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Critical Review and Simulation of Mid-range Wireless Power Transfer for Electronic Device

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Abstract. Functionality of wireless power transfer is yet to be utilized for the purpose of sustaining a green environment. This paper presents a critical review on the functionality of mid-range wireless power transfer using magnetic resonance coupling. Simulation of a 4-coils magnetic resonance for mid-range wireless power transfer is performed using CST microwave studio. The radius of source and load coil are 3 cm, while the radius of the transmitter and receiver coil are 5 cm. Distance between the source coil and load coil is set at 4 cm and resonance magnetic frequency is observed. At the load coil, electric field is achieved at 2140 V/m and surface current is recorded at 52.21 A. The change in impedance along the transmittance are plotted and discussed.

1. Introduction

Wireless Power Transfer (WPT) is defined as power transmission with the absence of any transition medium i.e. transmission grid, cable and wire. It has been widely studied and developed since the past decade [1-3]. WPT can be achieved with several methods such as inductive coupling, magnetic resonant coupling, radio frequency and microwave radiation. Studies on inductive coupling for short-range WPT are scanty; radio frequency or microwave radiation for long-range WPT is questionable in terms of long run health and environment impact, hence the focus is now on optimization of magnetic resonant coupling in the mid-range WPT [4-5].

Magnetic resonant coupling is based on evanescent waves between two resonant couplers which generate and transfer electrical energy through oscillation or variation in magnetic field [6]. The primary coil generates magnetic field, which induces voltage or current produced in the secondary coil with the same resonance frequency and strongly coupled together. When two coils operate at the same frequency, high efficiency of energy can be transferred with a small leakage or loss to the surrounding. Magnetic resonance coupling is environment friendly, with minimum hazardous exposure and line-of-sight transfer requirement. Previous research shows that a maximum efficiency of 97.6% can be achieved for a travelling distance of 0.3 cm [7-8].

Magnetic resonant coupling can transfer at a longer distance as compare to inductive coupling and is able to achieve a higher transmission efficiency as compare to far-range WPT [9-10]. Magnetic resonant coupling is transferred in few Megahertz which have a high quality factor (Q factor). When the charging distance increases, the high quality factor helps to mitigate the sharp decrease in coupling coefficient, and thus charging efficiency. In 2007, MIT proposed Witricity which is able to light up a 60 W light bulb with 40 % efficiency at a 2 meter of transmission distance [11]. At 1 meter of transmittance distance, the power efficiency is achieved at 90 %. However, the limitation of this set up



is that experimental work is too bulky as the magnetic resonant coupling require a capacitive coil to operate. This means that a proper tuned impedance is required to achieve a high efficiency wireless power transfer [12]. There are two methods in mid-range WPT namely the 2-coils resonance coupled WPT and 4-coils resonance coupled WPT [13-14]. The later method is preferable as it performs impedance matching and hence achieve a higher power transmission efficiency.

WPT technology grows vigorously in the past few years. As the research field in WPT is expanding, such technology would eliminate the usage of high transmission lines and cables, charging wires and cables. This is prudent to sustain a more environmental friendly mother nature. The main challenge in mid-range WPT is to achieve a high power transmission efficiency at an ideal distance between the transmitter and receiver coil. Hence, this paper presents the preliminary simulation result on 4-coils magnetic resonance coupling WPT. The finding presented could be made practical for wireless charging for electronic devices in the near future.

Section 2 discusses about the principle and numerical formula for magnetic coupled resonator applicable in the mid-range wireless power transfer. Functionality of 4-coils magnetic coupled resonator WPT circuitry is discussed. Section 3 presents the simulation result of 4-coils magnetic resonance using CST microwave studio. Magnetic resonance coupling is achieved at 14.175 GHz, electric and magnetic field as well as surface current distribution are presented and discussed.

2. Magnetic Resonance Formulation for Mid-range Wireless Power Transfer

Figure 1 shows the equivalent circuit of 4-coils magnetic coupled resonator WPT system which is made up of the source coil, transmitter (Tx) coil, receiver (Rx) coil and the load coil. The 4 coils comprise of circuit elements such as inductors (L), resistors (R) and capacitors (C). k_{12} , k_{23} and k_{34} are the coupling coefficient which is fundamental to connect the resonant circuit. The coupling effect will affect the amount of energy transferred. High coupling is desired to achieve a high rate of energy transfer [15].

