TELKOMNIKA Indonesian Journal of Electrical Engineering
Vol.12, No.6, June 2014, pp. 4572 ~ 4578
DOI: 10.11591/telkomnika.v12i6.5439

Multiple-Input Single-Output Wireless Power Transmission System for Coal Mine

Duan Zhao*, Enjie Ding, Xin Wang
IoT Perception Mine Research Center, China University of Mining and Technology
221008 Xuzhou, Jiangsu, China, +86 516 83899705
*Corresponding author, e-mail: zhaoduan1027@163.com

Abstract

In Wireless Power Transmission (WPT) systems, the proportion of energy received by the load is critical and the efficiency is the more significant parameter. The magnetic multiple input algorithms as well as many multiple overlapping coils structures in the transmitter side are proposed for the coal mine Internet of the Things (IOT) nodes. Different phase shifts cases for the input signal were considered to study their effect on the efficiency. Simulation results showed that the axial component of magnetic induction resulted from the multiple overlapping coils structure has preferable homogeneous distribution over the traditional single input coil. The proposed system achieved an efficiency value of 60% for a receiver placed 40cm away from a 4 coils transmitter comparing to an efficiency value of 50% for the same distance using a single coil transmitter. Simulation results shows that the proposed model is well adapted for the movable charging mode for the IOT nodes in coal mine.

Keywords: *wireless power transmission, MISO, internet of the things, coal mine*

1. Introduction

There are majority of incompatible monitoring systems in coal mine underground which makes tremendous waste of network resources. With the development of Internet of the Things (IOT), it provide a unified network platform to integrate such systems and also provide the technology of wireless communication coverage, which makes the personnel and equipments perceiving and locating realize easily in coal mine underground. As an important part of coal mine monitoring system, Localization System based on IOT is responsible for real-time locating and tracing of the personnel and equipments, for environment information awareness as well as for the searching and rescuing the persons in distress, which is also an important guarantee to keep coal mine safety production.

However, the battery of wireless nodes are energy constrained, especially for the IOT (Internet of the Things) wireless nodes, which will cost more energy when sometimes transmitting audio and video data. Therefore, the application of Wireless Power Transmission (WPT) technology in coal mine will overcome such problems and make sure that all the wireless nodes underground can keep enough energy, even the disaster occurred. In order to achieve the above goals, this paper provides a Multiple Input Single Output (MISO) WPT system which can be applied to coal mine IOT. The presented MISO model is able to achieve more than 60% transmission efficiency, by simulation verification. The results show that the resonant coupling power transmission system based on MISO model are more adaptable in coal mine than the traditional SISO WPT system.

2. WPT System

In this part a general overview about the designed wireless power transfer system will be presented. Figure shows the general diagram for the designed WPT system.

An alternative current (AC) power source will be connected to the transmitter, which consists of multi-overlapping coils that are arranged into symmetric distribution with the same radius. The receiver is assumed to be placed some distance away from the transmitter, up to 40cm. The pick-up coils in the receiver side will induce the power from the radiated magnetic field and power the connected load which can be a mobile or another portable device.

Received December 28, 2013; Revised February 26, 2014; Accepted March 12, 2014

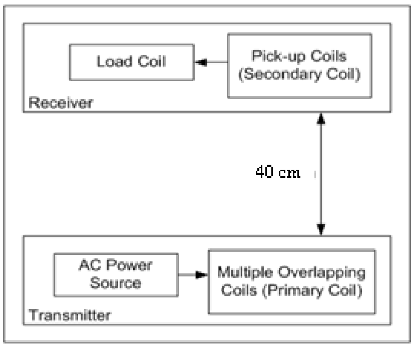


Figure 1. Wireless Power Transfer System Model

The WPT system constructed from several transmitter coils and a receiver coil which they have the same frequency by adjusting the interrelated parameters. The resonance coils are in the state of self-resonant to achieve the magnetic coupling [1]. The efficiency of the WPT system can be defined as the ratio of the received power in the load resistance to the delivered power from the electric power source [2, 3].

3. Multiple Input Transmitter Structure

The transmitter consists of multi-input coils which are arranged into symmetric distribution with the same radius. And the coverage area is as the traditional single input coil.

