Wireless Power Transfer System via Magnetic Resonant Coupling at Restricted Frequency Range

——Fixing Resonance Frequency With Impedance Matching ——

Teck Chuan Beh*, Student Member, Takehiro Imura, Member,
Masaki Kato, Student Member, Yoichi Hori, Senior Member (The University of Tokyo)

Recently, a highly efficiency mid-range wireless power transfer technology using magnetic resonant coupling, WiTricity, was proposed, and has received much attention due to its practical range and high efficiency. Studies show that the resonance frequency of the antennas changes as the gap between the antennas change. However, the usable frequency is bounded by the Industrial, Scientific, Medical (ISM) band. In this paper, the possibility of using impedance matching (IM) networks to adjust the resonance frequency to 13.56MHz is studied. The simulations and experiments show that the IM circuits can change the resonance frequency to 13.56MHz for different air gaps, improving the power transfer efficiency. Experiments also show that IM can be achieved by observing and minimizing the reflected wave.

Keywords : wireless power transfer, magnetic resonance, magnetic coupling, WiTricity, impedance matching

1. Introduction

Nowadays, with the widespread usage of mobile appliances such as mobile phones and laptops, as well as the recent boom in environmentally friendly EVs, the need for a technique to wirelessly charge these devices has increased. Wireless power transfer systems can not only increase the mobility of the electronic devices, it is also essential for the spread of EVs. 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 devices, the battery size can be reduced. This will not only reduce the cost of the devices, the small sized of the batteries will further increase the portability of the devices. Also, in the case of EVs, the danger of being electrocuted due to the wear and tear of an old cord, or rain will be avoided, making the charging process safer. To achieve wireless charging, the wireless power transfer system must satisfy these three conditions: high efficiency, large air gaps, and high power.

Currently, the most common wireless power transfer technologies are the electromagnetic induction and the microwave power transfer. However, the electromagnetic induction method has a short range[3], and microwave power transfer has a low efficiency as it involves radiation of electromagnetic waves. Recently, a highly efficient mid-range wireless power transfer technology using magnetic resonant coupling, WiTricity, was proposed. It is a system that transfers power in between two resonating antennas through magnetic coupling. It satisfies all three conditions to make wireless charging possible as it has a high efficiency at mid range.(approximately 90% at 1m and 50% at 2m[1] at 60W)

Until now, this phenomenon was explained using mode coupling theory. However, this theory is often complicated, and inconvenient when it comes to designing the circuits around the system. We study this phenomenon using antenna design theories and circuit design theories. The characteristics of the antennas are explained using equivalent circuits, electromagnetic analysis, and experiments. The frequency characteristic of the antennas and its relation to efficiency is studied.

This paper studies the wireless power transfer system via magnetic resonant coupling at a restricted frequency range (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. The parameters of the tuning circuit are calculated based on the equivalent circuit of the antennas, and impedance matching theories.

2. Theory of Magnetic Resonant Coupling

2.1 Equivalent Circuit of Magnetic Resonant Coupling

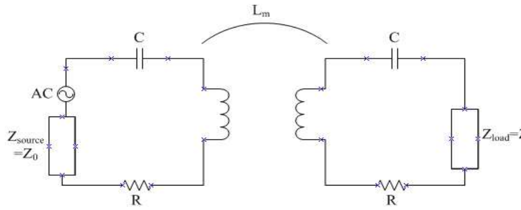


Fig 2.1 Equivalent circuit of magnetic resonant coupling

Magnetic resonant coupling involves creating an LC resonance, and transferring the power with electromagnetic coupling. Hence, the magnetic coupling can be represented as mutual inductance L_m as in Fig 2.1. 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 ohm loss and the radiation loss of the antennas are represented by R.

The resonance frequency can be calculated from the equivalent circuit. To satisfy the resonance condition, the reactance of Fig 2.1 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 (2-2) and (2-3) to become equation (2-4). 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.

