Optimization using Transmitting Circuit of Multiple Receiving Antennas for Wireless Power Transfer via Magnetic Resonance Coupling

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***Abstract*—Electromagnetic resonance coupling technology has received more attention than other wireless power transfer technologies due to its capability to transfers energy across large air gap with high efficiency. The fundamental characteristics of a paired transmitting antenna and receiving antenna have been examined. However, in practical use, more than one receiving antenna is sometimes used, and some applications require multiple receiving antennas. In particular, this electromagnetic resonance coupling technology is desirable for powering multiple receiving antennas simultaneously because it is robust to displacement. In this paper, the multiple antennas efficiency optimization by transmitting circuit considering effect of cross-coupling and sign of mutual inductances, are proposed. The equivalent circuits for multiple antennas enable calculation of impedance matching circuit's parameters which will be used to optimize the transmitting antenna to achieve high efficiency. The equivalent circuits for multiple antennas enable to calculate high efficiency and it is optimized by changing transmitting circuit. This is also verified by electromagnetic field analysis, experiment and equivalent circuit theory. Proposed method is suitable for designing multiple antenna power supply system.**

Keywords-multiple receiving antennas; wireless power transfer; magnetic resonance coupling; optimization

I. INTRODUCTION

The demand for wireless power transfer via electromagnetic resonance coupling has recently increased. Electromagnetic resonance coupling technology has received more attention than other wireless power transfer technologies due to its capability to transfers energy across its large air gap and high efficiency[1]. The fundamental characteristics of a paired transmitting antenna and receiving antenna have been examined[2][3][4][5] and recently repeater antennas are studied[6]. However, in practical use, more than one receiving antenna is sometimes used, and some applications require multiple receiving antennas. In particular, this electromagnetic resonance coupling technology is desirable for powering multiple receiving antennas simultaneously because it is robust to displacement. In this paper, the multiple antennas efficiency optimization by transmitting circuit is proposed. In section 2, the equivalent circuit for multiple receiving antennas is investigated. To determine the basic characteristics of multiple receiving antennas, we investigate the case of three antennas. Equivalent circuit for multiple antennas which is even considered effect of cross-coupling and sign of mutual inductances, is proposed. Then the proposed models are verified by electromagnetic field analysis and experimental results. In section 3, efficiency optimization by transmitting circuit for multiple antennas is developed. The equivalent circuits for multiple antennas enable calculation of impedance matching circuit's parameters which will be used to optimize the transmitting antenna to achieve high efficiency. This is also verified by electromagnetic field analysis and experimental result. Lastly section 4 presents the conclusions.

II. MULTIPLE FEED FOR RECEIVERS

In this section, the multiple receiving antennas are discussed. In this case, coupling does not occur between the transmitting antenna and receiving antenna but also between the receiving antennas. Therefore, all coupling should be considered.

To determine the basic characteristics of multiple receiving antennas, we investigate the case of three antennas. The multiple antennas were represented by a series resonance circuit defined by inductance L, C, and R with loads existing at each receiving antenna. L is the self inductance, C is the capacitance, and R is the internal resistance plus the radiation resistance. Therefore equivalent circuit for multiple antennas which includes effect of cross-coupling and sign of mutual inductances could be proposed.

Therefore, the equivalent circuit is represented as in Fig. 1. Antenna 1 is the transmitting antenna and antenna 2 and antenna 3 are receiving antennas. The self-inductances and mutual-inductances of the antennas are shown in equation (1), and the impedances are shown in equation (2); therefore, equation (3) is obtained by using the L, C, and R values of the antenna in equation (2). The S-parameter is shown in equation (4). The impedance of a circuit directly connected to the antenna and the receiving antenna can be described using equation(5). Equations (6) to (9) yield equation (10) and (11), which are the definition of the efficiency of wireless power transfer to antenna 2 and antenna 3, named η_{21} and η_{31} respectively. The efficiency is evaluated between the transmitting and receiving antennas. The ratio of reflected power is defined as η_{11} and is given in equation(12).

