Wireless power transfer using multiple-transmitters for high stability for position

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ABSTRACT

The aim of this study is to optimize the system in the wireless power supply using multiple transmitters by algebraically analyzing the effects of both a circuit parameter and an axis displacement, etc. In addition to these analyses, the other aim is designing, producing and evaluating wireless charger with high stability for position. In the proposed method, we analyzed the situation in which three transmitters are used as power sources. It is turned out that the optimum arrangement of three transmitters is equilateral triangular from Biot-Savart law and circuit equation. In the experiment, transmitted power is measured when the receiver is moved on the vertical plane in regard to central axis of coils. It is confirmed that 4~4.5mW is transmitted at the face-to-face of transmitters and 2.4mW is transmitted at the center of transmitters.

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1. INTRODUCTION

1Wireless power transfer (WPT) has been studied in various fields such as industry [1, 2], manufacturing [3], medicine [4, 5], and information [6, 7]. The basic principle has been proposed in the 19th century, and since the MIT report in 2007 [8], it has much attracted many researchers. Recently, many papers about WPT have been published, and various products have been examining and commercializing. For example, studies such as examination of design of coils [9-12] and comparison of efficiency by change of applied voltage waveform [13, 14], are investigating. As products, WPT system is applied for power supply on various fields, for instance mobile devices and IoT [15], vehicles traveling on the road [16-19], and micro implant devices [20-22]. As mentioned above, researches finding ideal conditions are actively conducted to improve the performance of WPT [23, 24].

On the other hand, analysis of the situations which degrade performance are not viewed as important, for example leakage flux and misalignment between transmitters and receivers [25, 26]. As a result, there are some restrictions with relation to design of circuits. On the other hand, considering flexibility of the receiver position, the size of the receiving coil depends on the receiving device, and the loss due to leakage magnetic flux etc. occurs remarkably when transmitting coil is too large. Therefore, it is assumed that it is more advantageous to operate WPT circuit by using a few coils than to handle a single large coil in some situations.

This paper aims realization of stable power transmission regardless of the position of the receiving coil with using multiple transmitters. In order to utilize multiple transmitters, the electromagnetic interaction between transmitters and receiver must be considered. A calculation method is considered and a mathematical formula based on electromagnetism and circuit theory is expressed so that the user could arbitrarily set parameters such as the number and position of transmitters to improve the versatility. Finally, the experimental verification is performed using the actually designed electric circuit, and it is compared with the theoretical result.

2. CALCULATION OF POWER

2.1. Calculation of mutual inductance occurred between two coils arranged in three-dimensional space

Analysis is performed on the case where two coils are arranged in a three-dimensional space in Figure 1. The coordinate of the transmitting coil is (0,0,0), and the coordinate of the receiving coil is (d_x,d_y,h). At this time, d_x and d_y represent an off-axis distance from z-axis, and h represents a facing distance between the coils.

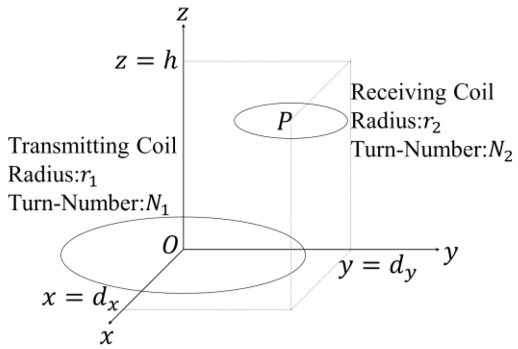

Figure 1. Two coils arranged in three-dimensional space

From the above, the mutual inductance between the coils is obtained according to the Biot-Savart law as follows:

$$M \simeq \frac{\mu_0 S_1 S_2}{2\pi\left(r_1^2+d_x^2+d_y^2+h^2\right)^{\frac{3}{2}}}[\mathrm{H}] \tag{2}$$

$$S_1 = \pi r_1^2 N_1, S_2 = \pi r_2^2 N_2$$

2.2. Power calculation of wireless power transfer circuits using three transmitting circuits

A wireless power transfer circuit for charging a battery is designed as follows in Figure 2. The left side is a group of transmitting circuits, and the right side is a receiving circuit which contains which battery device. u is the voltage of power supply, $R_1, R_2, R_3, R_0, C_1, C_2, C_3, C_0$ are parasitic components, L_1, L_2, L_3, L_0 are the self inductances, M_{10}, M_{20}, M_{30} are mutual inductances between transmitting circuits and receiving circuit, M_{12}, M_{13}, M_{23} are mutual inductances between both transmitting circuits and R_L is the resistance of device. From Figure 2, a circuit equation is obtained as (2).