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

$$\omega_m = \frac{\omega_0}{\sqrt{(1+k)}} = \frac{1}{\sqrt{(L+L_m)C}} \qquad (2\text{-}2)$$

$$\omega_e = \frac{\omega_0}{\sqrt{(1-k)}} = \frac{1}{\sqrt{(L-L_m)C}} \qquad (2\text{-}3)$$

$$k = \frac{L_m}{L} = \frac{\omega_e^2 - \omega_m^2}{\omega_e^2 + \omega_m^2} \qquad (2\text{-}4)$$

Next the efficiency of the power transfer is calculated based on the equivalent circuit. The ratio of power reflection η_{11} and transmission η_{21} 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. To simplify the calculations, R is considered to be 0Ω. Here, S_{21} can be calculated with equation (2-7). [2]

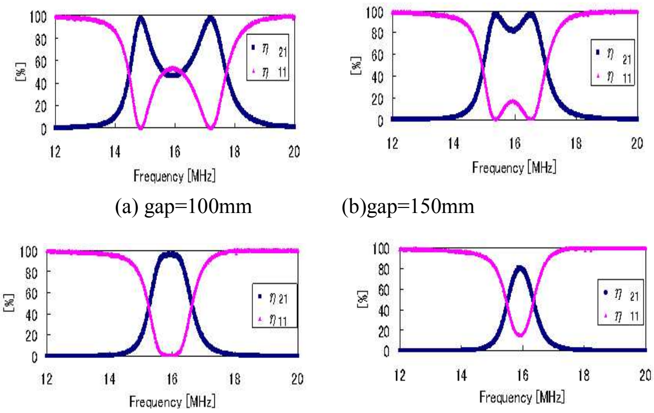
$$\eta_{11} = S_{11}^2 \times 100[\%] \qquad (2\text{-}5)$$

$$\eta_{21} = S_{21}^2 \times 100[\%] \qquad (2\text{-}6)$$

$$S_{21} = \frac{2jL_m Z_0 \omega}{L_M^2 \omega^2 - (\omega L - \frac{1}{\omega C})^2 + 2jZ_0(\omega L - \frac{1}{\omega C}) + Z_0^2} \qquad (2\text{-}7)$$

2.2 Frequency Characteristics of Magnetic Resonant Coupling

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



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

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

Fig 2.2 The efficiency vs frequency graph [2]

Fig 2.2 shows the ratio of power reflection η_{11} and transmission η_{21}, and the frequency characteristics of the system when the air gap, g, is changed between 100mm-250mm. The antenna used here is a self resonating 5 turn, 150mm radius, 5mm pitch, open type helical antenna. When the gap is small and the coupling is strong, two resonance frequencies that permit power transfer at maximum efficiency exist. 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.

2.3 Necessity of Impedance Matching

When this wireless power transfer system is applied in the MHz range (which allows smaller antennas), the usable frequency range is bounded by the Industrial -Scientific-Medical(ISM) band as shown in Fig 2.3. The ISM band dictates the usable frequency range for purposes other than communication. According to the ISM band, the usable frequency ranges are extremely narrow. For example, at 13.56MHz, the usable frequency range is 13.56MHz±7kHz.

As a result, to apply this technology in restricted frequency ranges such as the MHz range, the frequency of the power source must be fixed at a usable range, and the system has to be tuned so that its resonance frequency matches the frequency of the power source. In this paper, a tuning circuit based on the IM theory is used to match the resonance frequency of the antennas to that of the power source fixed at 13.56MHz.

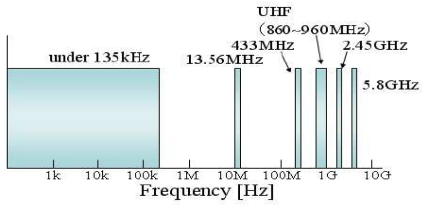


Fig 2.3 ISM Band

2.3.1 Basic Theory of Impedance Matching

IM is a technique commonly used in power transfer systems and communication systems to improve the efficiency of the system. It usually involves inserting a matching network (such as an LC circuit) to minimize the power reflection ratio to the power source of the system.

In Fig 2.4, 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 power transferred 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.

