DESIGN OF WIRELESS POWER TRANSFER SYSTEM WITH TRIPLET COIL CONFIGURATION BASED ON MAGNETIC RESONANCE

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Abstract: *Wireless power transfer (WPT) system based on magnetic resonance is presented here. The aim is to transfer energy wirelessly from transmitter coil to receiver coil based on magnetic resonance. A novel system with a two-coil transmitter connected to a single power source is proposed here in a triplet configuration with a single receiving coil. The two-coil transmitter is introduced as an extension to the converge area. The equivalent lumped element circuit model is presented and mathematical equations for scattering parameters have been derived. The proposed configuration is simulated using both circuit (ADS) and electromagnetic (EMPRO) simulators. The effect of the coupling between coils is investigated using simulation. The proposed configuration is practically implemented using solenoid coils and tested to verify the simulation results. The effect of receiver displacement on efficiency is also investigated.*
Keywords: *Magnetic resonance, Triplet configuration, Two-coil transmitter, Wireless Power Transfer.*

1. Introduction

In the recent years, an extensive research has been done on wireless power transfer, particularly between two coils across an air gap via magnetic coupling. Wireless power transfer can be used in many applications such as battery charging for portable electronic devices [1], electric vehicles [2,3], robots [4,5] and implantable medical devices [6,7]. In [8], researchers in Massachusetts Institute of Technology presented wireless energy transmission via strong magnetic resonant coupling with experimental demonstration. The transfer efficiency rapidly decreases as the transmission distance increases. Hence, several researches reported in literature are focused on increasing transfer distance as well as efficiency. To increase the transmission distance, extra coils called repeaters may be added between the transmitter and receiver as reported in [9]-[11]. Furthermore, the transfer efficiency is affected by the orientation and displacement of the receiving coil. In [12], the study demonstrates the efficiency dependence on receiver orientation and deviation.

Some applications need powering various devices at the same time and studies on multi-receiver wireless power transfer systems have been reported [13,14]. Other applications require multiple transmitters to cover larger area available for wireless power transfer, but most of the research reported in literature considered only a single transmitting coil. In [15], a parallel line feeder is proposed as the transmitter in wireless power transfer system to extend the coverage area. However, the efficiency of such system still needs further study for enhancement. In [16], a multiple-input multiple-output wireless power transfer systems is proposed whereby multiple separated transmission sources are used. However, this system still needs multiple voltage sources. Here we propose a wireless power transfer system using two-transmitting coils connected to a single voltage source so that the power of the single source is divided and delivered to both transmitting coils as depicted in Figure 1 (b). In such configuration, the coverage area is extended in comparison to conventional configuration in Figure 1 (a). Mathematical equations have been derived for the proposed system and circuit simulation has been performed based on the equivalent lumped element model. Moreover, Electromagnetic professional program EMPRO [17] has been utilized to model the proposed configurations. The proposed system is practically implemented and tested to verify the simulation results.

2. Equivalent Lumped Element Model

The lumped element equivalent circuits for the single-coil transmitter and two-coil transmitter systems are shown in Figure 2 (a) and Figure 2 (b), respectively. The AC voltage source has internal resistance R_s and the driving loop is represented by internal resistance R_1 and self

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inductance L_1. Similarly, the load loop is represented by internal resistance and self inductance connected to a load $Z_L=R_L$.

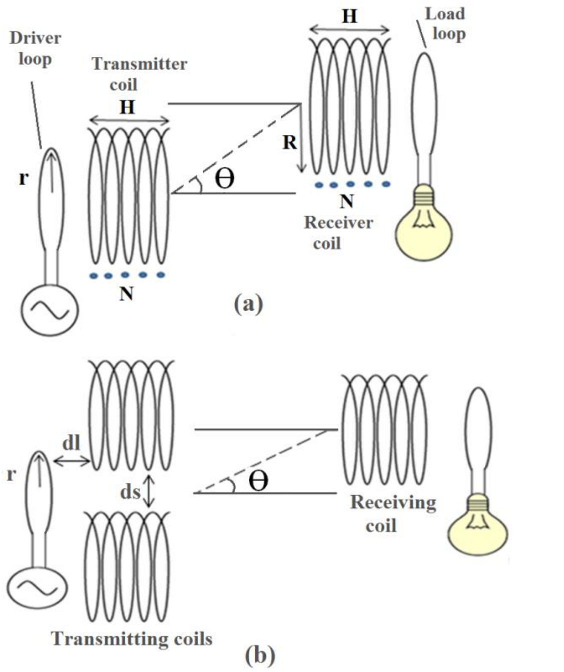

Figure 1. Wireless power transfer system (a) Single-coil transmitter configuration, (b) Proposed two-coil transmitter configuration