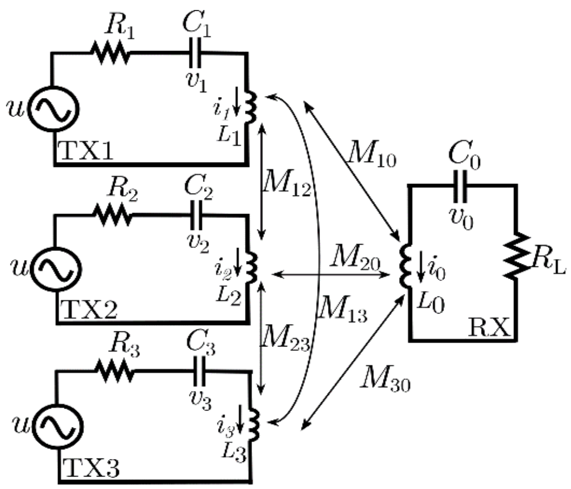

Figure 2. Wireless power transfer circuits using three transmitting circuits

$$\begin{bmatrix} u \\ u \\ u \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega M_{12} & j\omega M_{13} & j\omega M_{10} \\ j\omega M_{12} & Z_2 & j\omega M_{23} & j\omega M_{20} \\ j\omega M_{13} & j\omega M_{23} & Z_3 & j\omega M_{30} \\ j\omega M_{10} & j\omega M_{20} & j\omega M_{30} & Z_0 \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_0 \end{bmatrix} \quad (2)$$

$$Z_n = R_n + (j\omega C_n)^{-1} + j\omega L_n [\Omega], n = 0,1,2,3$$

The power at the load P_{L} can be obtained by solving the current i_o of receiving circuit from the above simultaneous equations and substituting it into the following equation:

$$P_{\mathrm{load}} = R_{\mathrm{L}} i_0^2 \text{ [W]} \quad (3)$$

3. EXPERIMENTAL VERIFICATION

3.1. Condition of experiment for wireless power transfer by using three transmitting circuits

The experimental circuit is shown in Figure 3. The values of the circuit elements and the setting of the coordinate conditions are shown in Table 1 and Table 2 respectively.

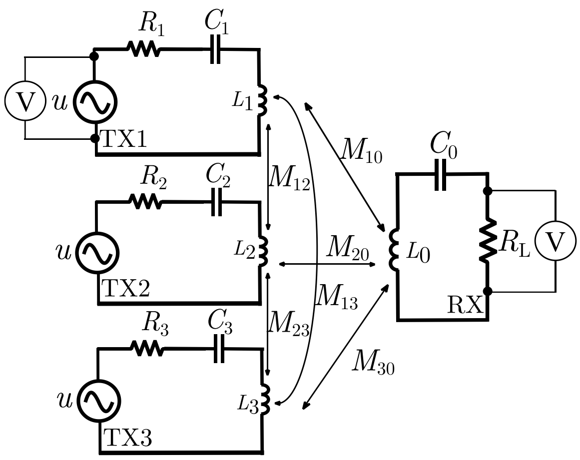

Figure 3. Experimental circuit

Table 1. Values of circuit elements

Values of circuit elements							
R_1	46.5Ω	R_2	46.3Ω	R_3	46.7Ω	R_0	46.8Ω
C_1	367pF	C_2	374pF	C_3	360pF	C_0	372pF
L_1	24.8μH	L_2	24.8μH	L_3	24.9μH	L_0	24.9μH

Table 2. The coordinate conditions

Parameters	Values [mm]
Facing distance between coils h	15 or 35
Center coordinates of transmitting coils	(-25-25,h) , (25,-25,h) , (0,25,h)
Moving range in the x-axis direction	-50~50
Moving range in the y-axis direction	-50~50
Moving width in the x-axis direction	5
Moving width in the y-axis direction	10

3.2. Variation of load power versus receiver coil coordinates

The variation of load power is investigated by changing the coordinates of the receiving coil with respect to the transmitting coil and the facing distance between the transmitting coil and the receiving coil. The calculated power is shown in Figures 4 and 5, and the experimental power are shown in Figures 6 and 7, respectively.