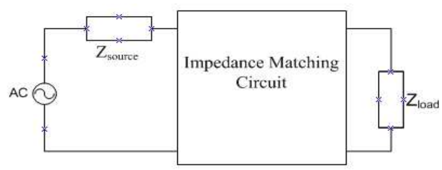


Fig 2.4 Theory of impedance matching

$$P = I^2 Z = \frac{V^2}{Z_{source}} \left(\frac{1}{\frac{Z_{source}}{Z_{load}} + 2 + \frac{Z_{load}}{Z_{source}}} \right) \qquad (2\text{-}8)$$

$$P_{\max} = \frac{V^2}{4Z_{source}} \qquad (2\text{-}9)$$

The IM circuit can be considered as a two-port network that can be described with equation (2-10). The matching conditions are satisfied when the parameters satisfy equation (2-11).

$$\begin{pmatrix} V_1 \\ I_1 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} V_2 \\ I_2 \end{pmatrix} \quad (2\text{-}10)$$

$$Z_{source} = \sqrt{\frac{AB}{CD}} \quad (2\text{-}11)$$

$$Z_{load} = \sqrt{\frac{DB}{CA}}$$

3. Proposed Wireless Power Transfer System

Fig 3.1 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 resonant coupling in between the two antennas at the resonance frequencies. The power transferred is rectified and used to charge energy storage mediums such as batteries and electric double layer capacitors (EDLC).

This research focuses on the transmitting part of the system. Under normal circumstances, the coupling factor k (affected by the air gap) and the load (50Ω in this case) are variable and unknown. Only the voltage, current and power reflection ratio can be measured in the power transmitting side of the system. In this system, a directional coupler is inserted before the transmitting antenna to measure the reflected power in between the antennas. 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 so that the reflected power ratio measured by the directional coupler reaches its minimum.

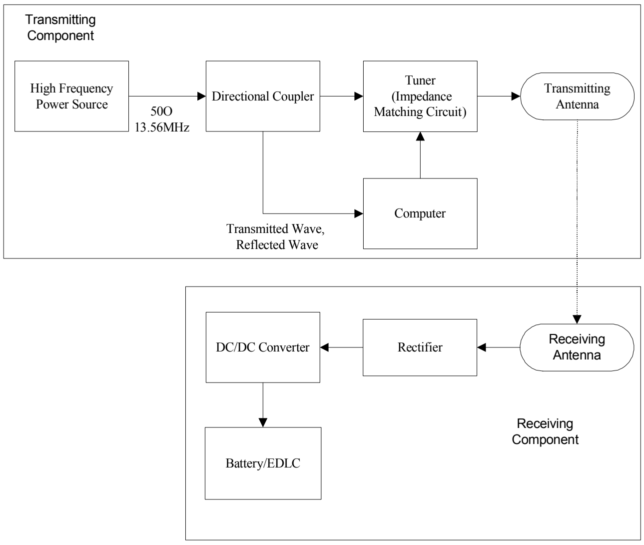


Fig 3.1 Wireless power transfer system with tuning circuits

4. Experiment Results

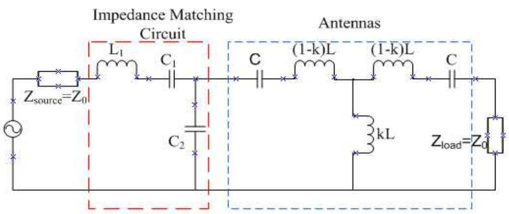


Fig. 4.1a Equivalent circuit of experiment setup

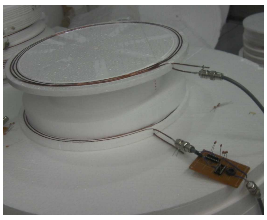
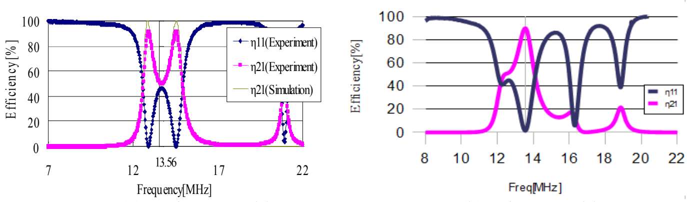


