devices to keep it in the line of sight position. It is certainly difficult when the system is used on steep and dynamic areas.

Another method of far-field techniques uses an RF broadcast which transmits power in all directions. With this method, the power transfer can be performed anywhere within the coverage area of the broadcast. This increases the mobility of devices. However, the efficiency decreases when the power density decreases, which is proportional to 1/r2. So that the received power is much smaller than the radiated power [5].

Wireless power transfer can also be made by using inductive coupling or near-field techniques. These techniques do not use the propagation of electromagnetic waves such as the RF system, so that the transfer distance is not as far as the transmitted signal. An implementation of this technology is the surface charging board [6]. These techniques are very efficient but very limited on distance range, which is only about one centimeter.

The next development is the uses of magnetic coupling resonators for wireless power transfer [7]. This method can transmit power with higher efficiency than the far-field techniques, and has a longer range than the usual inductive coupling technique. However, such performance is limited to a certain distance and direction of the fixed transmitter. The efficiency of the system will decrease drastically if the receiver moves from the optimal operating point.

In this paper, the magnetic resonance coupled systems used in wireless power transfer will theoretically and experimentally analyzed. The results of this analysis will then be processed and presented in graphical form. This analysis is for knowing the effect of the existing parameters on the performance of the system. Thus, the characteristics of the coupled magnetic resonance system can be well understood. The adequate knowledge about this is very necessary in the process of system design. In addition, the characteristics of the system are also used in planning control mechanism, so that the system can work at the optimum operating point.

2. Equivalent Circuit For Wireless Power Transfer Application

The series of wireless power transfer experiments with the coupled magnetic resonance system can be described by a simplified equivalent circuit as shown in Fig.1. V_t, C_1, L_T, and R_T are on the transmitter side. V_t is the source that supplies electricity back and forth to the transmitter circuit. C_1 is a capacitor located on the side of the transmitter to produce LC resonant circuit. L_T is an inductive reactant value of the transmitter coil. R_T is the parasitic resistance values contained in the transmitter coil. The equivalent circuit of the coupled magnetic resonance can be seen in Fig.1.

The transmission coil will induce coil in the receiver side. Mutual inductance is formed between the transmitter coil and the receiver coil. This mutual inductance is then symbolized as M. At the receiver circuit, there is also LC resonant circuit formed from C_2 and L_R. C_2 is a capacitor on the receiver side, whereas the L_R is the value of the inductive reactant in receiver coil. The receiver coil contains parasitic resistance symbolized as R_R. Power is transferred to the receiver circuit and then dissipated by the resistive load symbolized as R_L.

3. Determination of Parameters

By using Kirchoff's law, transmitter circuit equation and the receivers circuit equation can be obtained (1), (2),

$$v_t = \left(R_T + j\omega L_T + \frac{1}{j\omega C_1}\right) i_T + j\omega M\, i_R \qquad (1)$$

$$0 = \left(R_R + j\omega L_R + \frac{1}{j\omega C_2} + R_L\right) i_R + j\omega M\, i_T \qquad (2)$$

Where v_t is voltage of the source, i_1 is transmitter current, i_2 is receiver current, v_r is voltage at the load, ω is 2π times f (electrical frequency), and j is imaginary number. So it can be expressed in a matrix form,

$$\begin{bmatrix} v_t \\ 0 \end{bmatrix} = \begin{bmatrix} R_T + j\omega L_T + \dfrac{1}{j\omega C_1} & j\omega M \\ j\omega M & R_R + j\omega L_R + \dfrac{1}{j\omega C_2} + R_L \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} \qquad (3)$$

By stating Δ as a determinant of the matrix (3), the receiver voltage can be expressed in equation (4),

$$v_r = i_2 R_L = -\frac{j\omega M v_t R_L}{\Delta} \qquad (4)$$

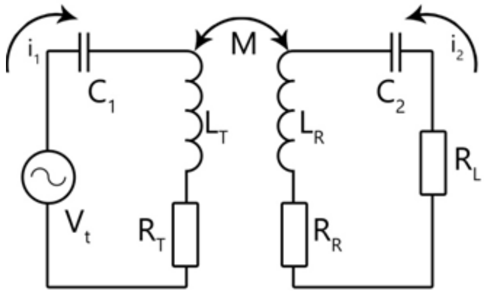

Fig.1.Equivalent circuit of coupled magnetic resonance.

