4-COILS MAGNETIC RESONANCE COUPLING WIRELESS POWER TRANSFER WITH VARYING ROTATIONAL ANGLE

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Abstract

This research work performs a study on Wireless Power Transfer (WPT) using 4-coils magnetic resonance where research focuses on varying the rotational angle of the receiver coil from the centre of system. Simulation work is performed by using CST Microwave Studio to observe the magnetic coupling for 4-coils system at a varied rotational angle. Comparative analysis was performed at different rotational angle which are 0°, 15°, 30° and 45°. Few parameters are examined and analysed which are scattering parameter, impedance parameter, electric field and magnetic field.

1 Introduction

Nowadays, electronic devices such as smartphone and laptop are very common and make our life more convenient. Those electronic devices provide a lot of convenient, joy and knowledge. However, when the battery is low, we need to find a socket to connect the electricity supply by using a bulky and messy adapter. The battery will die off when the socket or adapter is not functioning. Most often, one power socket is used to power one device. The limitation of the socket, the bulky and messy adapter has become the main issues. To solve this issue, wireless power transfer (WPT) has been introduced.

Wireless Power Transfer is defined as power transmission without the presence of a solid medium such as grid, cable or wire. WPT stood up as one of the major transmission innovation recently. This technology is convenient, safe and flexible which tackles the main concern in this new era of technology. Wireless transmission implementations are not only more convenient but quite practical as compared to traditional wired power delivery implementations [1–3]. WPT technology has been widely developed since the past decade [4-7].

Generally, WPT can be classified into three types, short-range WPT which is inductive coupling, mid-range WPT which is magnetic resonant coupling and long-range WPT which are RF, microwave, and light beam. Each different technique has their pros and cons in terms of efficiency, distance and also side effects toward human being. Table 1 lists the pros and cons of different WPT methods.

Wireless Charging Technique	Advantage	Disadvantage	Effective Distance
Inductive Coupling	Ease to implement	Short Distance	few millimetres up to few centimetres
	Convenient	Heating Effect	
	High Efficiency	Need tight alignment	
Magnetic Resonant Coupling	Charge multiple devices at the same times	Need fined tuned	few centimetres up to few meters
	High charging efficiency if it is fine tuned	Complex implementation	
	Omnidirectional charging	Large in term of size	
RF/ Microwave Radiation	Long distance charging	Healthy issue may be occurred due to high density of RF	within several meters to several kilometres
	Suitable for mobile device	Low charging efficiency	
		Unidirectional charging	

Table 1: Overview of WPT.

In this work, magnetic resonant coupling is focused as it is environment friendly, minimum exposure hazardous and line-of-sight transfer requirement [8]. Moreover, magnetic resonant coupling can be used to create a single transmitter with multiple receivers. This means that it can charge few devices simultaneously [9-10]. Advantages wise, magnetic resonant coupling can transfer at a further distance as compared to inductive coupling, and have a higher efficiency as compare to far-range WPT. Magnetic resonant coupling is transferred in few Megahertz which have a high Q factor. With the increase in charging distance, the high-quality factor helps to mitigate the sharp decrease in coupling coefficient, and thus the charging efficiency.

Magnetic resonance coupling was experimentally proven to transmit up to 2 meters with 40 % efficiency by MIT [11]. The efficiency can be increased up to 90% when the distance is reduced to 1 meter. But, the main disadvantage of this experiment is that it is too bulky as magnetic resonant coupling needs a capacitive coil to operate. In other words, to ensure a high efficiency wireless power transfer, a proper tuned impedance is required [10].

Research trend focuses on optimizing the design of magnetic resonance coupling in term of efficiency and transmission distance [12]. Automated impedance matching was undertaken to ensure the higher transmission efficiency [13-14]. Based on critical review, recent research focuses on mid-range wireless power transfer which is able to transmit energy and to power up devices in the range of centimetres up to the range of meters. Unidirectional transmitting devices and transmission lost are the two main issues to counter to ensure more practicable. Hence, the gap of research would be to perform simulation work and to suggest an optimize design parameters to achieve an omnidirectional and ideal transmission efficiency in mid-range power transfer.