Fig. 4.1b Antennas used in the experiments

The equivalent circuit used in the simulations and experiments are shown in Fig. 4.1a, where an impedance matching network is inserted in between the power source and the transmitting antenna. The antenna used here is a 5 turn, 15cm radius, 5mm pitch, open type spiral antenna that is self-resonating at 13.56MHz (Fig 4.1b). Here both the input and output impedance, Z_{source} and Z_{load} are set at Z_0, 50Ω. Using the vector network analyzer (VNA), the L and C parameters of the antennas were calculated to be 10300nH and 13.26pF respectively. These experiments are conducted at low power. The system is expected to function similarly in high power situations [2].

4.1 Simulations and Experiments to Confirm the IM Theory



(a) Before matching (b) After matching

Fig 4.2 Experiment results and comparison with simulations

To confirm the effect of IM on the antennas, an L circuit was inserted in between the transmitting antenna and the power source as in Fig 4.1a. The inductors L_1 is an air core coil (4.8μH). Multiple ceramic condensers connected in parallel were used to make C_1 and C_2. Here, the VNA is used to measure the power reflection ratio, the matching parameters (C_1, C_2) that minimize the reflection ratio are chosen. In this experiment, the gap in between the antennas is fixed at 9cm, and the horizontal displacement at 0cm (coaxial).

As shown in Fig 4.2, the reflection ratio of the post-matching system at 13.56MHz is almost 0. Therefore, it can be concluded that the resonant frequency of the antennas can be tuned to match the frequency of the power source at 13.56MHz using an L type matching circuit.

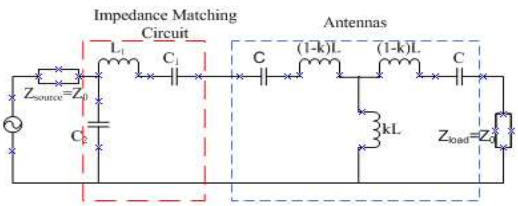
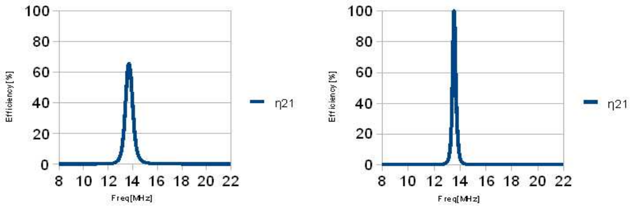


Fig 4.3 Equivalent circuit of modified L type IM network used when the coupling is weak (single peak situations)

When the coupling between the antennas is weak, the efficiency cannot be increased using the tuning circuit at Fig 4.1a as the resonant frequency is already at the frequency of the power source. However, the impedance can matched using a modified circuit, where the C_2 component is shifted to the power source side of the matching network (Fig 4.3). A simulation was run using pSpice to study its effects when the coupling coefficient k is very small (k=0.03). The results show that the efficiency can be increased in these situations, thus potentially extending the gap that allows high efficiency power transfer further. (Fig 4.4) This will be an interesting topic to work on in the future.



(a)Before matching (b) After Matching

Fig 4.4 Simulation results of the system at extremely weak coupling (k=0.03)

4.2 Experiments to Study the Maximum Efficiency Achievable via IM at Varying Gaps and Displacements

Subsection 4.1 confirmed that the efficiency can be increased by tuning the resonant frequency of the system to match that of the power source using an IM circuit. This subsection studies the effects of the system when the displacements and gaps are varied. Variable condensers (~100pF) and air-core coil (4.8μH) are used to conduct these experiments (Fig 4.5), and they are set up according to Fig 4.1a. The gaps are varied from 5~24cm and the antennas coaxial for the experiment to test the system at varying gaps. On the other hand, the gap is fixed at 9cm and the displacements set from 0~21cm for the experiments to test the system in varying displacements. The system is matched the same way as in subsection 4.1.