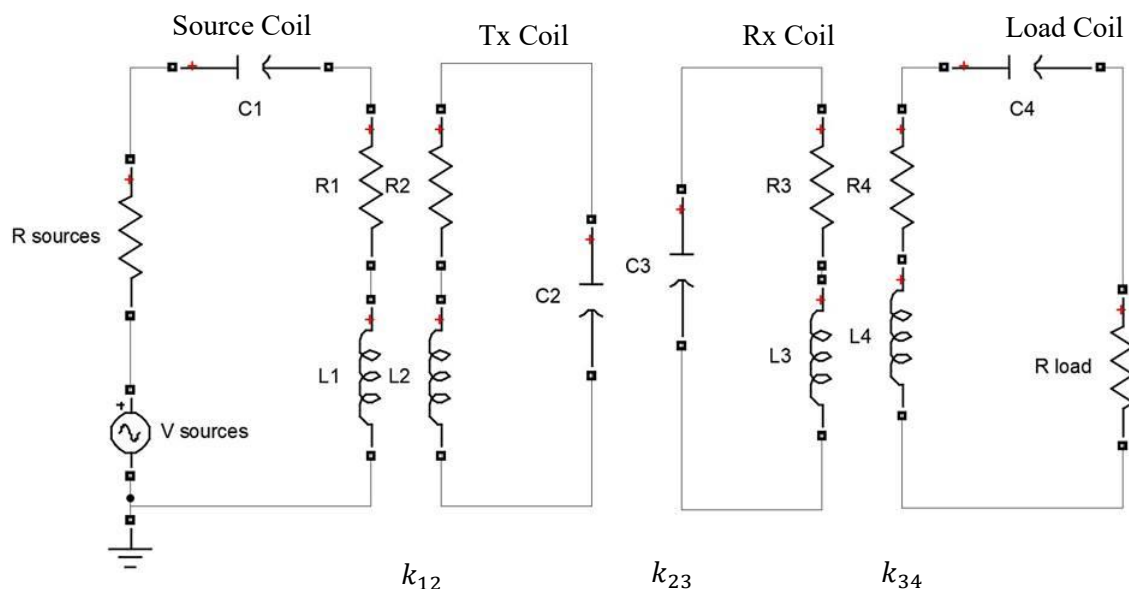


Figure 1. Equivalent circuit of 4-coils magnetic coupled resonator WPT

The current flow in figure 1 can be expressed using the matrix below [16]:

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

where $Z_{11}, Z_{22}, Z_{33}, Z_{44}$ are the impedance value at source coil, transmitter coil, receiver coil, and load coil, respectively:

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

To calculate the flow of current in both the source and load loop, equation (1) has to be solved with the impedance parameters. To simplify, current at the source loop and load loop are expressed as equation 3 and 4:

$$I_1 = \frac{Z_{22}Z_{33}Z_{44} + (\omega M_{23})^2 Z_{44} + (\omega M_{34})^2 Z_{22}}{Z_{11}Z_{22}Z_{33}Z_{44} + (\omega M_{23})^2 Z_{11}Z_{44} + (\omega M_{34})^2 Z_{11}Z_{22} + (\omega M_{12})^2 (\omega M_{34})^2} V_S \quad (3)$$

$$I_4 = \frac{j(\omega M_{12})(\omega M_{23})(\omega M_{34})}{Z_{11}Z_{22}Z_{33}Z_{44} + (\omega M_{23})^2 Z_{11}Z_{44} + (\omega M_{34})^2 Z_{11}Z_{22} + (\omega M_{12})^2 (\omega M_{34})^2} V_S \quad (4)$$

In such case, voltage transfer is presented as:

$$|S_{12}| \cong \frac{2 k_{12} k_{23} k_{34} Q_2 Q_3 \sqrt{Q_1 Q_4}}{(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + 1 + k_{23}^2 Q_2 Q_3} \quad (5)$$

The efficiency of transmittance rate which is expressed as ratio of output power versus output power:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{I_4^2 R_L}{I_1^2 \left(\frac{R_S}{4}\right)} = |S_{12}|^2 \quad (6)$$

The efficiency of transmittance rate explains the amount of energy transferred from the transmitter to the receiver. Maximum $|S_{12}|$ is achieved when reasonable amount of k_{23}^* is substituted, where k_{23}^* is the maximum range achievable by the transmitter to transfer power efficiently to transfer power towards receiver. Hence, $|S_{12}|_{\max}$ is expressed as:

$$|S_{12}|_{\max} = \frac{k_{12} k_{34} Q_1 Q_4 R_L}{k_{23}^* \sqrt{L_1 \omega_1 L_4 \omega_4}} \quad (7)$$

Equation 7 shows that a lower k_{23}^* value is desired to achieve a high $|S_{12}|_{\max}$.