This research work is undertaken to perform simulation on 4-coils magnetic resonance for wireless power transfer. Section 2 presents the mathematical fundamental of 4-coils structure for mid-range wireless power transfer. The block diagram of 4-coils system and its equivalent circuit are presented. Section 3 then shows the simulation result of 4-coils system using CST microwave studio. The performance parameters are varying the rotational angle between the centre of the receiver coil and the centre point of the system which are 0°, 15°, 30° and 45°.

2 4-Coils Magnetic Resonance Coupling Design and Formula

2.1 4-Coil System Design

Figure 1 shows the overall design of 4-coil system of magnetic resonance coupling wireless power transfer. In this research work, 4-coil system is focused and examined. Figure 2 shows the 4-coil 3D design by using CST Microwave Studio. Also, Figure 3 shows the rotational angle between the center of the receiver coil and the center point of the system, ɵ of 4-coils system which include 0°, 15°, 30° and 45°.

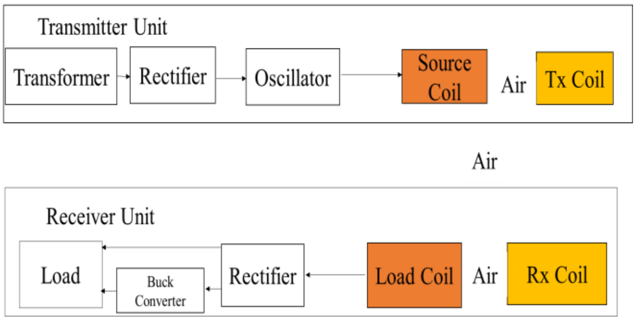


Figure 1: Transmitter and receiver unit of WPT

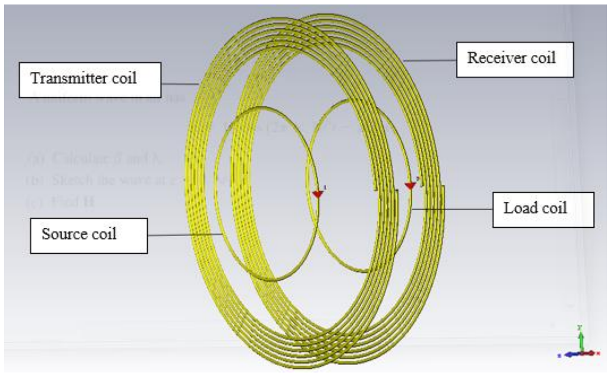
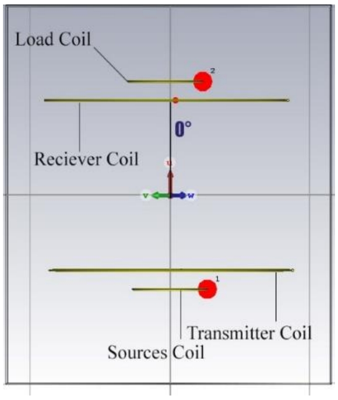
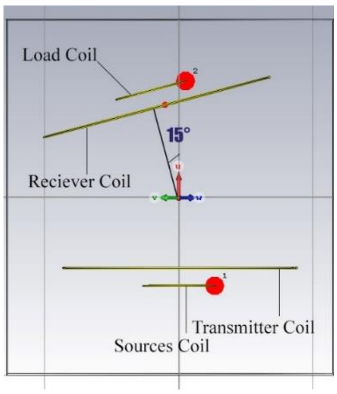


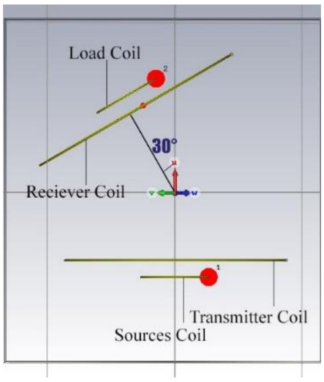
Figure 2: 4-coils system for magnetic resonance



