A Review of Wireless Power Transfer System via Magnetic Resonant Coupling

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Abstract—recently, an efficient mid-range wireless power transfer that uses magnetic resonant coupling, WiTricity, was proposed, and has received much attention due to its practical range and efficiency. By referring studies the resonance frequency of the antennas changes as the gap between the antennas change. To achieve maximum power transmission efficiency, the resonance frequency has to be fixed within the particular band. In this paper, the possibility of using impedance matching (IM) networks to adjust the resonance frequency of a pair of antennas at 13.56MHz is studied. Experiments also show that IM can be achieved just by observing and minimizing the reflected wave.

Keywords: Wireless Power Transfer; Magnetic Resonance; Magnetic Coupling; Impedance Matching.

I. INTRODUCTION

When wireless power transfer is achieved, the process of charging the devices will be made a lot more convenient as we do not have to plug the cord into the socket. Furthermore, as power can be constantly transferred to the device, the battery size can be reduced. Also, the danger of being electrocuted due to the wear and tear of an old cord, or rain will be avoided as the process of handling the power cord is unnecessary, thus making the charging process safer. To achieve wireless charging, the wireless power transfer system must satisfy these three conditions: high power, large air gaps and high efficiency.

Presently, the most popular wireless transfer technology is the electromagnetic induction. However, the electromagnetic induction method has a short range. Recently, a highly efficient mid-range wireless power transfer technology using magnetic resonant coupling was proposed. It is a system that transfers power in between two resonating antennas through magnetic coupling.

In this paper, we study this phenomenon using antenna design theories and circuit design theories. The characteristics of the antennas are explained using equivalent circuits, electromagnetic analysis.

This paper studies the wireless power transfer system via magnetic resonance coupling at a fixed resonance frequency (13.56MHz). A system to improve the efficiency of the power transfer based on impedance matching (IM) is proposed. The aim is to improve the efficiency by using an IM circuit to tune the resonance frequency of the system to the frequency of the power source.

II. THEORY OF MAGNETIC RESONANT COUPLING

In this paper, we study this phenomenon using antenna design theories and circuit design theories.

A. Equivalent Circuit of MRC

Magnetic resonant coupling involves creating an LC resonance, and transferring the power with electromagnetic couplings without radiating electromagnetic waves. Hence, the magnetic coupling can be represented as mutual inductance Lm as in Fig.1.

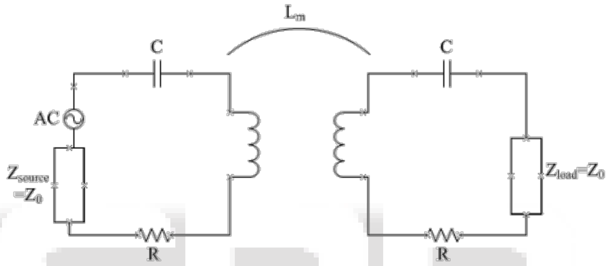


Fig.1: Equivalent circuit of MRC

Z_{source} represents the characteristic impedance, and Z_{load} is the impedance of the load. In this paper, they are both considered to be the same at Z_0, 50Ω the default characteristic impedance of most high frequency systems. The resistive loss and theradiation loss of the antennas are represented by R.

To satisfy the resonance condition, the reactance of Fig.1 must be zero, as in equation (2.1). The condition in equation (2.1) can be satisfied by two resonant frequencies as calculated in equation (2.2) and (2.3). The coupling coefficient k can be calculated from equation (2.4) which are derived from equation (2.2) & (2.3).It represents the strength of the magnetic coupling between the antennas, which is closely related to factors such as the air gap between the antennas and the obstacles between them.

$$\frac{1}{\omega L_m} + \frac{2}{\omega (L - L_m) - \frac{1}{\omega C}} = 0 \quad (2.1)$$

$$\omega_m = \frac{\omega_0}{\sqrt{(1+k)}} = \frac{1}{\sqrt{(L+L_m)C}} \quad (2.2)$$

$$\omega_e = \frac{\omega_0}{\sqrt{(1-k)}} = \frac{1}{\sqrt{(L-L_m)C}} \quad (2.3)$$

$$k = \frac{L_m}{L} = \frac{\omega_e^2 - \omega_m^2}{\omega_e^2 + \omega_m^2} \quad (2.4)$$