The equivalent model of a transmitting or receiving coil is a series *RLC* resonating circuit with an internal resistance *R*, self inductance *L* and capacitance *C*. The mutual coupling between coils is represented in the model by inductive coupling coefficient $K_{i,j}$ between coil *i* and coil *j* and it is calculated by:

$$K_{i,j}=M_{i,j}\Big/\sqrt{L_i L_j} \tag{1}$$

where $M_{i,j}$ is the mutual inductance between coils *i* and *j* and L_i and L_j are self-inductances of coils *i* and *j* respectively. The self-inductance of coil *i* is calculated by [9],

$$L_i=4\pi\times10^{-7}\times n_i^2\times r_i\left[ln\left(\frac{8r_i}{a_i}\right)-2\right] \tag{2}$$

where n_i and r_i are the number of turns and radius of coil *i* respectively, and a_i is the radius of copper wire for coil *i*. The mutual inductance $M_{i,j}$ between coils *i* and *j* is calculated by [12],

$$M_{i,j}=\frac{\pi\times\left(4\pi\times10^{-7}\right)\times\sqrt{n_i n_j}\times r_i r_j}{2D^3} \tag{3}$$

where n_i and n_j are number of turns of coils *i* and *j*, r_i and r_j are the radii of coils *i* and *j* and *D* is the distance between the two coils.

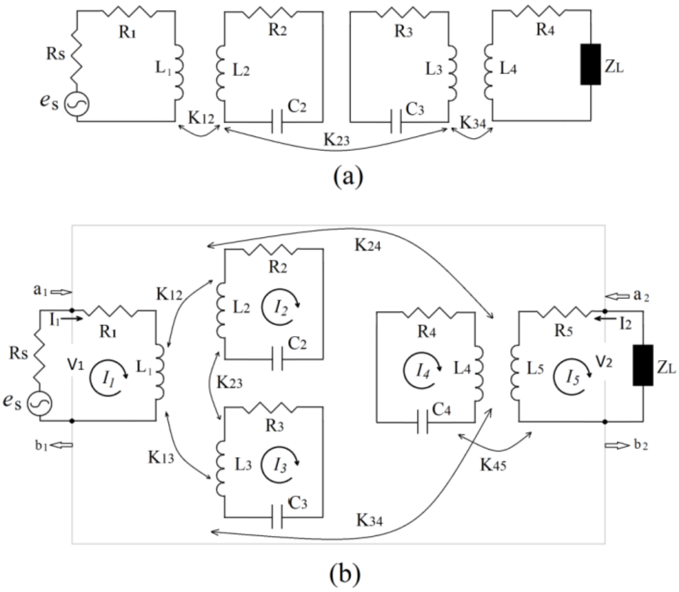

Figure 2. Equivalent circuit models for configurations in Figure 1 (a) Model for system in Figure 1 (a), (b) Model for system in Figure 1 (b).

The operating angular frequency for the single-coil transmitter in Figure 2 (a) is $\omega_o=1/(L_2C_2)^{0.5}=1/(L_3C_3)^{0.5}$ and for the two-coil transmitter in Figure 2 (b) is $\omega_o=1/(L_2C_2)^{0.5}=1/(L_3C_3)^{0.5}=1/(L_4C_4)^{0.5}$. The mathematical equations for the conventional model in Figure 2 (a) are reported in literature and the mathematical description of the proposed model in Figure 2 (b) can be written in matrix form as $[Z][i]=[e]$ where

$$[i]=\begin{bmatrix} i_1\\ i_2\\ i_3\\ i_4\\ i_5\end{bmatrix}\quad ,\ and\quad [e]=\begin{bmatrix} e_s\\ 0\\ 0\\ 0\\ 0\end{bmatrix} \tag{4}$$

$$[Z]=\begin{bmatrix} Z_{11} & j\omega M_{12} & j\omega M_{13} & 0 & 0\\ j\omega M_{21} & Z_{22} & j\omega M_{23} & j\omega M_{24} & 0\\ j\omega M_{31} & j\omega M_{32} & Z_{33} & j\omega M_{34} & 0\\ 0 & j\omega M_{42} & j\omega M_{43} & Z_{44} & j\omega M_{45}\\ 0 & 0 & 0 & j\omega M_{54} & Z_{55}\end{bmatrix} \tag{5}$$

where $[Z]$ is the impedance matrix and

$$\begin{aligned} Z_{11}&=R_1+R_s+j\omega L_1\\ Z_{22}&=R_2+j\omega L_2+\left(1/j\omega C_2\right)\\ Z_{33}&=R_3+j\omega L_3+\left(1/j\omega C_3\right)\\ Z_{44}&=R_4+j\omega L_4+\left(1/j\omega C_4\right)\\ Z_{55}&=R_5+j\omega L_5+R_L \end{aligned} \tag{6}$$