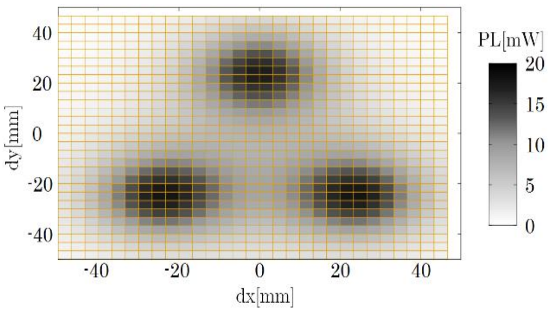

Figure 4. Calculated power where $h = 15\text{mm}$

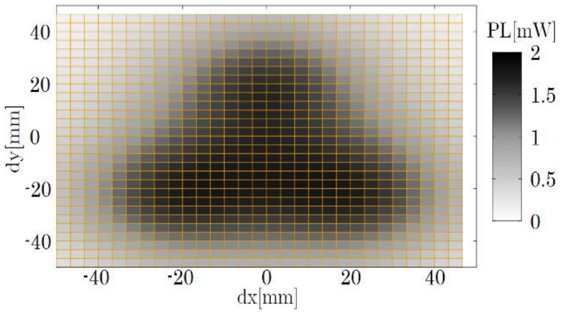

Figure 5. Calculated power where $h = 35\text{mm}$

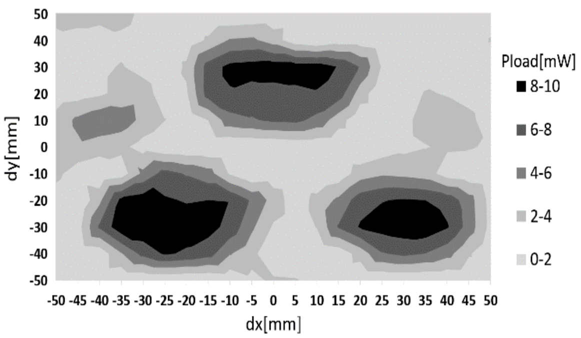

Figure 6. Experimental power where $h = 15\text{mm}$

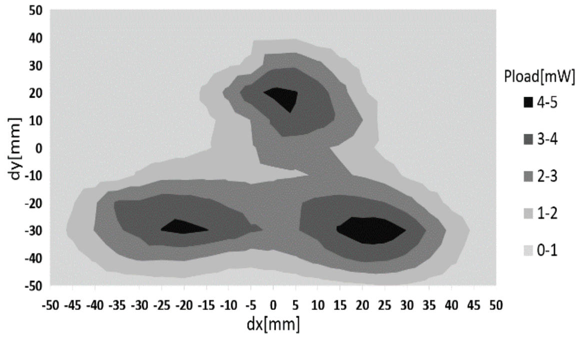

Figure 7. Experimental power where $h = 35\text{mm}$

3.3. Discussion

The comparison of the maximum power and the stability region is shown in Table 3. Then, the stability region is a range in which the output power is 80% or more of the maximum power. As the facing distance of the coils increases, the maximum power decreases significantly while the stability region expands. Therefore, it is important to consider the trade-off between power and region in the situation. The defect in the approximation of calculation and experimental circuit are considered as the cause of error.

Table 3. Maximum power and Stability region

	Maximum power [mW]		Stability region [%]	
	$h = 15\text{mm}$	$h = 35\text{mm}$	$h = 15\text{mm}$	$h = 35\text{mm}$
Calculated	17.82	1.585	9.62	38.4
Experiment	9.55	4.65	12.6	4.8

4. CONCLUSION

This study tried to realize stable wireless power transfer regardless of the arrangement of receiving coil by using multiple transmitters in the circuit. Mutual inductance was derived by using geometrical equation and the power was obtained from the circuit equation considering interactions. Moreover, experiments were performed to prove the validity of the calculation and investigate errors and their causes. As a result, while it was possible to transmit power less than that of expectation, some similarities were found in the trends. In the future, it is necessary to consider the increase in transmission power, the improvement in efficiency, and the effects caused by the increase in coils.

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