Wireless Power Transfer via Magnetic Resonance Coupling from the Standpoint of an Equivalent Circuit

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Abstract

Wireless power transfer via magnetic resonant coupling has generated considerable attention because such transfers have high efficiency and produce a large air gap. In this paper, this phenomenon is examined from the standpoint of an equivalent circuit. The topics discussed in this paper are (1) the equivalent circuit of the transmitting antenna and the receiving antenna and (2) the difference between typical circuits representing wireless power transfer and (3) repeater antennas.

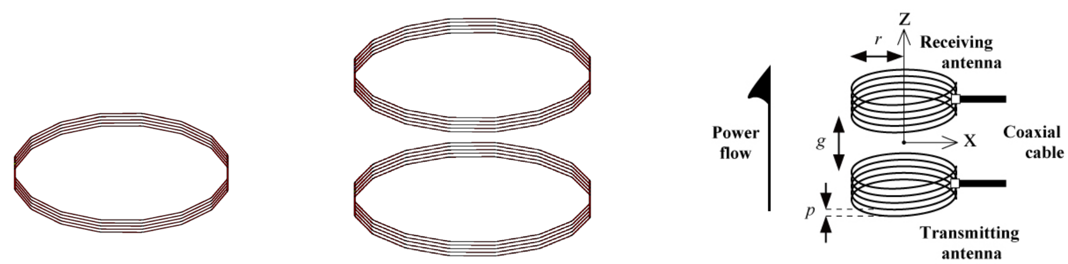
Keywords: Electromagnetic resonance coupling Equivalent circuit Repeater antenna

1. Introduction

Wireless power transfer via magnetic resonance coupling has generated considerable attention because such transfers have high efficiency and produce a large air gap[1]. This phenomenon can be explained using the coupled-mode theory; however, it is easy to design peripheral circuits and antennas using an equivalent circuit[2]. Therefore, it is necessary to comprehend this phenomenon using equivalent circuits. In this paper, the transmitting antenna and the receiving antenna used for electromagnetic resonance coupling are described using an equivalent circuit. The difference between typical circuits representing wireless power transfers is also described. Finally, we describe the equivalent circuit of repeater antennas. The obtained results indicate that this phenomenon can be represented using equivalent circuits.

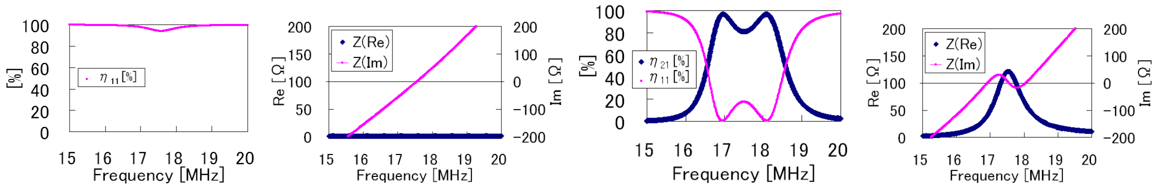
2. Equivalent Circuit of Magnetic Resonance Coupling

A helical antenna used for magnetic resonance coupling is shown in Fig.1 (a). The transmitting antenna and the receiving antenna are shown in Fig.1 (b). These are the models of the magnetic field analysis. Note that the transmitting antenna and the receiving antenna are the same. The parameters are shown in Fig.1 (c). The radius is r = 150 mm with 5 turns, and the pitch is 5 mm. The feeding position is the center of the whole length of the antenna. The antennas are connected to the circuit with the characteristic impedance Z_0 equal to 50 ohm. The results of the magnetic field analysis of the single antenna and the pair of antennas are shown Fig.2. With the single antenna, almost all of the input power from the power source to the antenna is refracted as shown in Fig.2 (a). There is a loss of resonant frequency as shown in Fig.2 (b), and the total amount of ohmic loss and the radiative loss is less than 1% in this configuration. The efficiency of the wireless power transfer is shown in Fig.2 (c); the figure shows the high efficiency at the air gap g = 150 mm. The two resonance frequencies are shown in Fig.2 (d). Note that the efficiencies are high at these two frequencies. The magnetic fields at the two resonant frequencies are shown in Fig.3. The magnetic field is focused at the center of the lower resonant frequency f_m therefore making a magnetic wall. On the other hand, the magnetic field is focused at the edge of antenna at a higher resonant frequency f_e, making an electric wall.