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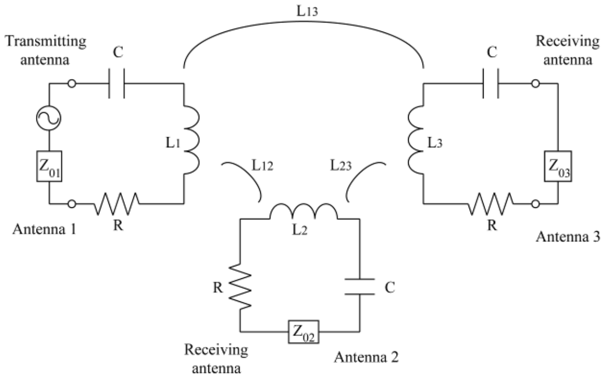


Figure 1 Equivalent circuit of multiple receiving antennas.

$$[L]=\begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{bmatrix} \tag{1}$$

$$[Z]=\begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \tag{2}$$

$$[Z]=\begin{bmatrix} R+j\left(\omega L-\dfrac{1}{\omega C}\right) & j\omega L_{12} & j\omega L_{13} \\ j\omega L_{21} & R+j\left(\omega L-\dfrac{1}{\omega C}\right) & j\omega L_{23} \\ j\omega L_{31} & j\omega L_{32} & R+j\left(\omega L-\dfrac{1}{\omega C}\right) \end{bmatrix} \tag{3}$$

$$[S]=\begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix} \tag{4}$$

$$[Z_0]=\begin{bmatrix} Z_{01} & 0 & 0 \\ 0 & Z_{02} & 0 \\ 0 & 0 & Z_{03} \end{bmatrix} \tag{5}$$

$$[S]=\left\{[\hat{Z}]+[1]\right\}^{-1}\left\{[\hat{Z}]-[1]\right\} \tag{6}$$

$$[Y_0]=[Z_0]^{-1} \tag{7}$$

$$\left[\hat{Z}\right]=\left[\sqrt{Y_0}\right][Z]\left[\sqrt{Y_0}\right] \tag{8}$$

$$[1]=\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{9}$$

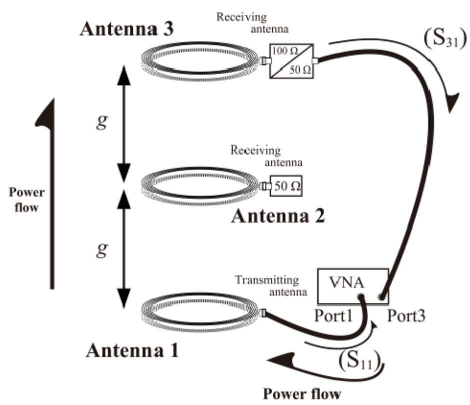
$$\eta_{31}=|S_{31}|^2 \tag{10}$$

$$\eta_{21}=|S_{21}|^2 \tag{11}$$

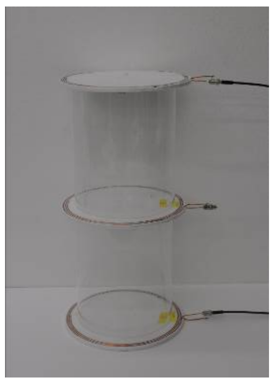
$$\eta_{11}=|S_{11}|^2 \tag{12}$$

At first, the minimum configuration of multiple receiving antenna system consisting of 3 elements is studied. Then the three elements are positioned vertically where coupling is strong. The parameters are shown in Fig. 2(a). The radius of antenna is 150 mm, 5 turns and the pitch is 5 mm. The air gap g = 300 mm. The impedances of each antenna are Z_{01} = 50 Ω, Z_{02} = 50 Ω and Z_{03} = 100 Ω. To verify the equivalent circuit, the electromagnetic field analysis which is method of moment and experiment are conducted and compared with each other. The results are shown is Fig. 3. The electromagnetic field analysis result, experimental results and equivalent circuit results are consistent. Therefore, equivalent circuit is verified and can be used as a model in evaluation. With these antennas positions and loads values, the efficiency of wireless power transfer is low because of power reflection at resonance frequency. Electromagnetic field analysis result shows that the efficiency of antenna 2 is 50.00 % and the efficiency of antenna 3 is 6.92 %. The sum of efficiency of antenna 2 and antenna 3 is 56.92 %. Therefore, the impedance matching is necessary to transfer the power to loads without reflections. Impedance matching will be discussed at next session.

We conducted experiments using the configuration shown in Fig. 2. The experiments were conducted using a vector network analyzer. The efficiency of wireless power transfer and the ratio of reflected power can be obtained by using the measured values and equations (10) to (12) because the vector network analyzer can measure the transmitted wave ratio S_{31}, S_{21}, and reflected wave ratio, S_{11}.

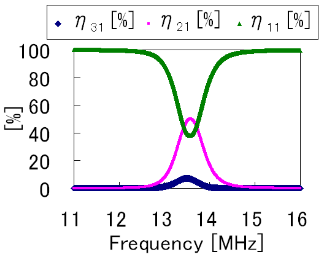


(a) Parameters of three antennas.

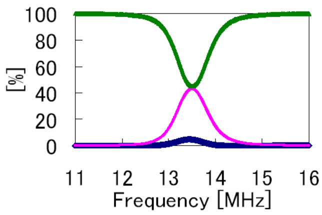


(b) Photograph of experimental setup.