The transmitter current is expressed in equation (5),

$$i_1 = \frac{(R_R + j\omega L_R + \frac{1}{j\omega C_2} + R_L)v_t}{\Delta} \quad (5)$$

The receiver current is expressed in equation (6),

$$i_2 = -\frac{j\omega M v_t}{\Delta} \quad (6)$$

Input power supplied by the source at the transmitter (P_t) is expressed in equation (7),

$$P_t = v_t i_1 = \frac{(R_R + j\omega L_R + \frac{1}{j\omega C_2} + R_L)(v_t)^2}{|\Delta|} \quad (7)$$

Output power at the load on the receiver (P_r) is expressed in equation (8),

$$P_r = (i_2)^2 R_L = \frac{(\omega M v_t)^2 R_L}{|\Delta|^2} \quad (8)$$

Then the ratio between output power and input power (η) can be expressed in equation (5),

$$\eta = \frac{P_r}{P_t} = \frac{(\omega M)^2 R_L}{\left|\Delta(R_R + j\omega L_R + \frac{1}{j\omega C_2} + R_L)\right|} \quad (9)$$

Value of mutual inductance (M) between the two coil system is illustrated in equation (10),

$$M = \frac{\mu_0 N^2 A^2}{2\pi d^3} \quad (10)$$

Where μ_0 is electrical permeability, N is number of coil's turns, A is area of the coil, and d is the distance between two coils. Here, it can be observed that the mutual inductance value is inversely proportional to d^3. This is confirmed by Schauber [7]. This charasteristic will affect the power efficiency of wireless power transfer process coupled magnetic resonance.

A transmitter coil and a receiver coil are used to the wireless power transfer resonator experiment. A resonant capacitor is mounted in each coil circuit. The transmitter coil has a inner diameter of 12.5 cm and the outer diameter of 15 cm, 320 turns (N), 21 957 mH of optimum inductance value (L). The receiver coil has a inner diameter of 12.5 cm and the outer diameter of 15 cm, 320 turns (N), 21.861 mH of optimum inductance value (L). To determine the value of L, LCR meter instruments are used, using a frequency of 5 kHz. The maximum current that can be passed to a second coil is 2 A. The physical appearance is shown in Fig. 2.

Operated frequency is determined in according to the measured value of transmitter coil inductance and receiver coil inductance. The value is affected by changes of the frequency. The value of L is selected on the maximum frequency where the value of L does not change compared to the frequency of 0 Hz. So the result for the L_T is 21.957 mH and L_R is 21, 861 mH which occurred at a frequency of 5 kHz.

Series resonant capacitor values (C) are determined by calculation as shown in equation (11) and (12),

$$C_T = \frac{1}{(2\pi f)^2 L_T} = \frac{1}{(2.\pi.(5000))^2 (21.957x10^{-3})} = 46{,}19\mu F \approx 47\mu F \quad (11)$$

$$C_R = \frac{1}{(2\pi f)^2 L_R} = \frac{1}{(2.\pi.(5000))^2 (21.861x10^{-3})} = 46{,}39\mu F \approx 47\mu F \quad (12)$$

The selected capacitor value is chosen of about 47μF as it can be easily found in the market.

After the equipments of the experiment are assembled, it is tested at around the specified value of operating frequency resonant, ie, from 3 kHz to 7.5 kHz. The frequency response graph is shown in Fig. 3.

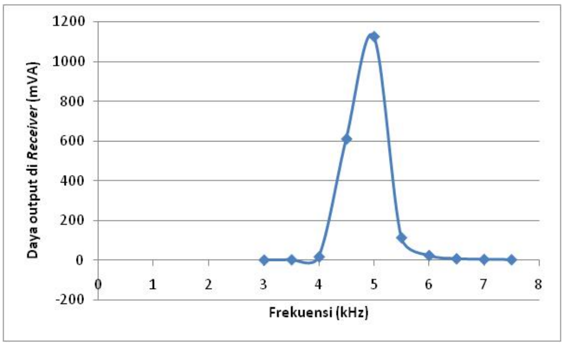

Fig.3.Frequency response of power at the receiver.

