# Research on Wireless Power Transmission System for Coal Mine Wireless Sensor Networks

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Abstract
In order to solve the problems of the underground wireless sensor network sensor nodes' power timely supply, circuit model of wireless energy transfer system via magnetic resonance coupling is established. The calculation model for the transmission power and its efficiency of the wireless energy transfer system was given by using mutual inductance coupling theory. Orcad simulation software was used to get the maximum received power, and further analyzed the relationship between the coupling coefficient, input frequency, the load and the received power. When the coupling coefficient is different, the system will appear different degrees of frequency splitting phenomenon, and received power obtained the maximum at inherent resonance frequency. To test and verify the correctness of theory and simulation analysis, established relevant experiment system. When the input frequency is near the inherent resonance frequency, get the best transmission distance and the best matching load. The best input frequency will increase with distance away from the inherent resonance frequency.

Keywords: COAL MINE, WIRELESS POWER TRANSMISSION, RESONANCE COUPLING, MAXIMUM POWER, THE BEST TRANSMISSION DISTANCE

## 1. Introduction

Wireless sensor network (WSN) technology greatly improved the level of coal mines safety production in the application of coal mine safety monitoring system, especially plays an irreplaceable role in post-disaster rescue [1-4]. Due to the small sensor nodes' battery capacity, it can't satisfy the demand of the coal mine in a long time. Changing the nodes increases the cost of manpower[5]. In order to ensure the wireless sensor network can effective work, we charge the sensor nodes in time by wireless power transmission, which has important significance for ensuring smooth wireless network.

At present, there are four types of wireless power transmission: induction type, electromagnetic radiation type, electric field coupling and magnetic resonance coupling[6]. The distance of Induction and electric field coupling charging is only a few millimeter. However, electromagnetic radiation uses electromagnetic wave to transmit the power, which will be influenced by multipath effect and is not ideal. Compared with other power transmission technology, magnetic resonance coupling technology can transmit larger power in long distance[7]. Many domestic literature have studied on wireless power transmission via magnetic resonance coupling. By the literature [8], increasing the transmit coil and receive coil radius and the wire diameter can improve the received power and transmission distance. However, that will be limited by the conditions of practical application. In addition, different system structure will affect receiving power and transmission distance [9]. For two coils structure, since the power supply and load directly connect to transmit coil and receive coil, Q value is very small. In order to increase the received power and transmission distance, wireless energy transmission system with four resonant coils based on magnetic resonance coupling is established. Receive power and efficiency calculation model are given. The factors influencing the received power and efficiency are studied. The simulation software and experimental analysis are used to prove the validity of the theory.

## 2. System Modeling and Theoretical Analysis

### 2.1. System Topology

To improve the Q value of the coil, the four coils structure was used to energy transfer. Figure 1 is four coils structure block diagram of power transmission system. Four coils are excitation coil, transmission coil, receiving coil and load coil respectively. Their inherent resonance frequencies are the same. When the frequency of power supply is the same as the four coils inherent resonance frequencies, power transports through magnetic resonance coupling from the excitation coil to the load coil.

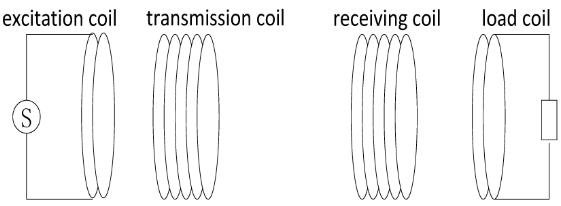


**Figure 1.** Schematic diagram of system

### 2.2. Equivalent Circuit of Wireless Power Transmission

The wireless power transmission system in Figure 1 can be abstracted as shown in Figure 2.

In Figure 2, Us is input voltage; L1, L2, L3, L4 are the equivalent inductances of the excitation coil, transmission coil receiving coil and load coils respectively. C1, C2, C3, C4 are the equivalent capacitances of the four coils. Rs is equivalent resistance of the power, RL is the load of the load coil. Transmission coil's ohmic resistance is R2, and receiving coil's ohmic resistance is R3. The ohmic resistance of excitation coil and load coil is far less than RS and RL, we can ignore them. The best transmission frequency is between 1 MHz and 50MHz. The radiation resistance is far less than ohmic resistance, and therefore we can ignore the effects of radiation resistance [10].

