Efficiency improvement of wireless power transfer via magnetic resonance using the third coil

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1. Introduction

A wireless power transfer system via magnetic resonance has been reported by several groups [1-3]. In those reports, two resonance coils work as a transmission coil and a reception coil, respectively. The transfer efficiency between two coils is a function of the distance and the orientation between the coils. When the distance between the two coils is long, the transfer efficiency is small. When two coils share a single axis, the transfer efficiency is maximal, but otherwise the efficiency becomes lower. If the axes of them are orthogonal and the center of one coil lies on the axis of another, the transfer efficiency becomes minimal. In some applications where the distance and the orientation of the coils are difficult to keep fixed, an appropriate countermeasure against the decline of transfer efficiency is desired.

In this paper, a wireless power transfer system via magnetic resonance using the third coil is proposed to improve the transfer efficiency. The third coil, which is implemented in the wireless power transfer system, does not need to carry any electrical device such as an amplifier circuit or a rectifier circuit. The proposed system can improve the transfer efficiency when the distance between two coils is large. Also, the proposed system can improve the transfer efficiency when one of the coils rotates and their axes become separated. The effectiveness of the proposed system is confirmed by measurement using a vector network analyzer.

2. Configuration of the proposed wireless power transfer system

Figure 1 shows the configuration of the proposed wireless power transfer system. A transmission coil and a reception coil are put at distance d. The third coil is placed between the transmission coil and the reception coil. Parameters in shape of the transmission coil, the reception coil, and the third coil are the same. The parameters of the coil are as follows. The diameter of the coil r_1 is 15 cm. The height of the coil h is 3 cm. The diameter of the coil wire is 2.2 mm. The coil is formed by winding copper wire.

The transmission coil and the reception coil are induced by a loop. The gap between the transmission coil and the loop is g_1. The gap between the reception coil and the loop is g_2. Input impedance is matched to 50 ohms by tuning the gaps g_1 and g_2.

In the measurement, S-parameters are measured by a vector network analyzer. Port-1 and port-2 are connected to the loop for the transmission coil and the loop for the reception coil, respectively. Input impedance of each port is tuned by adjusting the gap g_1 and g_2, respectively. Figure 2 is a photograph of the measurement system.

3. Measurement Results

In general, the transfer efficiency of a large coil is higher than that of a small coil. In this paper, the transmission distance d is normalized by the diameter of the coil. A normalized distance d_n is defined as $d_n=d/r_1$. The effectiveness of the proposed system is confirmed by the following three measurements.

3.1 Performance enhancement by the third coil at the center of other two coils

First, the distance d between the transmission coil and the reception coil is changed. The third coil is put at the center between two coils ($d_1=d_2=d/2$).

Figure 3 shows the measurement results. The transfer efficiency is shown in Fig. 3(a) and S_{11} and S_{22} are shown in Fig. 3(b). The transfer efficiency becomes the maximum at approx. 27 MHz. S_{11} and S_{22} in Fig. 3(b) are measured at the frequency at which the maximum transfer efficiency is obtained. Measurement results without the third coil are also shown in Fig. 3. The transfer efficiency of the proposed system is higher than that of the conventional system.

Figure 4 shows the quantity of improvement of the transfer efficiency. The maximum efficiency improvement of 39.6 % is obtained when the normalized distance d_n is four.

3.2 Effect of location of the third coil

In the second measurement, the distance d_1 between the transmission coil and the third coil is changed. The normalized distance d_n is set to 5.33.

Measurement results are shown in Figure 5. Transfer efficiency without the third coil is 5.6 %. The transfer efficiency is improved by using the third coil. The maximum efficiency of 40.2 % is obtained when the $d_1/d_2=1$.

3.3 Effect of separation of axes of two coils and improvement by the third coil

In the third measurement, the rotation angle, which is here defined as the angle between the axes of a coil under test and transmission coil, of the reception coil is set to 90 degrees. Figure 6 shows the configuration of the third measurement. The transfer efficiency without the third coil becomes the minimum when the rotation angle of the reception coil is set to 90 degrees. The third coil is put at the center between two coils ($d_1=d_2=d/2$). The rotation angle of the third coil is defined as θ. The normalized distance d_n is set to 5.33, which is the same as the case described in section 3.2.

Measurement results are shown in Figure 7. The transfer efficiency without the third coil is only 0.4%. The maximum transfer efficiency of 9.9 % is obtained when the rotation angle θ is 45 degrees. Using the third coil, the transfer efficiency becomes 25 times greater.