In Fig.3, the peak of the power graph is at a frequency of 5 kHz. The frequency response indicates that the equipment has a resonant frequency of 5 kHz similar to the expectation.

The wireless power transfer has characteristics in some specific scenarios which is the changes in the distance between the transmitter coil and the receiver coil.

The distance between the transmitter and receiver coil is varied from 4.5 cm to 50 cm. The characteristics of the transmitter current (I_{Tx}), the receiver current (I_{Rx}), the receiver voltage (V_{Rx}), active power at the transmitter (P_{Tx}), active power at the receiver (P_{Rx}), and active power efficiency (η) are investigated.

Once the wireless power transfer characteristic data are obtained, then the analysis for a correlation between the magnitude of the wireless power transfer characteristics is obtained

4. Results and Discussion

The influence of the distance between the transmitter and the receiver theoretically can be derived by substituting equation (10) into the equations (4)-(9). As a simplification in the writing of the equation Δ, α, and β are expressed as shown in equation (11). α is defined in equation (12) and β is defined in equation (13).

$$\Delta = \alpha\beta - (j\omega M)^2 \quad (11)$$

$$\alpha = \left(R_T + j\omega L_T + \frac{1}{j\omega C_1}\right) \quad (12)$$

$$\beta = \left(R_R + j\omega L_R + \frac{1}{j\omega C_2} + R_L\right) \quad (13)$$

Then new equations that describe the changes of various magnitudes as a function of the distance between the coils (d) are obtained. The dimensionsin the equations are voltage in the receiver (14), current in the transmitter (15), current in the receiver (16), active power at the transmitter (17), active power at the receiver (18), and efficiency (19). With these equations, the effect of changing the various quantities of the distance can be known.

$$v_r(d) = i_2 R_L = -\frac{j\omega k v_t R_L d^3}{\alpha\beta d^6 + (\omega k)^2} \quad (14)$$

$$i_t(d) = \frac{\beta v_t}{\alpha\beta - (j\omega M)^2} = \frac{\beta v_t}{\alpha\beta + \frac{(\omega k)^2}{d^6}} = \frac{\beta v_t d^6}{\alpha\beta d^6 + (\omega k)^2} \quad (15)$$

$$i_r(d) = -\frac{j\omega M v_t}{\alpha\beta + (\omega M)^2} = -\frac{\frac{j\omega k v_t}{d^3}}{\alpha\beta + \frac{(\omega k)^2}{d^6}} = -\frac{j\omega k v_t d^3}{\alpha\beta d^6 + (\omega k)^2} \quad (16)$$

$$P_t(d) = \frac{\beta (v_t)^2}{\alpha\beta + (\omega M)^2} = \frac{\beta (v_t)^2}{\alpha\beta + \frac{(\omega k)^2}{d^6}} = \frac{\beta (v_t)^2 d^6}{\alpha\beta d^6 + (\omega k)^2} \quad (17)$$

$$P_r(d) = \frac{(\omega M v_t)^2 R_L}{|\alpha\beta + (\omega M)^2|^2} = \frac{\frac{(\omega k v_t)^2}{d^6} R_L}{\left|\alpha\beta + \frac{(\omega k)^2}{d^6}\right|^2} = \frac{(\omega k v_t)^2 R_L d^6}{|\alpha\beta d^6 + (\omega k)^2|^2} \quad (18)$$

$$\eta(d) = \frac{(\omega k v_t)^2 R_L}{(\alpha\beta d^6 + (\omega k)^2)\beta} \quad (19)$$

5. Conclusion

From the results, it can be concluded that the overall performance of wireless power transfer system using a series-series inductive coupled magnetic resonance is affected by the distance between the coil and the value of the load on the receiver side. Trends of electrical quantities variation which are current, voltage, power, and efficiency are accordance with the analysis of theoretical calculations.

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