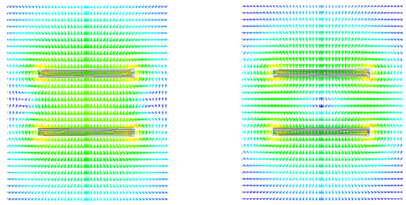
(a) An element model (b) Two element models, g = 150 mm (c) Antenna parameters

Fig.1. Electromagnetic analysis model of the helical antenna and its parameters



(a) (b) (c) (d)

Fig.2. Magnetic field analysis of the efficiency of power transfer and input impedance. (a) An element, η_{11}. (b) An element and input impedance. (c) Two elements, η_{21}, η_{11}. (d) Two elements and input impedance



(a) Magnetic wall at f_m (b) Electric wall at f_e

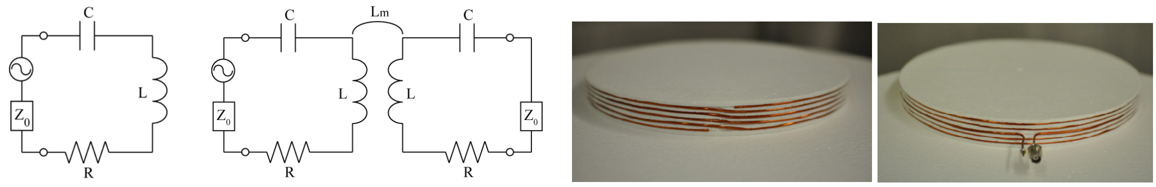
Fig.3. Magnetic field

The single antenna resonates by itself and is described using the series resonance of the L, C, and R circuit. Therefore, this antenna can be described using the equivalent circuit as shown in Fig.4(a). The connection between the transmitting antenna and the receiving antenna is determined by the magnetic field, which is described by the mutual inductance L_m. The equivalent circuit of the transmitting antenna and the receiving antenna of the magnetic resonance coupling is shown in Fig.4(b). The real antenna is shown in Fig.4 (c) and Fig.4 (d). The front of the antenna is shown in Fig.4(c), and the feeding point is shown in Fig.4 (d). From the equivalent circuit, the equation of transition S_{21} is described in equation (1), and the efficiency η_{21} is described in equation (2). The relation of reflection S_{11} and the ratio of reflection power are described as equation (3). The results of the electromagnetic field analysis, the equivalent circuit, and the experiment are shown in Fig.5, which match and show the validity of equivalent circuit theory. L = 8.5 μH, C = 9.7 pF, L_m = 0.71 μH, coupling coefficient k = 0.08 and R = 0.82 Ω.

$$S_{21}(\omega)=\frac{2jL_mZ_0\omega}{L_m^2\omega^2+\left\{(Z_0+R)+j\left(\omega L-\frac{1}{\omega C}\right)\right\}^2} \quad (1)$$

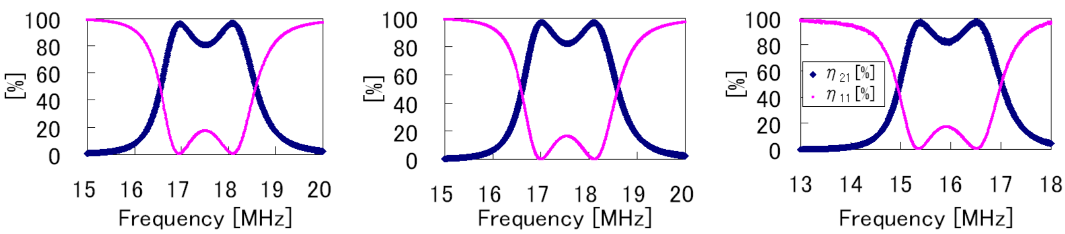
$$\eta_{21}=\left|S_{21}\right|^2\times 100\ [\%] \quad (2)$$

$$\eta_{11}=\left|S_{11}\right|^2\times 100\ [\%] \quad (3)$$



(a) (b) (c) (d)

Fig.4. Equivalent circuit of magnetic resonance coupling and the antenna used for the experiment. (a) An antenna. (b) Two antennas. (c) Experimental antenna, front side. (d) Experimental antenna, feeding side