In the second measurement, the maximum transfer efficiency is obtained when the third coil is set at the center between two coils. In the third measurement, the maximum transfer efficiency is obtained when the rotation angle is set to 45 degrees. In these cases, the coupling coefficient k_{13} between the transmission coil and the third coil and the coupling coefficient k_{32} between the third coil and the reception coil are the same. Therefore, it is necessary to equate the coupling coefficient k_{12} with the coupling coefficient k_{32} to maximize the transfer efficiency.

4. Conclusions

A wireless power transfer system via magnetic resonance using the third coil was proposed. The effectiveness of the proposed system was confirmed by three kinds of measurement using a vector network analyzer. In the first measurement, the transfer efficiency was found to be improved by the third coil. In the second and third measurement, the relationship between the coupling coefficient k_{13} and coupling coefficient k_{32} were found to be similarly important for maximizing the transfer efficiency. In this paper, good impedance matching was obtained by tuning the gap between the coil and the loop. Study on impedance matching without the tuning of the gap is a subject for future work.

References

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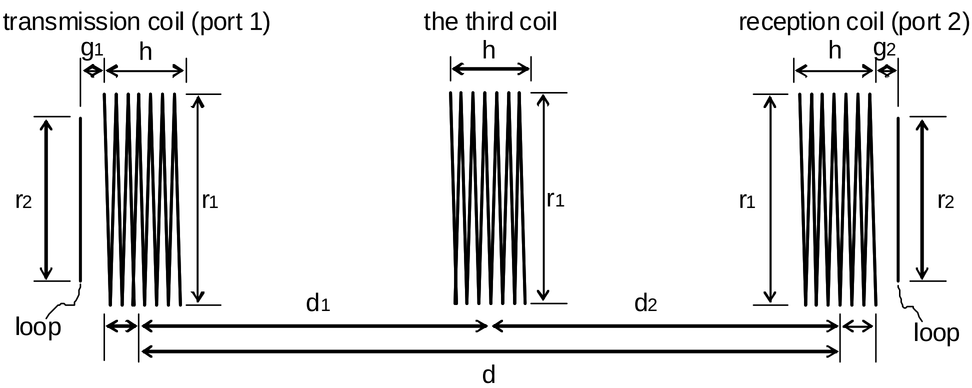
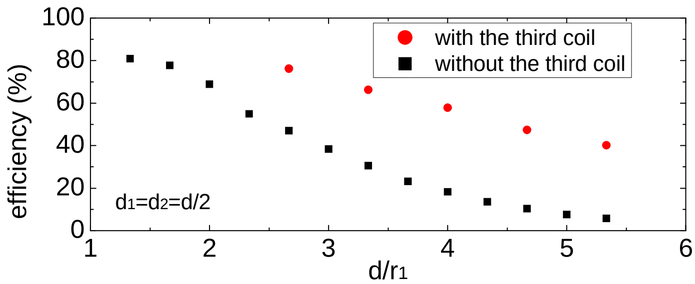
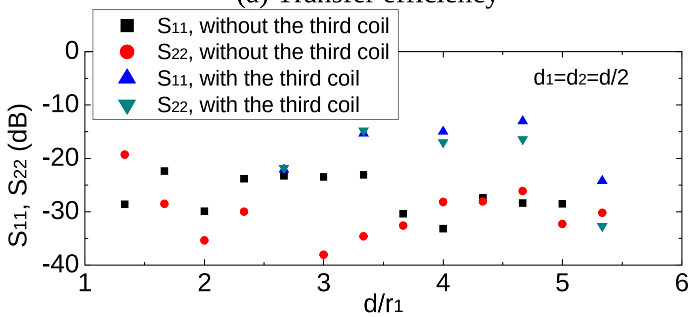


Figure 1: Configuration of the proposed wireless power transfer system

Figure 2: Photograph of the measurement system



(a) Transfer efficiency



(b) S11 and S22

Figure 3: The first measurement results, (a) transfer efficiency, (b) S11 and S22