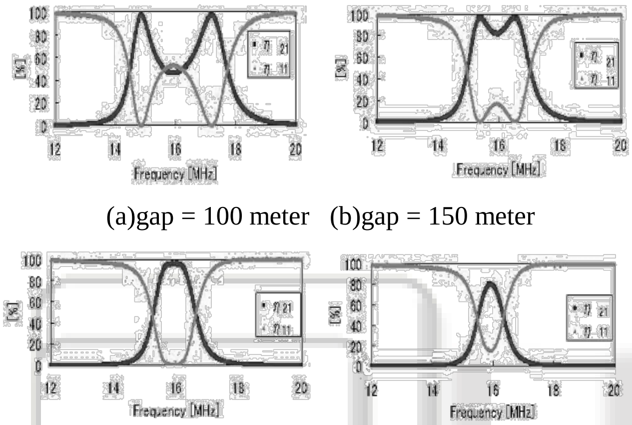
The efficiency of the power transfer is calculated by the equivalent circuit. The ratio of power reflection η11transmission η21 can be defined by equations (2.5) and (2.6), where S_{11} is the reflected wave ratio and S_{21} is the transmitted wave ratio.

$$\eta_{11} = S_{11}^2 \times 100[\%] \quad (2.5)$$

$$\eta_{21} = S_{21}^2 \times 100[\%] \quad (2.6)$$

B. Frequency Characteristic of Magnetic Resonant Coupling

As the air gap between the antennas increases, thecoupling in between the antennas weaken, and thecoupling coefficient will be smaller. Therefore, the impedance of the circuit will change which affect the power transfer efficiency and resonance frequency.



(a)gap = 100 meter (b)gap = 150 meter

(c)gap = 200 meter (d)gap = 250 meter

Fig.2: Efficiency vs frequency graph

As shown in the figure above, when the gap is small and the coupling is strong, two resonance frequencies that permit power transfer at maximum efficiency exists. As the gap becomes larger, the two resonance frequencies moves closer to each other and eventually merges into one. If the gap gets even larger, the maximum efficiency will drop.

C. Necessity of Impedance Matching

When this wireless power transfer system is applied in the MHz range which allows smaller antennas. But the usable frequency range is bounded by the Industrial- Scientific-Medical(ISM) band as shown in Fig.3. According to theISM band, theusable frequency ranges are extremely narrow. Forexample, at 13.56MHz, the usable frequency range is13.56MHz±7kHz.

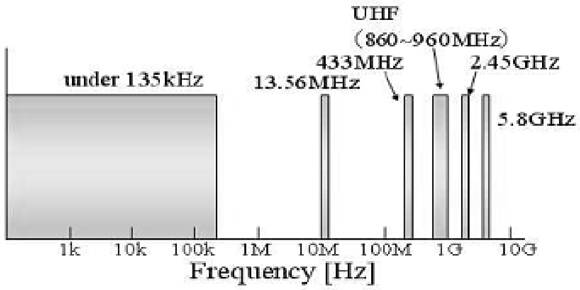


Fig.3: ISM Band

As a result, to apply this technology in restrictedfrequencyranges such as the MHz range, the frequency of the power sourcemust be fixed at a usable range, and thesystem has to be tuned sothat its resonance frequencymatches the frequency of the power source.

D. Theory of Impedance Matching

In power transfer or communication system Impedance Matchingtheory is commonly used to improve the efficiency of the system.

Itusually involves inserting a matching network (such as an LC circuit) to minimize the power reflection ratio to the power sourceof the system.

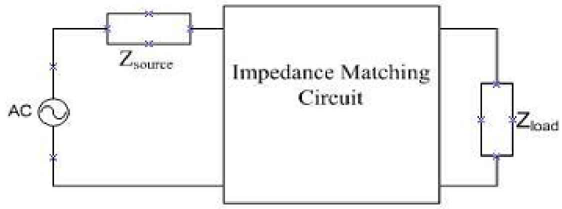


Fig.4: Impedance Matching

In Fig.4, the power transferred to the load is written as equation (2.8) when the impedance of the power source is defined as Z_{source} and that of the load is defined as Z_{load}. The powertransferred to the load reaches its maximum when $Z_{source}=Z^*_{load}$, as in equation (2.9). Therefore, the circuit is considered matched and the maximum efficiency achieved when the impedance of the load from the source's point of view matches Z_{source}, vice versa.