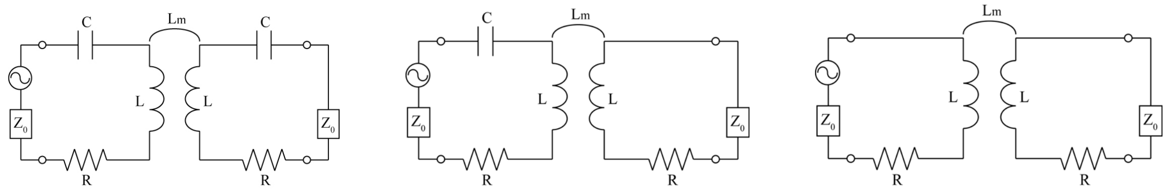


(a) Electromagnetic analysis (b) Equivalent circuit (c) Experimental result

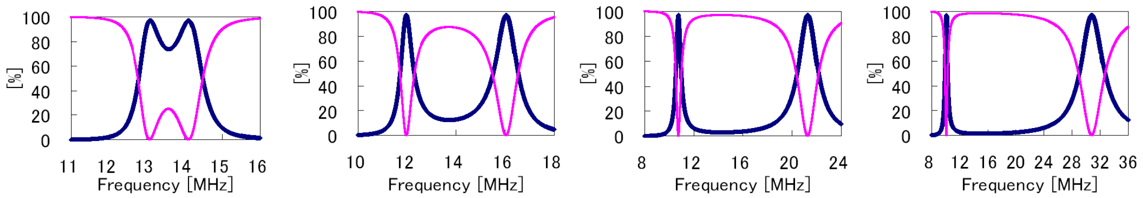
Fig.5. Comparison of efficiency, η_{21}, η_{11} (5 turns, p = 5 mm, r = 150 mm, g = 150 mm)

3. Comparison to typical circuits

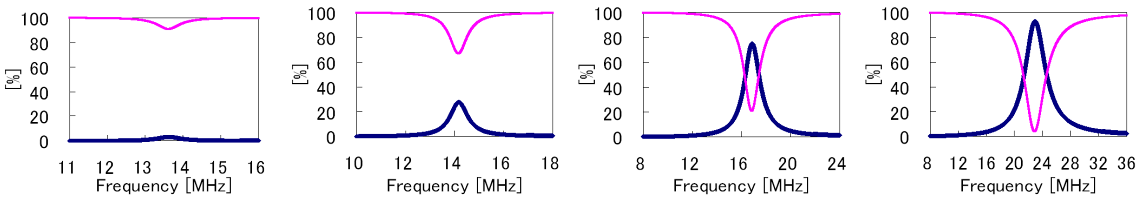
The magnetic resonant coupling is described in the equivalent circuits as shown in the section before. The typical circuits of wireless power transfer are compared, as shown in Fig.6. The equivalent circuit of the magnetic resonant coupling is shown in Fig.6 (a). The circuit using the compensating condenser is installed in the transmitting antenna as shown in Fig.6 (b), which can compensate the induction of the coils and has a single resonance. There is no condenser, which means there is no resonance, as shown in Fig.6(c). In this comparison, the spiral antenna parameters are used. The spiral antenna is almost the same as the helical antenna, but the turn goes into the inner direction. The radius of the spiral antenna is 150 mm with 5 turns and 5 mm pitch. The parameters are L = 11.0 μH, C = 12.5 pF, R = 0.77 Ω. The coupling coefficient k, which is related to the air gap g, is changed in each circuit. The results are shown in Fig.7, Fig.8, andFig.9. When the air gap is large and the coupling coefficient is small, the efficiency of the magnetic resonant coupling circuit is high as shown in Fig.7 (a) as compared to Fig.8 (a) and Fig.9 (a). Therefore, whether these two circuits have one condenser or no condenser, the circuit needs more coupling, which means that air gap should be closer than g = 150 mm. Only when the coupling is strong do these two circuits achieve high efficiency. Of course, it is better to use the compensating condenser than not use it.