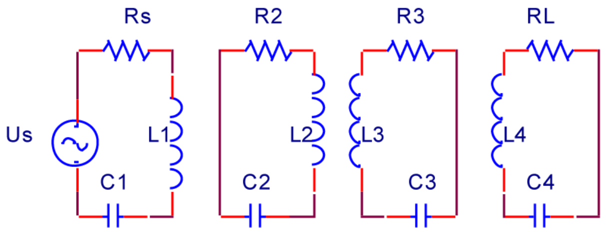


**Figure 2.** Equivalent circuit of wireless power transmission

### 2.3. Receive power and efficiency

Cross coupling between coils will be ignored, only the direct coupling between adjacent coils are considered. Mutual inductance between the excitation coil and the transmission coil is $M_{12}$; Mutual inductance between the transmission coil and receiving coil is $M_{23}$; Mutual inductance between the receiving coil and load coil is $M_{34}$.

The resistances of the four coils are $Z_1$, $Z_2$, $Z_3$, $Z_4$, the current in the four coils are $I_1$, $I_2$, $I_3$, $I_4$ respectively. KVL equation can get (1):

$$\begin{bmatrix} U_S \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega M_{12} & 0 & 0 \\ j\omega M_{21} & Z_2 & j\omega M_{23} & 0 \\ 0 & j\omega M_{32} & Z_3 & j\omega M_{34} \\ 0 & 0 & j\omega M_{43} & Z_4 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (1)$$

Four loops will present pure resistance characteristics, when the system is in resonance state. We can get (2) from (1):

$$\begin{bmatrix} U_S \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_S & j\omega M_{12} & 0 & 0 \\ j\omega M_{21} & R_2 & j\omega M_{23} & 0 \\ 0 & j\omega M_{32} & R_3 & j\omega M_{34} \\ 0 & 0 & j\omega M_{43} & R_L \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \quad (2)$$

So, $I_1$ and $I_4$ can be getting according to (2).

$$I_1 = \frac{U_S\left(R_2R_3R_L + \omega^2 M_{23}^2 R_L + \omega^2 M_{34}^2 R_2\right)}{(R_S R_2 + \omega^2 M_{12}^2)(R_3 R_L + \omega^2 M_{34}^2) + \omega^2 M_{23}^2 R_S R_L} \quad (3)$$

$$I_4 = \frac{U_S \omega^3 M_{12} M_{23} M_{34}}{(R_S R_2 + \omega^2 M_{12}^2)(R_3 R_L + \omega^2 M_{34}^2) + \omega^2 M_{23}^2 R_S R_L} \quad (4)$$

Then receive power and efficiency are :

$$P_L = I_4^2 R_L \quad (5)$$

$$\eta_L = \frac{I_4^2 R_L}{U_S I_1} \tag{6}$$

## 3. Simulation and Analysis

In conclusion, received power and efficiency are affected by many factors. Not only coil inductance, capacitance, resistance, number of turns, radius and so on, but also the system input frequency, the load, the mutual inductance between the coil will affect received power and efficiency.

Orcad software simulation is used to analyse the relationship between receive power, efficiency and input frequency, the load, the mutual inductance between the coils. Simulation circuit diagram is shown in figure 2. Inherent resonance frequency ($f_0$) is1.7MHz. Input voltage is 7V.

The relationship between receive power, efficiency and distance , input frequency

Mutual inductance is connected with the distance. The distances that effect receives power and efficiency are: the distance between excitation coil and transmission coil ($d_{12}$), the distance between transmission coil and receiving coil ($d_{23}$), and the distance between receiving coil and load coil (d34). $k_{ij} = M_{ij} / \sqrt{L_i L_j}$ . (i,j=1,2,3,4). Therefore, we use $K_{12}$, $K_{23}$, $K_{34}$ represent $d_{12}$, $d_{23}$, $d_{34}$ respectively.