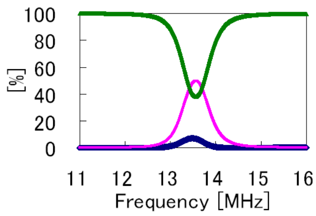
Figure 2 Experimental setup.



(a) Electromagnetic field analysis result.

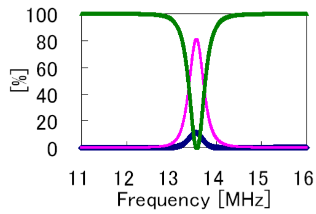


(b) Experimental result.

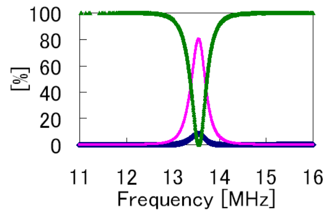


(c) Equivalent circuit result.

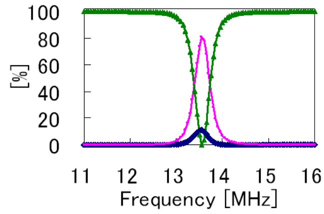
Figure 3 Efficiency comparition of electromagnetic field analysis result, experimental result and equivalent circuit result of multiple reciving antennas with 3 elements. Z_{01} = 50 Ω, Z_{02} = 50 Ω and Z_{03} = 100 Ω.



(a) Electromagnetic field analysis result.



(b) Experimental result.



(c) Equivalent circuit result.

Figure 4 Efficiency comparision of electromagnetic field analysis, experiment and equivalent circuit results of multiple receiving antennas with 3 elements. Z_{02} = 50 Ω, Z_{03} = 100 Ω. Following Z_{01} are at 13.56 MHz (a) Z_{01} = 11.80+j0.78 Ω (b) Z_{01} = 9.98+j8.31 Ω (c) Z_{01} = 11.74+j0.92 Ω.

III. Optimization of Multtiple Recivers at Primary Side

In previous section, the electromagnetic field analysis result, experimental result and equivalent circuit result are consistent. Therefore, in this section, only the electromagnetic field analysis will be used.

A. *Minimum Configuration by three elements*

High efficiency wireless power transfer system is necessary to have the impedance matching circuit; otherwise the efficiency in same situation could be low, as shown in Fig. 3. Therefore, impedance matching will be done by connecting matching circuit to antenna 1. For impedance matching, the source impedance is made equal to the complex conjugate of the load impedance. Fig. 4 shows the electromagnetic field analysis result, experimental result and equivalent circuit result when the impedance matching circuit, which makes complex conjugate, is connected to the transmitting antenna and these results are consistent. In this configuration, transmitting distance is 300 mm, which is considered a long distance compared to the antenna size, and efficiency becomes higher after matching. Due to the electromagnetic field analysis result, the efficiency to antenna #2 is 80.91 % and antenna #3 is 11.20%. The sum of efficiency of antenna #2 and #3 is 92.11 % that means the efficiency improved 35.19 % compared to before impedance matching. Therefore, the usage of impedance matching at transmitting circuit for multiple receiving antennas is proved to be valid.

B. *Asymmetrical and multiple receivers*

Next, to further confirm the validity of impedance matching at transmitting circuit for non-minimum case, the configuration is changed and this shows impedance matching at transmitting circuit is also accepted if there are more antennas and the positions are changed. In this case, the antenna arrangement is changed and antenna number is increased from three to six. Then, impedance matching and equivalent circuit calculation are done in the same way of the previous section. Therefore just the setup and results are shown here. The transmitting antenna's radius is 480 mm, number of turn is 2 and pitch is 5 mm as shown in Fig. 5. The 5 receiver antennas are the same as Fig. 2 whose radius is 150 mm 5 turns and pitch is 5 mm and these antennas are placed 10 mm away each other. The equivalent circuit is shown in Fig. 6.

When Z_{01} = 50 Ω, Z_{02} = 50 Ω, Z_{03} = 50 Ω, Z_{04} = 50 Ω, Z_{05} = 50 Ω, Z_{06} = 50 Ω and the result before impedance matching is shown in Fig. 7(a). After impedance matching, result is shown in Fig. 7(b). Both results are obtained by electromagnetic field analysis and impedance matching is done at 13.56 MHz. These results show that the average efficiency of each antenna is improved from 9.98 % to 18.91 % and the sum of efficiency improved from 49.92 % to 94.54 %. The improved efficiency due to impedance matching is 44.62 %.