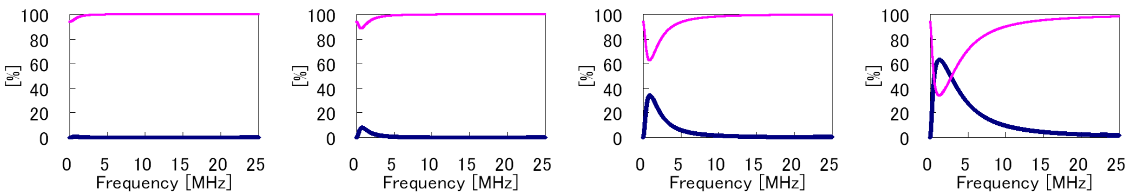
(a) Magnetic resonant coupling circuit (b) Compensating condenser circuit (c) No resonant circuit
Fig.6 Equivalent circuit of three types



(a) k = 0.092 (g = 150 mm) (b) k = 0.29 (g = 50 mm) (c) k = 0.59 (g = 10 mm) (d) k = 0.81 (g = 2 mm)
Fig.7 Relation of wireless power transfer efficiency η_{21} and coupling coefficient k with the equivalent circuit of magnetic resonant coupling



(a) k = 0.092 (g = 150 mm) (b) k = 0.29 (g = 50 mm) (c) k = 0.59 (g = 10 mm) (d) k = 0.81 (g = 2 mm)
Fig.8 Relation of wireless power transfer efficiency η_{21} and coupling coefficient k with the circuit comprising a compensating condenser and single resonant circuit



(a) k = 0.092 (g = 150 mm) (b) k = 0.29 (g = 50 mm) (c) k = 0.59 (g = 10 mm) (d) k = 0.81 (g = 2 mm)
Fig.9 Relation of wireless power transfer efficiency η_{21} and coupling coefficient k with no condenser and no resonant circuit.

4. Repeater antennas

Magnetic resonance coupling antenna can extend the length of the wireless power transfer by using repeater antennas, as shown in Fig.10 (a); this figure shows the electromagnetic field analysis model. The repeater antennas are also described using the equivalent circuit as shown in Fig.10 (b). The impedances of the antennas include the repeater antenna as described in equation (4). The S-parameters are shown in equation (5) whereas the parameters are indicated in equations (6) and (7). Equation (8) is the efficiency of the wireless power transfer from the transmitting antenna to the receiving antenna through the repeater antenna, and it is calculated using equations (4) to (7). These equations are examined when comparing the magnetic field analysis. If there is no repeater antenna, when the air gap S_a is changed from 10 mm to 320 mm, the efficiency reduces, as shown in Fig.11. Therefore, the repeater antenna is installed between the transmitting antenna and the receiving antenna, as shown in Fig.10. Next, magnetic field analysis and calculation of the equivalent circuit is done. The mutual inductances $L_{12} = L_{23} = 0.542$ μH and coupling coefficients $k_{12} = L_{12}/L = k_{23} = L23/L = 0.049$ are obtained from the electromagnetic field analysis. The results are shown in Fig.12. If the number of the repeater antennas is increased, it can convey the power through multiple repeater antennas, as shown in Fig.13 and Fig.14. Equivalent circuits are dealt in the same way, that is, increase the number of *L*, *C,* and *R* circuits as the number of repeater antenna is increased. This is shown in Fig.15.

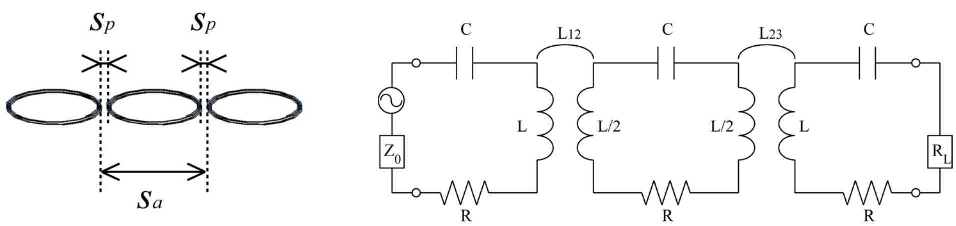
$$[Z]=\begin{bmatrix} R+j\left(\omega L-\frac{1}{\omega C}\right) & j\omega L_{12} & 0 \\ j\omega L_{21} & R+j\left(\omega L-\frac{1}{\omega C}\right) & j\omega L_{23} \\ 0 & j\omega L_{32} & R+j\left(\omega L-\frac{1}{\omega C}\right) \end{bmatrix} \quad (4)$$

$$[S]=\left\{[\hat{Z}]+[1]\right\}^{-1}\left\{[\hat{Z}]-[1]\right\} \quad (5)$$

$$[Y_0]=\begin{bmatrix} Z_{01} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & Z_{03} \end{bmatrix}^{-1} \quad (6)$$