$$P = I^2 Z = \frac{V^2}{Z_{source}} \left(\frac{1}{\frac{Z_{source}}{Z_{load}} + 2 + \frac{Z_{load}}{Z_{source}}} \right) \quad (2.8)$$

$$P_{max} = \frac{V^2}{4Z_{source}} \quad (2.9)$$

III. WIRELESS POWER SYSTEM

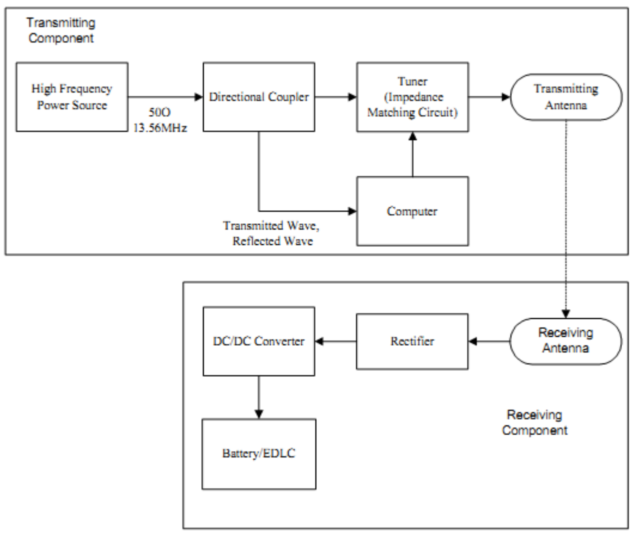


Fig.5:Wireless power transfer system with tuning circuits

Fig.5 shows the diagram of the proposed system to improve the efficiency of wireless power transfer via magnetic resonant coupling with a matching circuit. The system involves resonating two antennas with identical self resonance frequency (13.56MHz)using a high frequency power source.

The power is transmitted through magnetic resonantcoupling in between the two antennas at the resonance frequencies.The power transferred is rectified and used to charge energy storage mediums such as batteries.This research focuses on the transmitting part of the system. Under normal circumstances, the coupling factor k (affected bythe air gap) and the load (50Ω in this case) are variable andunknown. Only the voltage, current and power reflection ratio can be measured in the power transmitting side of the system. To measure the reflected power in between the antennasa directional coupler is inserted. The IM circuit functions as a tuner to change the characteristics of the antennas so that the resonance frequency can be adjusted to the frequency of the power source.This can be achieved by tuning the parameters.

IV. CONCLUSION

The frequency characteristics and the power transfer efficiency of the antennas can be studied using equivalent circuits, electromagnetic analysis, simulations and experiments. As the air gap changes the resonance frequency of the antennas changes. When this is applied in the MHz range, the usable frequency range is bounded by the ISM band. Since the maximum power transfer efficiency occurs at the resonance frequency, a system which uses an IM network to match the resonant frequency of the antennas to a power source at a fixed frequency (13.56MHz) was proposed.

The effects can be analyzed with equivalentcircuits, electromagnetic analysis, simulations andexperiments. By the experiments and simulations that the resonance frequency of the system can be changed using IM circuits fordifferent air gaps and displacements. And so on for ceertain resonance frequency, maximum power transfer can be achieved.

REFERENCE

[1] Trevor S. Bird, Nicholas Rypkema, and Ken W. Smart, “Antenna Impedance Matching for Maximum Power Transfer in Wireless Sensor Networks”,*IEEE SENSORS*, 2009 Conference.

[2] TeckChuan Beh, Masaki Kato, Takehiro Imura, Yoichi Hori, “Basic Study on Improving Efficiency of Wireless Power Transfer via Magnetic Resonance Coupling Based on Impedance Matching”, *IEEE International Symposium on Industrial Electronics*, ISIE 2010, IEEE pp2011-2016.

[3] TeckChuan Beh, Masaki Kato, Takehiro Imura, Yoichi Hori, “Wireless Power Transfer System via Magnetic Resonant Coupling at Fixed Resonance Frequency”,*World Electric Vehicle Journal Vol. 4, China*, Nov, 2010.