The $[Z]$ matrix can be written in term of coupling coefficients K_{ij} using (1) by replacing $j\omega M_{ij}$ by

$\omega K_{ij}\sqrt{L_i L_j}$. The scattering parameters of the circuit are found as,

$$S_{11}=\left.\frac{b_1}{a_1}\right|_{a_2=0} \quad , \quad S_{21}=\left.\frac{b_2}{a_1}\right|_{a_2=0} \tag{7}$$

where b_1, b_2 represent waves reflected from ports 1 and 2, respectively, and a_1, a_2 represent waves incident on ports 1 and 2 respectively, and they can be found by:

$$\begin{aligned} a_N &= \frac{1}{2}\left(\frac{V_N}{\sqrt{R}}+\sqrt{R}I_N\right) \\ b_N &= \frac{1}{2}\left(\frac{V_N}{\sqrt{R}}-\sqrt{R}I_N\right) \end{aligned} \tag{8}$$

where V_N and I_N represent the voltage and current at port N and they are found from the equivalent circuit in Figure 2 (*b*) as $V_1=e_s$ - I_1R_S and $V_2=-I_2R_L=$ I_5R_L. By substitution of V_1, V_2, I_1 and I_2 into (8) the wave equations are now found in terms of circuit parameters as follows:

$$a_1=\frac{e_S}{2\sqrt{R_s}}, \quad b_1=\frac{e_S-2I_1R_s}{2\sqrt{R_s}}, \quad b_2=I_5\sqrt{R_L} \tag{9}$$

The scattering parameters of the circuit are now found in terms of circuit parameters by substitution of (9) into (7) as follows:

$$S_{11}=1-\frac{2I_1R_s}{e_s} \quad and \quad S_{21}=\frac{2\sqrt{R_sR_L}\,I_5}{e_s} \tag{10}$$

Solving $[Z][i]=[e]$ for currents I_1 and I_5 we obtain,

$$I_1=[Z]_{11}^{-1}e_s \quad and \quad I_5=[Z]_{51}^{-1}e_s \tag{11}$$

and by substitution of (11) into (10), the scattering parameters are now found in terms of impedance matrix as follows,

$$S_{11}=1-2R_s[Z]_{11}^{-1} \quad , \quad S_{21}=2\sqrt{R_sR_L}\,[Z]_{51}^{-1} \tag{12}$$

3. Two-coil transmitter system simulation

The configuration of single transmitting coil is extensively studied and presented in literature. To extend the coverage area, the two-coil transmitter configuration in Figure 1 (b) is investigated here. Here we use a single driving loop connected to a single AC voltage source. The power is delivered from the driving loop and is divided to both the transmitting coils. The two-coil transmitter configuration is simulated firstly using ADS circuit simulator and then using EMPRO electromagnetic simulator.

3.1. Circuit Simulation

The system equivalent lumped-element circuit simulated using ADS is depicted in Figure 3 whereby coupling is represented by coupling coefficient *K*. The internal resistance of any coil is assumed 0.5 Ω and the transmitting and receiving coils have capacitance C=5 pF and inductance L=75 μH which give resonant frequency of 8.21873 MHz. The single-turn driving and receiving loops have an inductance of 1.7387 μH and R_s=R_L=50 Ω. The effect of the couplings between coils on power transfer efficiency is investigated by observing the scattering parameters S_{21} and S_{11}. The efficiency (η) is calculated directly by $\eta=|S_{21}|^2$ x 100%.

The coupling between the transmitting coils K_{23} is firstly investigated to study the effect on efficiency. Other coupling coefficients are kept constant with K_{12}=K_{13}=K_{45}=0.2, and K_{24}=K_{34}=0.04. The coupling K_{23} is changed from 0.07 to 0.28 and the S_{21} magnitude response is observed as depicted in Figure 4. It can be noticed that the transmission efficiency degrades as coupling between the transmitting coils is increased.