3. Results and Discussion

Simulation work on 4-coils mid-range magnetic resonance WPT has been performed using CST microwave studio. Figure 2 shows the 4-coils alignment in CST microwave studio, both the source coil and load coil are single turn with 3 cm radius, whereas the transmitter coil and receiver coil are pre-assigned at ten turns with 5 cm radius. A discrete port is inserted at both the source coil and receiver coil to transmit and receive electric and magnetic field. The distance between the transmitter coil and receiver coil is set at 2 cm, while the transmitter coil and receiver coil are set 1 cm apart from the source and load coil. The scattering parameters (S-parameters) is shown in figure 3. Simulation result shows the magnetic resonance occur at 14.17 MHz, and the S-parameter transferred from source to coil is 0.72371. Resonance magnetic coupling is achieved when energy is being transmitted from

the transmitter coil to receiver coil at the same frequency. This will generate an oscillating current in the coil system. The energy will deplete with respect to time in a high resonant coil. Therefore, an optimum energy is transferred from the transmitter coil to the receiver coil.

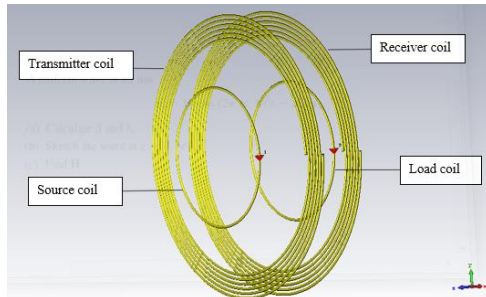


Figure 2. 4-coils design using CST

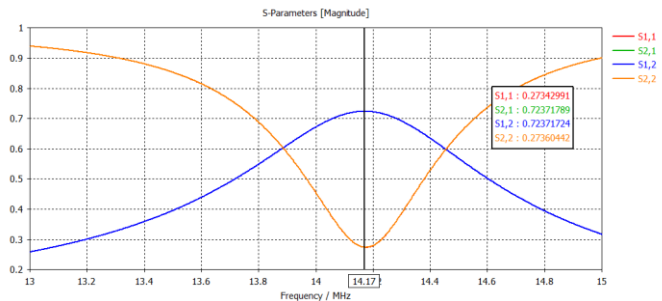


Figure 3. S-parameters

Figure 4 and 5 show the electric field (E) distribution at the resonance frequency ($f = 14.17$ MHz) and the change in electric field strength at each coil. It is observed that the E-field strength is recorded at 2424.50 V/m at the source coil and 2140 V/m at the load coil. This shows that an optimum electric field transmission is achieved with minimal information loss to surrounding.

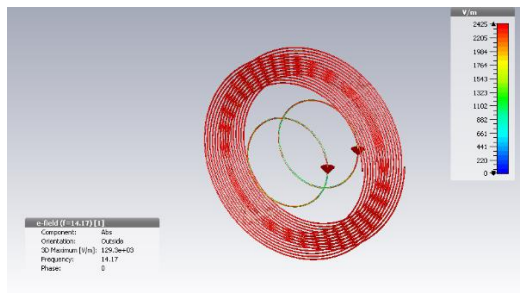


Figure 4. E-field distribution

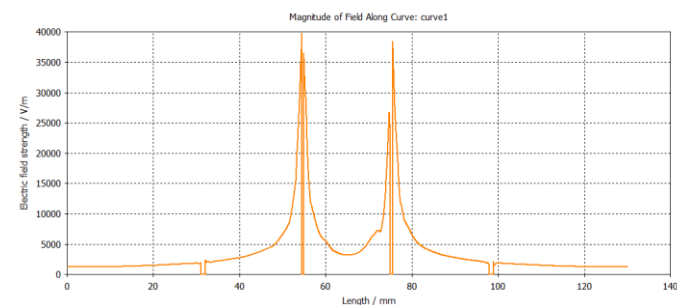


Figure 5. E-field strength versus distance

Figure 6 and 7 show the electric field (H) distribution at the resonance frequency ($f = 14.17$ MHz) and the change in magnetic field strength at all the four coils. The optimum current and voltage transmission will hence make this magnetic resonance coupling method a promising method for wireless power transfer to charge electronic device. The magnetic field at the source coil and load coil are record at 54.35 A/m and 38.71 A/m, respectively.