The impedances are changed and the same study is conducted. When Z_{01} = 50 Ω, Z_{02} = 25 Ω, Z_{03} = 50 Ω, Z_{04} = 100 Ω, Z_{05} = 200 Ω, Z_{06} = 300 Ω and the result before impedance matching, the result is shown in Fig. 8(a). After impedance matching result is shown in Fig. 8(b). Both results are obtained by electromagnetic field analysis and impedance matching is done again at 13.56 MHz. These results show that the average efficiency of each antenna is improved from 12.45 % to 19.39 % and the sum of efficiency improved from 62.22 % to 96.93 %. The improved efficiency due to impedance matching is 34.71 %.

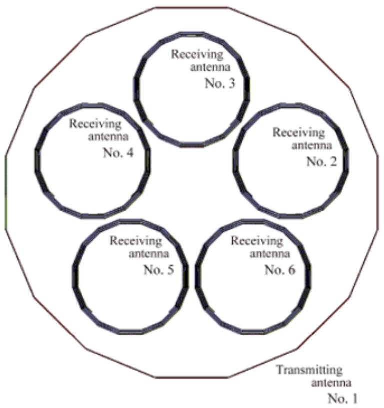


Figure 5 Configuration of six antennas.

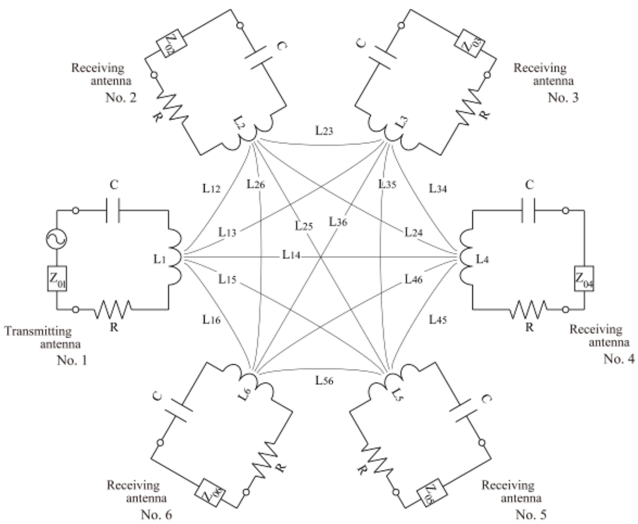
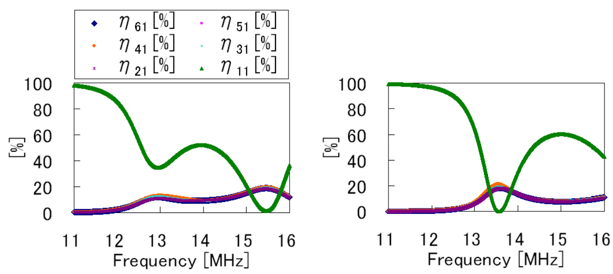
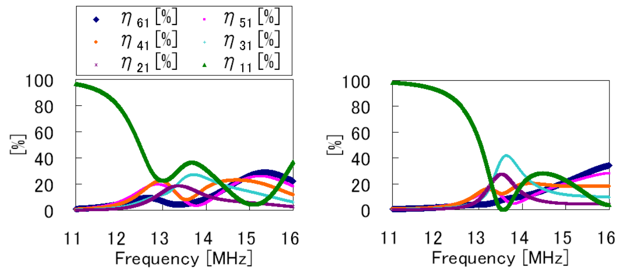


Figure 6 Equivalent circuit for six antennas considering cross-coupling.



(a) (b)

Figure 7 Electromagnetic field analysis of multiple receiving antennas with six elements. Z_{02} = 50 Ω, Z_{03} = 50 Ω, Z_{04} = 50 Ω, Z_{05} = 50 Ω, Z_{06} = 50 Ω. (a) Before matching Z_{01} = 50 Ω. (b) After matching Z_{01} = 46.68-j93.60 Ω at 13.56MHz.



(a) (b)

Figure 8 Electromagnetic field analysis of multiple receiving antennas with six elements. Z_{02} = 25 Ω, Z_{03} = 50 Ω, Z_{04} = 100 Ω, Z_{05} = 200 Ω, Z_{06} = 300 Ω. (a) Before matching Z_{01} = 50 Ω is before matched. (b) After matching Z_{01} = 51.98-j76.13 Ω at 13.56MHz.

IV. CONCLUSION

Optimization by impedance matching at transmitting circuit can achieve high efficiency wireless power to multiple receivers is confirmed. It is possible regardless number of antenna and position; however, the power ratio of each receiving antenna is different because there is no adjustment regarding power distribution. The balanced power distribution and its optimization using impedance matching will be addressed in future studies.

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