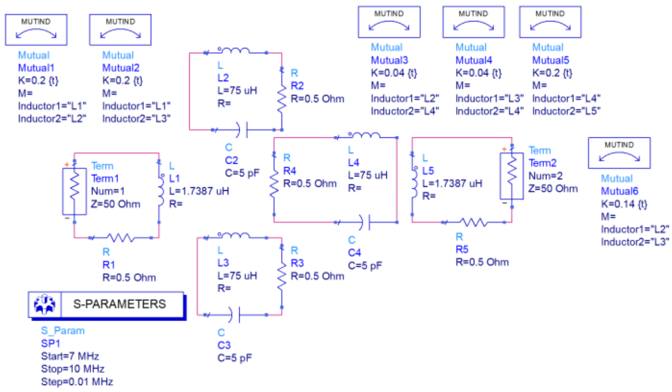

Figure 3. Two-coil transmitter ADS circuit.

Furthermore, the coupling between the transmitting coils and the receiving coil (K_{24} and K_{34}) is also investigated by varying the coupling K_{24} and K_{34} from 0.01 to 0.05 while keeping other coupling coefficients fixed as K_{12}=K_{13}=K_{45}=0.2 and K_{23}=0.14. The S_{21} magnitude response is shown in Figure 5 and it can be noticed that as the coupling decreases the efficiency decreases.

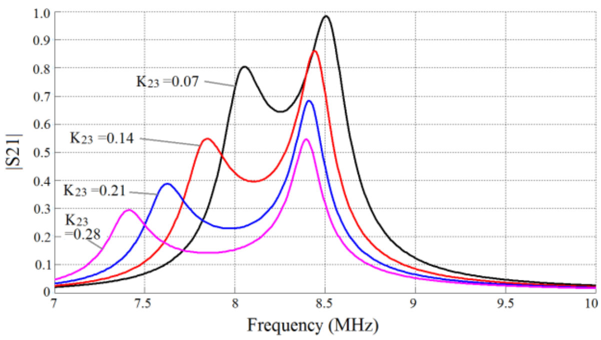

Figure 4. S_{21} magnitude response for various values of coupling K_{23} using ADS.

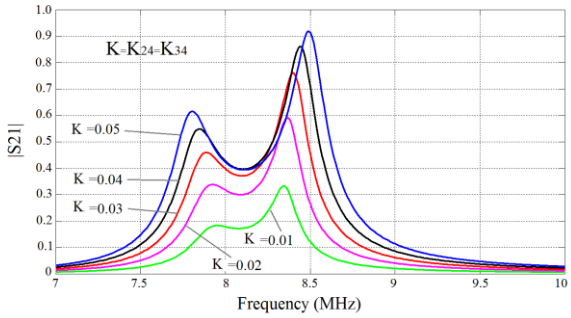

Figure 5. S_{21} magnitude response for various values of coupling K_{24}= K_{34}.

3.2. Electromagnetic Simulation

The two-coil transmitter configuration is simulated using electromagnetic simulator EMPRO to model the physical structure of the proposed configuration in Figure 1 (b). The transmitting and receiving coils are identical solenoid coils with height (*H*), radius (*R*), and number of turns (*N*). The transmission coils and the receiving coil are separated by a distance of 1 meter. The system parameters of the coils are set with fixed values: *H*=16 Cm, *N*= 5.5 and *R*=35 Cm. Other parameters such as the distance between two transmitters (*ds*), the distance between the transmitters and the driving loop (*dl*), and the radius of the driving loop (*r*) are set as variables. A parametric study has been carried out on these parameters and best efficiency of 66.49% is obtained at *r*=290 mm, *dl*=65 mm and *ds*= 30 mm. The simulated scattering parameters are shown in Figure 6 and the best transfer efficiency is obtained at frequency 8.4072 MHz. The structure of the two-coil transmitter system along with the magnetic field distribution is shown in Figure 7. The axis of the receiving coil lies in the middle of separation distance between the two transmitting coils.

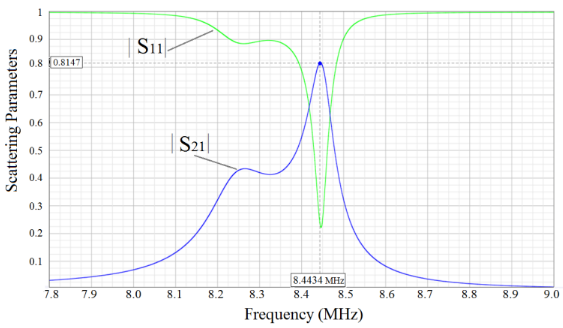

Figure 6. Simulated S-parameters for two-coil transmitter configuration**.**

4. Simulation of receiver displacement

The angle θ representing the displacement between the transmitter and receiver coils is also investigated to see its effect on the efficiency by using EMPRO. Table 1 shows the efficiency versus θ for the proposed configuration. It is noticed that the highest efficiency is obtained when (θ=0) that is when the axis of the receiving coil lies in the middle of separation distance between the two transmitting coils. Moreover, it is clear that when the angle θ is increased by displacing the receiving coil away from concentric axis the efficiency decreases. As we increase the angle θ from 0º to 35º, the efficiency for two-coil transmitter system drops from 66.49% to 40.37%.