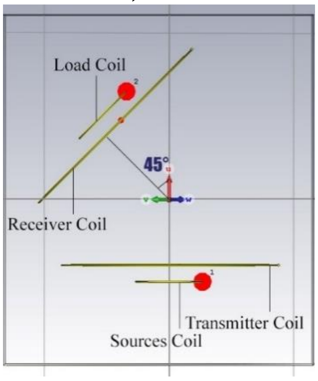
a) ɵ = 0°



b) ɵ = 15°



a) ɵ = 30°



d) ɵ = 45°

Figure 3: Rotational angle between the centre of the receiver coil and the centre point of the system, ɵ of 4-coils simulation using CST microwave studio

2.2 Mathematical fundamental of 4-coils system for magnetic resonance coupling wireless power transfer

The current is expressed using the matrix below [15]:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} & Z_{14} \\ Z_{21} & Z_{22} & Z_{23} & Z_{24} \\ Z_{31} & Z_{32} & Z_{33} & Z_{34} \\ Z_{41} & Z_{42} & Z_{43} & Z_{44} \end{bmatrix}^{-1} \begin{bmatrix} V_S \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

where,

$$Z_{ij} = j\omega M_{ij} = j\omega\sqrt{L_i L_j}\ (i, j = 1-4, i \neq j) \tag{2}$$

$$Z_{11} = R_S + R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) \tag{3}$$

$$Z_{22} = R_2 + j(\omega L_2 - \frac{1}{\omega C_2}) \tag{4}$$

$$Z_{33} = R_3 + j(\omega L_3 - \frac{1}{\omega C_3}) \tag{5}$$

$$Z_{44} = R_L + R_4 + j(\omega L_4 - \frac{1}{\omega C_4}) \tag{6}$$

Approximation is used in great distance:

$$Z_{13} = Z_{14} = Z_{24} \cong 0 \tag{7}$$

For simplification purpose [16],

$$Z_{12} = j\omega_0 k_{12}\sqrt{L_1 L_2} = jk_{12}\sqrt{Q_1 Q_2}\sqrt{(R_1 + R_s)R_1} \tag{8}$$

$$Z_{23} = j\omega_0 k_{23}\sqrt{L_2 L_3} = jk_{23}\sqrt{Q_2 Q_3}\sqrt{R_2 R_3} \tag{9}$$

$$Z_{34} = j\omega_0 k_{34}\sqrt{L_3 L_4} = jk_3\sqrt{Q_3 Q_4}\sqrt{R_3(R_4 + R_L)} \tag{101}$$

$$Z_{11} = R_1 + R_S;\ Z_{22} = R_2;\ Z_{33} = R_2;\ Z_{44} = R_4 + R_L \tag{11}$$

Q_1 is the quality factor. To calculate the flow of current in both the source and load loop, (7) has to be solved with the impedance parameter in Equation (8-11) [16]:

$$I_1 = \frac{Z_{22}Z_{33}Z_{44} + (\omega M_{23})^2 Z_{44} + (\omega M_{34})^2 Z_{22}}{Z_{11}Z_{22}Z_{33}Z_{44} + (\omega M_{23})^2 Z_{11}Z_{44} + (\omega M_{34})^2 Z_{11}Z_{22} + (\omega M_{12})^2(\omega M_{34})^2} V_S \tag{12}$$

$$I_4 = \frac{j(\omega M_{12})(\omega M_{23})(\omega M_{34})}{Z_{11}Z_{22}Z_{33}Z_{44} + (\omega M_{23})^2 Z_{11}Z_{44} + (\omega M_{34})^2 Z_{11}Z_{22} + (\omega M_{12})^2(\omega M_{34})^2} V_S \tag{13}$$