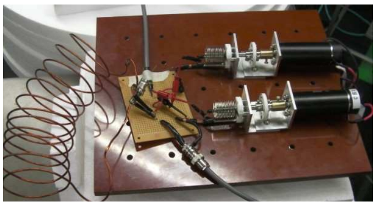


Fig. 4.5 Air core coil and variable condensers of the IM network

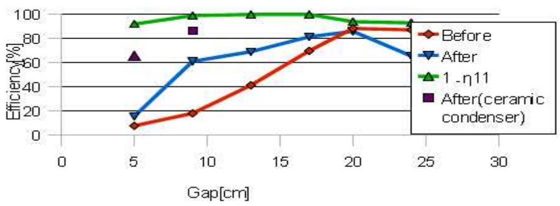


Fig 4.6 Efficiency (at 13.56MHz) vs gap graph.

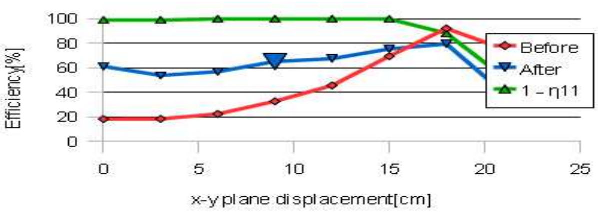


Fig 4.7 Efficiency (at 13.56MHz) vs displacement graph.

Fig 4.6 and Fig 4.7 shows the efficiency of the system at 13.56MHz before and after matching for different gap and displacement. According to the results, the efficiency can be improved by tuning the resonance frequency to that of the power source using an impedance matching circuit when the coupling is still sufficiency strong (two peaks exist). The frequency characteristics for both experiments resemble Fig 4 2 so the graphs will not be displayed due to space constraints. The efficiency after matching does not reach its theoretical value ($1-\eta_{11}$) because the variable condensers were used in an unstable range (low capacitance), causing the Q value of the component to decrease. The efficiency is predicted to increase further (up to the maximum potential of the antennas) when high Q components are used (as shown in the efficiency when ceramic condenser is used in Fig 4.6). Also, when the coupling between the antennas are extremely weak (single peak), the efficiency is predicted to increase by inserting the matching circuit shown in Fig 4.3.

5. Conclusion

The frequency characteristics and the power transfer efficiency of the antennas were studied using equivalent circuits, electromagnetic analysis, simulations and experiments. The resonance frequency of the antennas changes as the air gap changes. When this is applied in the MHz range (which allows smaller size antennas), 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 tuning parameters of the IM circuits were estimated using the equivalent circuits. The effects were analyzed with equivalent circuits, electromagnetic analysis, simulations and experiments. The experiments and simulations show that the resonance frequency of the system can be changed using IM circuits for different air gaps and displacements. The matching can be achieved by tuning the circuits so that the power reflection ratio (measured by the directional coupler) of the system reaches its minimum.

Experiments show that the stability and ohmic loss of the components in the tuning circuit contributes to the drop in efficiency around the resonance frequency. Therefore, core losses of the coils and the stable range of the variable condensers will have to be put into consideration when designing the circuit.

References

(1) Andre Kurs, Aristeidis Karalis, Robert Mofatt, J.D. Joannopoulos, Peter Fisher, Marin Soljacic, "Wireless Power Transfer via Strongly Coupled Magnetic Resonance", Science Express, 7 June 2007, Vol. 3.17 no.5834,pp.83-86

(2) Takehiro Imura, Hiroyuki Okabe, Yoichi Hori, "Basic Experimental Study on Helical Antennas of Wireless Power Transfer for Electric Vehicles by using Magnetic Resonant Couplings", Vehicle Power and Propulsion Conference, 2009. IEEE Pages 936-940

(3) Takehiro Imura, Toshiyuki Ushida, Yoichi Hori, "Experimental Analysis of High Efficiency Power Transfer using Resonance of Magnetic Antennas for the Near Field – Geometry and Fundamental Characteristics - ",IEE Japan Industry Applications Society Conference, No.2-62, pp.539-542, Kochi,Japan,2008.8

(4) Takehiro Imura, Yoichi Hori, "Wireless Power Tranfer using Electromagnetic Resonant Coupling", The Journal of The Institute of Electrical Engineering of Japan, VOL129, No.7, 2009.7