### 3.1. The relationship between receive power, efficiency and $K_{12}$ , input frequency

To study the impact of $K_{12}$ to receive power and efficiency, $K_{23}$ and $K_{34}$ are fixed, $K_{23}=K_{34}=0.2$. We pick up four typical $K_{12}$ to illustrate, they are: 0.05, 0.35, 0.65, 0.95. The relationship between receive power, efficiency and frequency are showed in Figure 3 when $K_{12}$ is different.

As is shown in Figure3, there will always be frequency division phenomenon, when $K_{12}$ is different. However, $P_L$ and $\eta_L$ will have maximum when the frequency is $f_0$. There is a $K_{12}$ that maximize $P_L$ and $\eta_L$ when the frequency is $f_0$. $\eta_L$ will maintain bigger value within1.5-2MHz, and fell sharply at others.

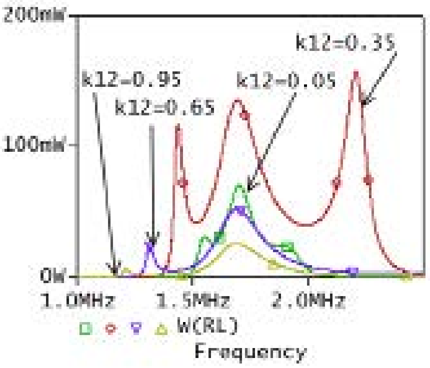
### 3.2. The relationship between receive power, efficiency and $K_{23}$ , input frequency

Figure 4 shows the relationship between $P_L$ , $\eta_L$ and f ($K_{12}=K_{34}=0.2$), when $K_{23}$ is 0.05, 0.35, 0.65, 0.95 respectively.

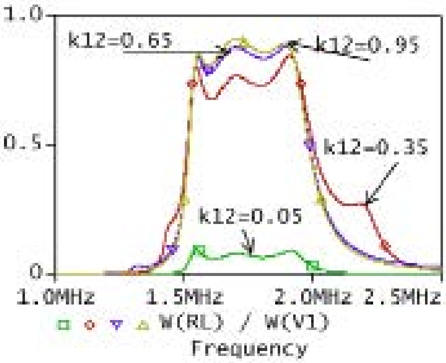
As is showed in Figure4, the optimal f isn't $f_0$, when $P_L$ and $\eta_L$ are maximum. Receive power achieve the maximum doesn't mean efficiency has maximum, when f is $f_0$.

### 3.3. The relationship between receive power, efficiency and $K_{34}$ , input frequency

Figure 5 shows the relationship between $P_L$ , $\eta_L$ and I($K_{12}=K_{23}=0.2$), when $K_{23}$ is 0.05, 0.35, 0.65, 0.95 respectively.

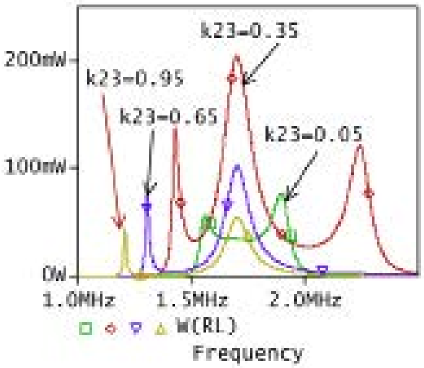


(a) The relationship between $P_L$ and f when $K_{12}$=0.05, 0.35, 0.65, 0.95 respectively

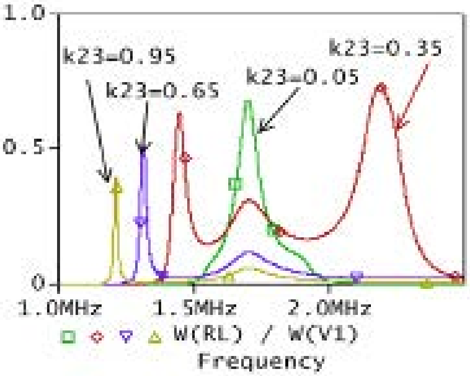


(b) The relationship between $\eta_L$ and f when $K_{12}$=0.05, 0.35, 0.65, 0.95 respectively