By substituting the impedance constants into Equation (12) and (13), I_1 and I_4 can be simplified as [16]:

$$I_1 = \frac{1 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4}{[(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + 1 + k_{23}^2 Q_2 Q_3]} \frac{V_S}{R_1 + R_S} \tag{14}$$

$$I_4 = \frac{j(k_{12}k_{23}k_{34}\sqrt{Q_1 Q_2}\sqrt{Q_2 Q_3}\sqrt{Q_3 Q_4}}{[(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + 1 + k_{23}^2 Q_2 Q_3]} \frac{V_S}{(R_1 + R_s)(R_4 + R_L)} \tag{15}$$

Voltage transfer is solved as [15]:

$$|S_{12}| \cong \frac{2\, k_{12}k_{23}k_{34}\, Q_2 Q_3\sqrt{Q_1 Q_4}}{(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + 1 + k_{23}^2 Q_2 Q_3} \tag{16}$$

The efficiency of transmittance rate is therefore calculated as [15]:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_4^2 R_L}{I_1^2 (\frac{R_S}{4})} = |S_{12}|^2 \tag{17}$$

The efficiency of transmittance rate explains the amount of energy transferred from the transmitter to the receiver. Coupling coefficient of k_{12} and k_{23} are constant. To calculate the resonator's range where a maximum $|S_{12}|$ is achieved, equations below are solved [16]:

$$\frac{d|S_{12}|}{dk_{23}} = 0 \tag{18}$$

$$k_{23}^* = \sqrt{\frac{(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4)}{Q_2 Q_3}} \tag{19}$$

In which k_{23}^{*} is the maximum range achievable by the transmitter to transfer power efficiently to transfer power towards receiver; k_{23}^{*} must be less than or equal to 1. Maximum $|S_{12}|$is achieved when reasonable amount of k_{23}^{*} is substituted, hence $|S_{12}|$ is therefore expressed as:

$$|S_{12}|_{\max} = \frac{k_{12}k_{34}Q_1Q_2R_L}{k_{23}^{*}\sqrt{L_1\omega_1L_4\omega_4}} \tag{20}$$

From (20), k_{23}^{*} has to be decreased to achieve a high $|S_{12}|_{\max}$.

3 Result and Discussion

This research work uses CST microwave studio to perform simulation on 4-coils magnetic resonance coupling at several of rotational angle. Figure 4 shows the E-field distribution while Figure 5 shows the H-field distribution across the 4-coils at a changing rotational angle. The H-field across the 4-coils are approximately the same which proves that it is not affected by the position of the coil.

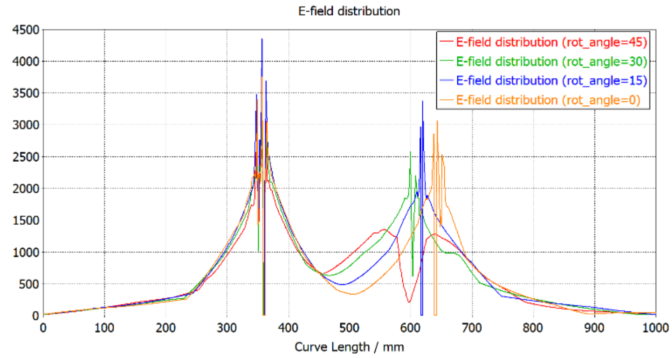


Figure 4: E-field distribution

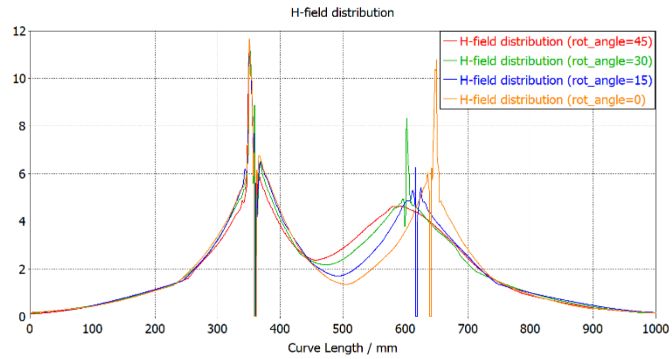


Figure 5: H-field distribution

Table 2 lists the S-Parameter of S_{12} transmission. It is observed that as the rotational angle between the centre of the receiver coil and the centre point of the system change, the S-parameter remain similar. Figure 6 shows the scattering parameters of the load coil at resonance frequency when the angle change from 0°, 15°, 30° and 45°. This shows that the position of the receiver coil did not affect the efficiency of the transmission as long as the tuning is well defined.