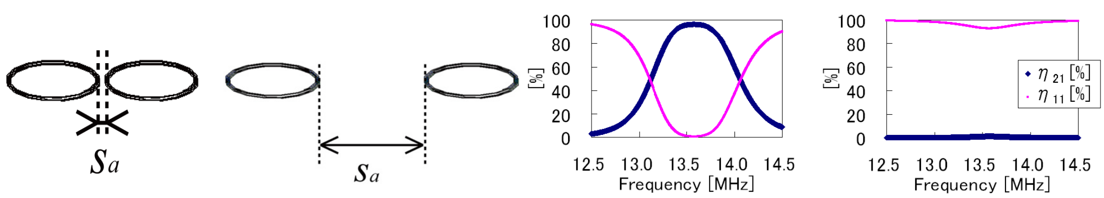
$$\left[\hat{Z}\right]=\left[\sqrt{Y_0}\right][Z]\left[\sqrt{Y_0}\right] \quad (7)$$

$$\eta_{31}=\left|S_{31}\right|^2 \quad (8)$$



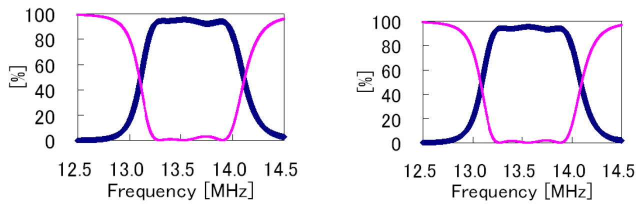
(a) Model of repeater antennas (b) Equivalent circuit of repeater antennas

Fig.10. Parameters of repeater antennas and equivalent circuit



(a) s_a = 10 mm (b) s_a = 320 mm (c) Result at s_a = 10 mm (d) Result at s_a = 320 mm

Fig.11. Transmitting and receiving antennas without repeater antennas



(b) Electromagnetic analysis (b) Equivalent circuit

Fig.12. Results of electromagnetic field analysis and equivalent circuit analysis with repeater antenna, s_a = 320 mm, s_p = 10 mm

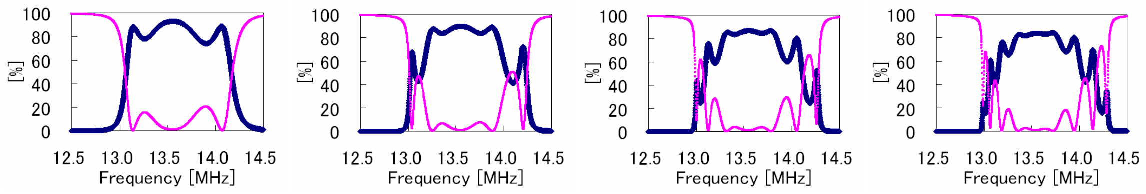
(a) 2 repeater antennas

(b) 4 repeater antennas

(c) 6 repeater antennas

(d) 8 repeater antennas

Fig.13 Electromagnetic field analysis model, S_p = 10 mm. The left antenna is the transmitting antenna and the right antenna is the receiving antenna.



(a) 2 repeater antennas (b) 4 repeater antennas (b) 6 repeater antennas (b) 8 repeater antennas

Fig.14 Efficiency of wireless power transfer, η_{21}, and ratio of power reflection, η_{11}

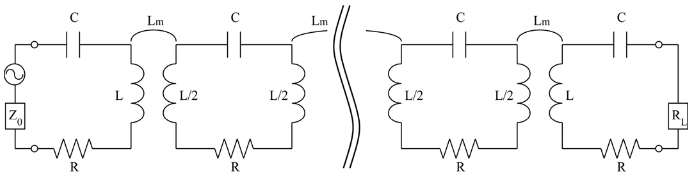


Fig.15 Equivalent circuit of repeater antennas

5. Conclusion

We propose that it is advantageous to represent a magnetic resonant coupling antenna by an equivalent circuit because such a circuit can be used to obtain a design circuit that can be connected to the magnetic resonance coupling antennas. Therefore, wireless power transfer via magnetic resonance coupling from the standpoint of an equivalent circuit is discussed in this paper. The equivalent circuit is well matched to the magnetic field analysis and experimental results. The difference between typical circuits is shown, and the unique feature of the magnetic resonant coupling antenna, which consists of repeater antennas and the equivalent circuit, is discussed.

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