**Figure 3.** The relationship between $P_L$, $\eta_L$ and f, $K_{12}$ when $K_{23}=K_{34}=0.2$

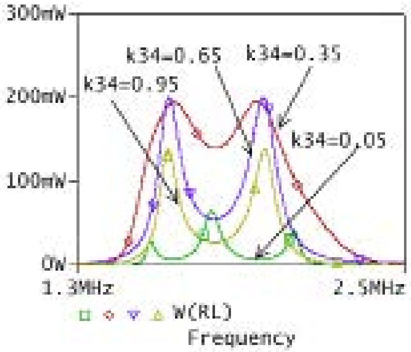


(a) The relationship between $P_L$ and f when $K_{23}$=0.05, 0.35, 0.65, 0.95 respectively

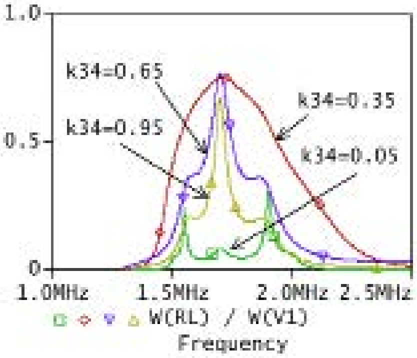


(b) The relationship between $\eta_L$and f when $K_{23}$=0.05, 0.35, 0.65, 0.95 respectively

**Figure 4.** The relationship between $P_L$, $\eta_L$ and f, $K_{23}$, when $K_{12}=K_{34}=0.2$

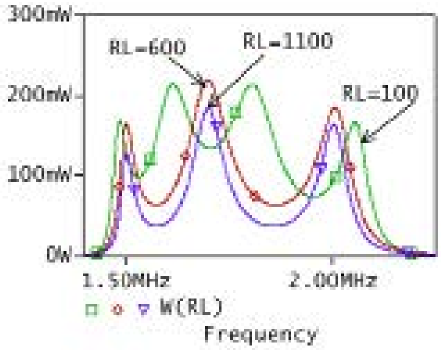


(a) The relationship between $P_L$ and f when $K_{34}$=0.05, 0.35, 0.65, 0.95 respectively

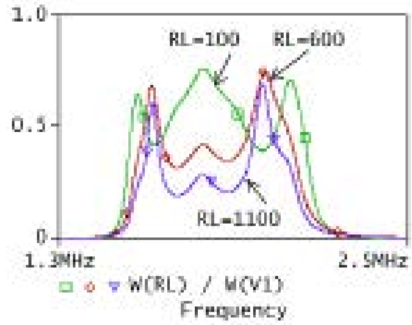


(b)The relationship between $\eta_L$ and f when $K_{34}$=0.05, 0.35, 0.65, 0.95 respectively

**Figure 5.** The relationship between $P_L$, $\eta_L$ and f, $K_{34}$ when $K_{12}$=$K_{23}$=0.2



(a) The relationship between $P_L$ and f when $R_L$=100Ω, 600Ω, 1100Ω respectively



(b) The relationship between $\eta_L$ and f when $R_L$=100Ω, 600Ω, 1100Ω respectively

**Figure 6.** The relationship between $P_L$, $\eta_L$ and f, $R_L$ when $K_{12}$=$K_{23}$=$K_{34}$=0.2

As is showed in Figure 5, receive power-frequency curve appears concave valley at the inherent frequency. The optimal frequency centered on the inherent resonance frequency to move on both sides. Compared Figure5a with 5b, $\eta_L$ is minimum when $P_L$ is maximum in inherent frequency.

### 3.4. The relationship between receive power, efficiency and load , input frequency

Figure 6 shows the relationship between $P_L$, $\eta_L$ and f ($K_{12}$=$K_{23}$=$K_{34}$=0.2), when RL is 100Ω, 600Ω, 1100Ω respectively.

$R_L$ will affect the receive power or efficiency can achieve maximum at inherent resonance frequency, when the distances are fixed. There is an optimal matching RL that maximum the $P_L$.