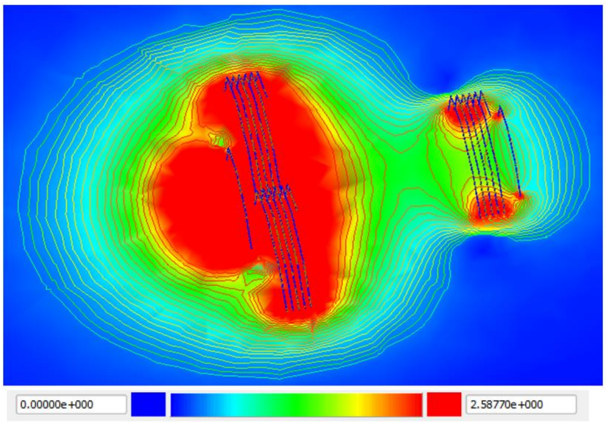

Figure 7. Magnetic field plots for two-coil transmitter configuration

Table 1. Efficiency versus receiver displacement

Angle (θº)	Efficiency (η) for two coil transmitter
0	66.49%
5	63.99%
10	61.45%
15	58.03%
20	57.65%
25	53.75%
30	44.35%
35	40.37%

5. Experimental results

To verify the simulation results, the proposed two-coil transmitter configuration has been implemented practically. The coils are made of copper wires of the same length and wire diameter of 2.75 mm and they are wounded around wooden cylinders to from solenoid coils. The parameters of the coils are those obtained from simulation results and they are *N*=5.5, *H*=160 mm and *R*=350 mm. A signal generator with frequency up to 10 MHz is used as the source for the transmitter and a digital oscilloscope has been utilized to show the received signal.

The two-coil transmitter experimental model is shown in Figure 8. The distance between the transmitting and receiving coils is 1 meter and the parameters of the system are *ds*= 30 mm, *dl*= 65 mm, and *r*= 290 mm. A sinewave of voltage amplitude 10 V is set at the generator and its frequency is tuned until maxim power transfer is obtained at resonant frequency of 9.3 MHz. The voltage at the receiving coil terminals was measured and the efficiency was then calculated and found about 61.01%.

The efficiency (η) has been experimentally found for different receiver displacement angles (θ) and the results are shown in Table 2. It can be noticed that the simulation results in Table 1 are slightly different from the experimental results due to imperfection in fabrication of coils that resulted in some changes in the dimensions in the structure. Moreover, the ohmic losses of the conducting coils contributed in efficiency degradation.

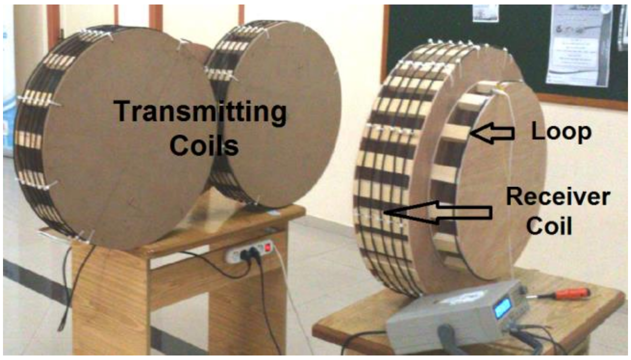

Figure 8. Experimental model for two-coil transmitter configuration

It is noticed that the highest simulated efficiency is 66.49% while the experimental efficiency is 61.01% that is about 5% lower than the simulated. The experimental results show a drop of efficiency of 30% when the angle θ is increased from 0° to 35°.

Table 2. Experimental results of efficiency versus receiver dispalcement

Angle (θ°)	Two-Coil Transmitter Experimental (η)
0	61.01%
5	57.32%
10	48.10%
15	44.23%
20	40.61%
25	38.25%
30	32.56%
35	30.90%

6. Conclusions

In this paper, a two-coil transmitter single-coil receiver wireless power transfer system is presented. The system is proposed as an extension for the coverage area in comparison to conventional single-transmitter configurations. Mathematical model has been derived and both circuit and electromagnetic simulations have been done to show the scattering parameters and transfer efficiency. Receiver displacement has also been investigated and experimental solenoid coil models have been implemented.

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