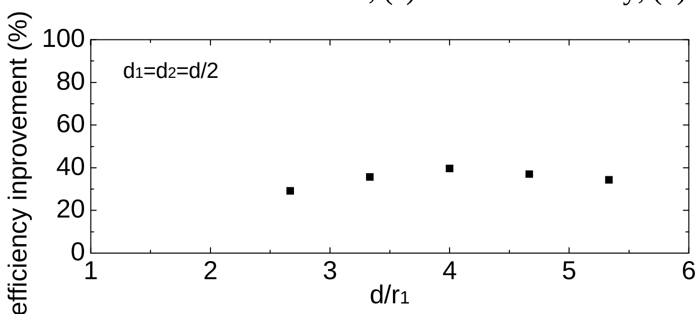
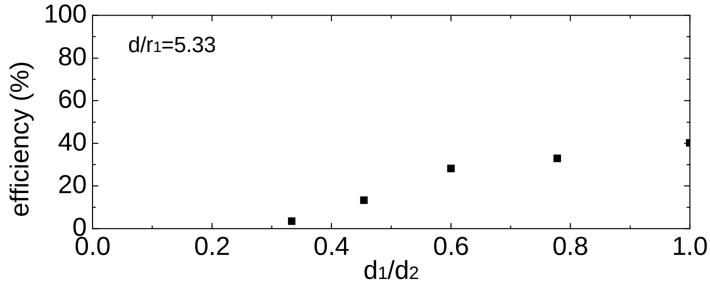
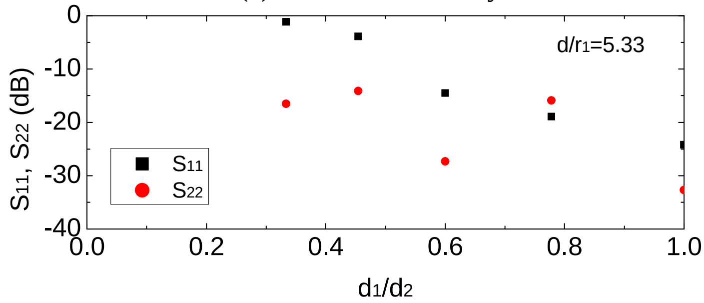


Figure 4: The efficiency improvement by the third coil



(a) Transfer efficiency



(b) S11 and S22

Figure 5: The second measurement results, (a) transfer efficiency, (b) S11 and S22

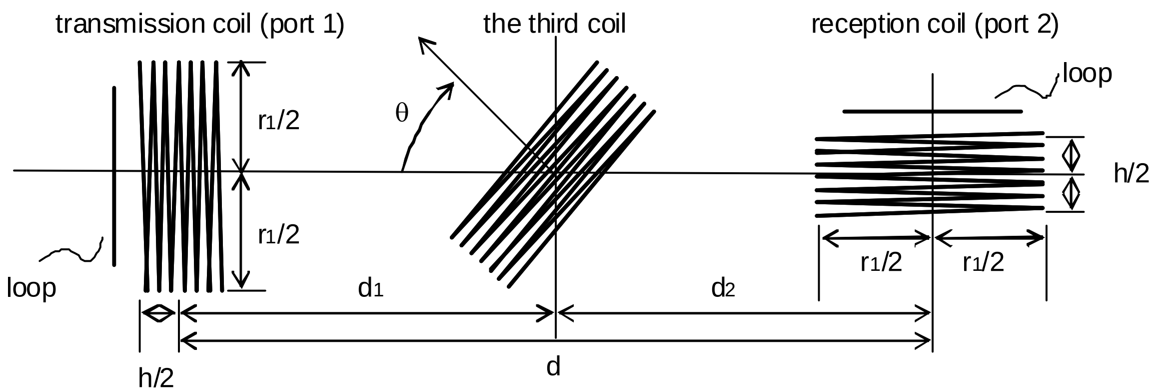
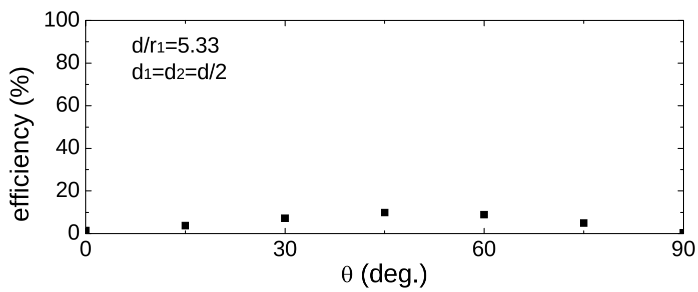
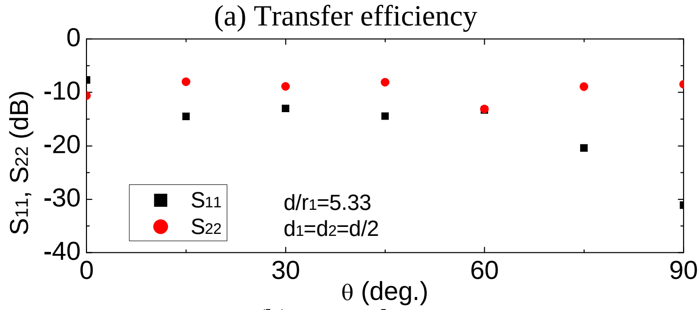


Figure 6: Configuration of the proposed wireless power transfer system



(a) Transfer efficiency



(b) S11 and S22

Figure 7: The third measurement result, (a) transfer efficiency, (b) S11 and S22