## 4. Experimental Results and Discussion

To study the transmission performance of the system, set up a wireless power transmission system base on magnetic resonance coupling according to Figure2. Experimental device is showed as Figure7. Four adjustable capacitances are connected to the four coils in order to make the four inherent frequencies of the four coils are the same in the experiment. Coil materials are copper enameled wire. The wire diameter is 2 mm. the turn of coils are 8 and radius is 13 cm. The experimental parameters are shown in table 1. Put voltage in a coil, measure the other coil's open circuit voltage, can get $M_{12}$, $M_{23}$, $M_{34}$. Calculate $K_{12}$, $K_{23}$, $K_{34}$ according to the formula. The following input frequency is inherent resonance frequency $f_0$ = 1.7 MHz.

**Table 1.** Parameters of wireless power transmission system

| Coil name | Inductance uH | Capacitance pF | resistance Ω |
|---|---|---|---|
| Excitation coil | 66.8 | 131.3 | 50 |
| Transmission coil | 61.8 | 141.8 | 5 |
| Receiving coil | 73 | 120 | 4 |
| Load coil | 77.8 | 112 | 330 |

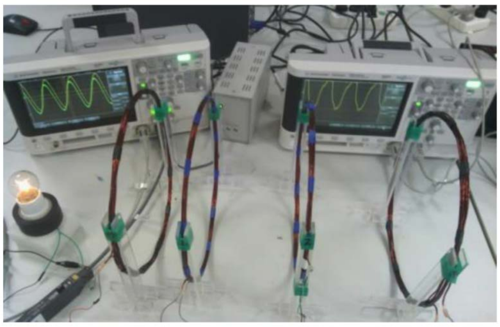
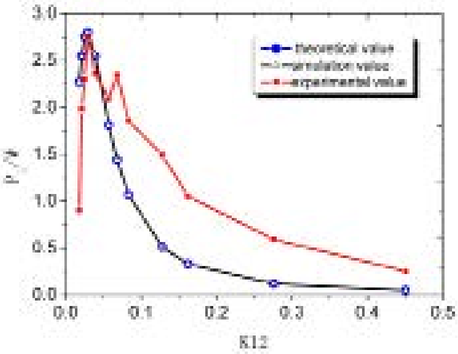


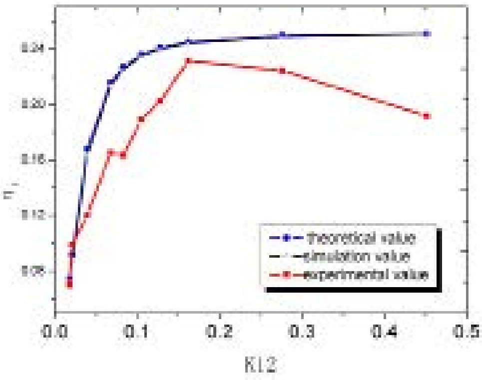
**Figure 7.** Wireless power transmission system experimental platform

### 4.1. The relationship between $P_L$, $\eta_L$ and $K_{12}$

Make $d_{23}$=17cm, $d_{34}$=9cm, $d_{12}$ changes from 2cm to 40cm. Receive power and output power can be measured by measuring the load coil's voltage and excitation coil's current and voltage respectively. Figure8 is the comparison between theoretical value, mulation value and experimental value of the system power and efficiency with the variation of $K_{12}$.



(a) The comparison between theoretical value, simulation value and experimental value of the systems power with the variation of $K_{12}$



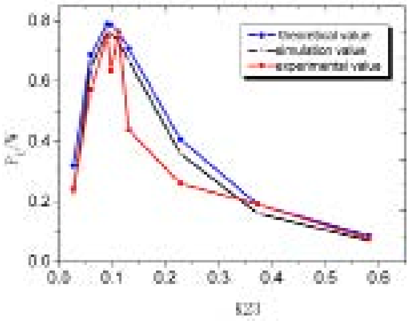
(b) The comparison between theoretical value, simulation value and experimental value of the system efficiency with the variation of $K_{12}$