Rotational angle, ø (°)	***S-Parameter***
	S_{12}
0	0.9694
15	0.9720
30	0.9796
45	0.9847

Table 2: S-Parameters

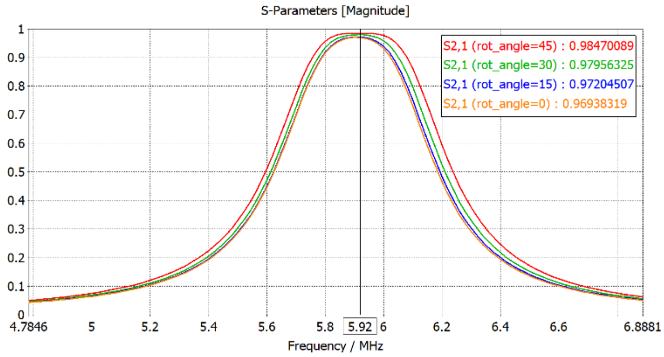


Figure 6: Scattering parameters at resonance frequency

Table 3 lists the Z-Parameter of Z_{12} at load 1 and 2, respectively. The impedance value would be of great reference for future experimental work or circuitry design. The decrease in angle causes the impedance value to increase. This is because when the rotational angle increases, the distance between the transmitter and the receiver coil increases which will eventually increase the coefficient, and therefore increases the impedance value. Figure 7 then plots the impedance parameters at resonance frequency.

Rotational angle, ø (°)	***Z-Parameter***
	Z_{12}
0	81.49
15	77.71
30	70.15
45	61.31

Table 3: Z-Parameters

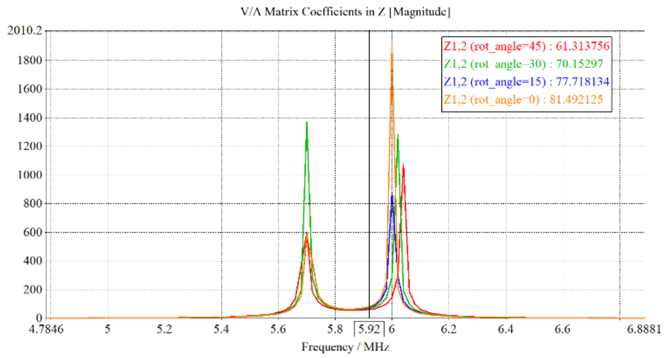


Figure 7: Impedance parameters at resonance frequency

Based on the results, few discussions can be done. S-parameter which indicate the efficiency of the transmission approximately same when the rotational angle changes when we using 4-coils magnetic resonant coupling. This is because the based-on Equation (20), the change of S_{12} is depend on the coefficient between the coils. When the rotational angle change, the S_{12} not changing due to the environment coefficient factor do not change as the material of the coil and the air remain constant. Also, when the rotational angle changing, the distance between the transmitter coil and receiver coil remain constant, this shows that there is no any affect in the S_{12}. S_{12} plays an important role in the system, as it determines the change in E-field and H-field as well.

4 Conclusion and Recommendation

This paper presented the functionality of 4-coils magnetic resonance circuitry in mid-range magnetic resonance wireless power transfer at various rotational angle between the receiver coils and the center of the system which are 0°, 15°, 30° and 45°. By using 4-coils magnetic resonant coupling wireless power transfer, S-parameter does not change due to the coefficient does not change when the angle changing. Simulation results show that the S-parameter approximately same as the rotational angle varied. As part of recommendation, the collected data would be a promising reference for hardware design of 4-coils magnetic resonance system to power up electronic devices and create an omnidirectional wireless power transfer.

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