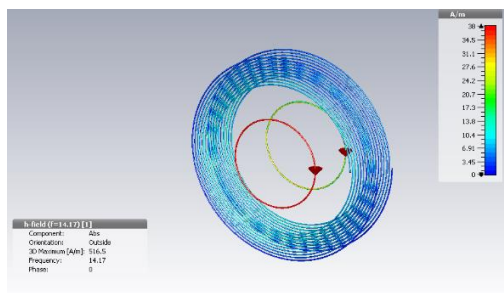


Figure 6. H-field distribution

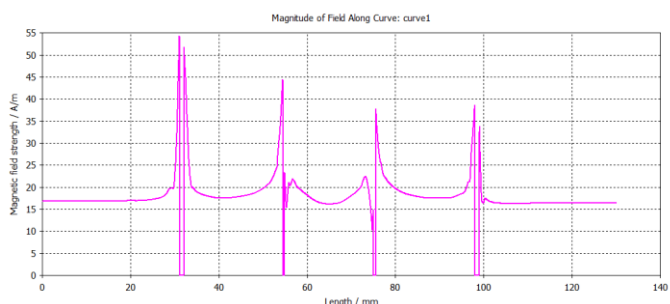


Figure 7. H-field strength versus distance

Figure 8 plots the surface current distribution versus distance. Assuming an ideal wireless transmission with no loss of signal, a surface current of 52.21 A is recorded at the load coil. Figure 9 shows the impedance value, Z at resonance frequency. It is crucial to adapt the ideal impedance parameter in order to identify the suitable inductance (L), capacitance (C) and resistance (R) values in the 4-coils system.

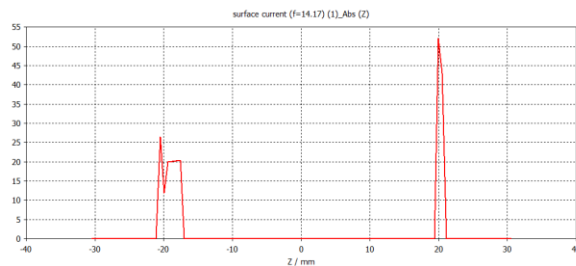


Figure 8. Surface current

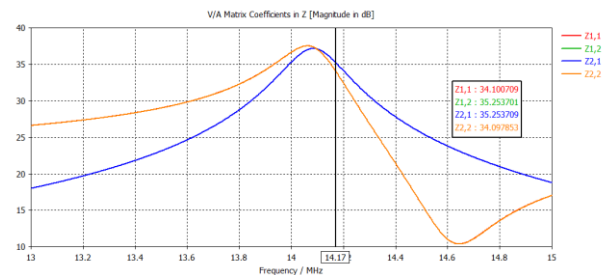


Figure 9. Z-parameters

4. Conclusion and Future Recommendation

This research work is undertaken to perform critical review and analysis on mid-range wireless power transfer. Preliminary simulation result for magnetic resonance coupling wireless power transfer using CST microwave studio is presented and discussed in this research paper. The electric and magnetic field transmission were successfully simulated. Result shows that at 14.17 MHz, magnetic resonance is achieved and the load coil is receiving both electric field and magnetic field from the source coil. Mid

-range wireless power transfer using magnetic resonance coupling would be the new key technology for researchers to investigate and employ into in the next decade. An achievable optimize distance for mid-range wireless transfer with a smaller coils size is yet to be proposed, it would be much convenient if a high efficiency charging process to occur over a distance which is applicable for electronic device such as mobile phone, electronic tabs and laptops. An ideal wireless charging would be an optimum power transmission from single transmitter to multiple receivers at a desired power transmission efficiency.

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