**Figure 8.** The comparison between theoretical value, simulation value and experimental value of the system's power and efficiency with the variation of $K_{12}$

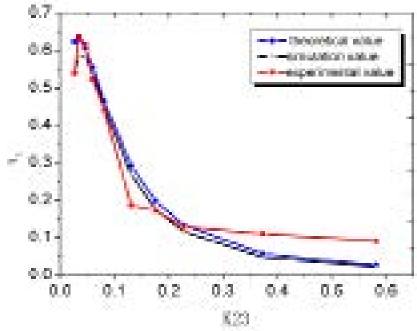
As shown in the Figure8, $P_L$ has two maximum with the variation of $K_{12}$. Receive power obtains maximum when $K_{12}$=0.03, $d_{12}$=26cm. However the efficiency is about 20%. The theoretical value and simulation value of the efficiency will increase with $K_{12}$ and basically remain unchanged. But in the experiment, there will be a maximum efficiency. This is because in theory and simulation analysis, the influence of cross coupling is not considered, which leads to the error between the theory and experiment.

### 4.2. The relationship between $P_L$, $\eta_L$ and $K_{23}$

Make $d_{12}$=9cm, $d_{34}$=9cm, $d_{23}$ changes from 2cm to 30cm. Receive power and output power can be measured by measuring the load coil's voltage and excitation coil's current and voltage respectively. Figure 9 is the comparison between theoretical value, simulation value and experimental value of the system's power and efficiency with the variation of $K_{23}$.



(a) The comparison between theoretical value, simulation value and experimental value of the system power with the variation of $K_{23}$



(b) The comparison between theoretical value, simulation value and experimental value of the system efficiency with the variation of $K_{23}$

**Figure 9.** The comparison between theoretical value, simulation value and experimental value of the system power and efficiency with the variation of $K_{23}$

In the description of Figure 9, $P_L$ has two maximum with the variation of $K_{23}$. Receive power obtains maximum when $K_{12}$=0.1, $d_{12}$=15cm, and the efficiency is about 44%. The maximum of $\eta_L$ is obtained at $K_{23}$=0.03, $d_{23}$=26cm, which is about 81%.

On this basis, adjust the input frequency at every $K_{23}$ to maximum receive power. Figure 10 shows the optimal input frequency along with the change of $K_{23}$ when received power achieves maximum value.

As can be seen from the Figure 10, each $K_{23}$ has an optimal input frequency to maximum the receive power. The optimal input frequency stays away from inherent resonance frequency with the increase of $K_{23}$.

Compared the experimental values with theoretical value and the simulation values, there are errors. This is because the signal source used in the experiment has a certain power of high frequency signal,

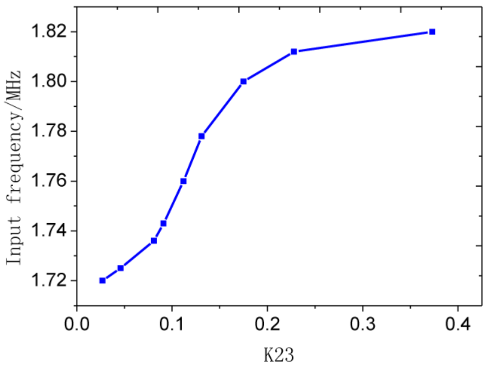


**Figure 10.** The relationship between the optimal frequency and $K_{23}$

and the output voltage is not stable voltage. In addition, the coil winded by hand is irregular, measurement is accurate. The influence of cross coupling is not considered in calculation process. All these lead to the existence of error. But the changing rule of the experiment and theory basic are similar.

## Conclusions

Four resonant coils wireless power transmission system based on magnetic resonance coupling is established. The factors influencing the received power and efficiency are so many. Factors, such as distance, input frequency and load are analyzed in the simulation and experiment. By the simulation analysis and experiment, receive power and efficiency is closely related to the distance and the input frequency. When the input frequency is inherent resonance frequency, there is optimal distance and load to maximum receive power. When distance is fixed, the optimal input frequency and the inherent resonance frequency are not the same, and the optimal frequency will stay away from the inherent frequency with the distance increases.

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