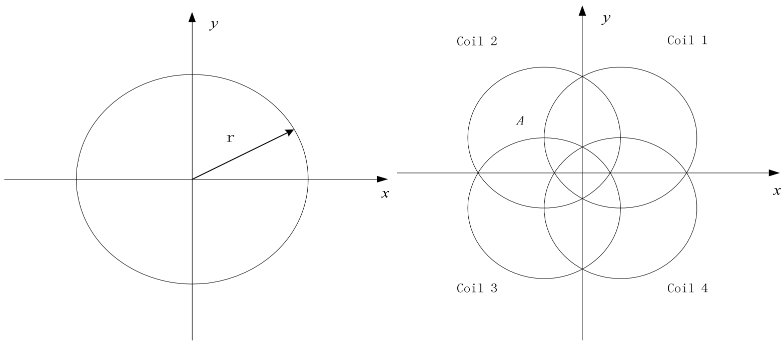


Figure 2. Single Input Structure and Multiple Input Structure

Describe the mechanism innovation with four coils structure as an example. Figure 2 shows four coils structure transmitter for magnetic beam forming comprising the first magnetic induction with the first phase component of coil 1, the second magnetic induction with the second phase component of coil 2 and so on. The relation of phases may be in an absolute or relative manner. In other words, the phase of coil1, coil2, coil3 and coil 4 may be set by a serious of related values, or the phases may be set by arbitrary values respectively, e.g. the phase shift could be offset π/4, π/2, π and so on for each coil. Another occasion is that the phase value can be set as arbitrary values separately. Assume that the transmitter can sense where the mobile device consuming power is. Therefore the four coils structure transmitter transfer effective power to mobile device with the optimized or maximized way according to the location of the receiver in the space with high efficiency for WPT system.

Comparing with the SISO WPT system, this magnetic field former consists of multiple overlapping coils with different relations of phases, whereas there is only one coil in the traditional transmitter. The proposed structure presents a viable and simple method to produce the magnetic field forming in the transmitter which makes the IOT nodes can be charged when the transmitter moves in a certain range. However, there is only one coil in the traditional transmitter. The transmitter could not be moved discretionarily, it should be put in the place where centers of the receiver and the transmitter should be in the same axes.

4. System Model and Efficiency Analysis

The transfer system is constituted by several transmitter coils and a receiver coil which have the same frequency by adjusting interrelated parameters. The resonance coils are in the state of self-resonant to achieve the energy coupling [4]. Magnetic coupling circuit is used only in the receiver antenna. L_t, L_{rp} and L_{rs} are the inductance of the transmitter, primary coil and secondary coil of the receiver separately. C_t, C_{rp} and C_{rs} are the compensation capacitor of the transmitter, primary coil and secondary coil of the receiver which should be adjusted for appropriate value to make the system (transmitter and receiver) work in the resonance frequency as shown in Equation (1) . R_t and R_{rp} and R_{rs} represent the internal resistances of transmitter and receiver coils respectively. R_L is the load resistance of the receiver coil. M_{t1_2}, M_{t2_2}, M_{t3_2}, M_{t4_2} are the mutual inductance between each transmitter coil and the receiver respectively. M_{2_3} is the mutual inductance between the primary coil and secondary coil in the receiver. Us is the alternating current power supply with frequency ω_0 for the transmitter.

$$\omega_0 = \frac{1}{\sqrt{L_t C_t}} = \frac{1}{\sqrt{L_{rp} C_{rp}}} = \frac{1}{\sqrt{L_{rs} C_{rs}}} \quad (1)$$

Figure 3 shows the circuit diagram of WPT system with four coils in the transmitter. Assume that the resistance, inductance and capacitance values are same in all four coils. As in [5] four-coil system can achieve high efficiency than two-coil system due to high quality factor of the primary and the secondary coil. Because internal resistance of source is not considered in this WPT model, there is no coupling in the transmitter.

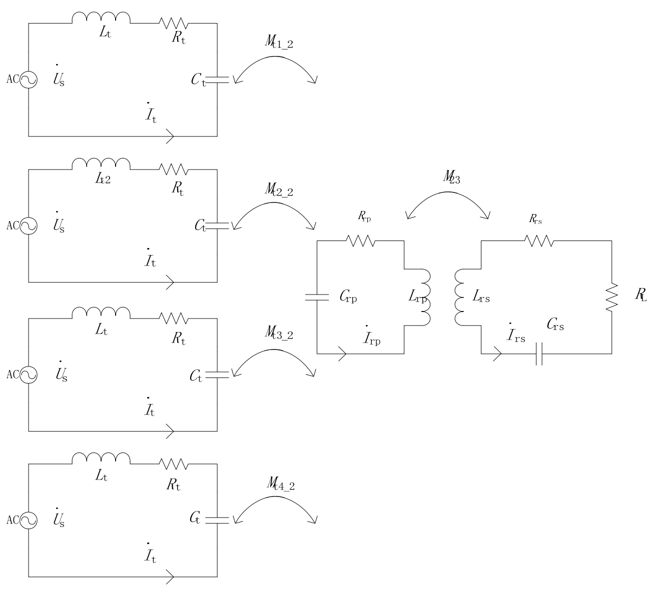


Figure 3. Wireless Power Transfer System Model of Four Coils Structure

The circuit model provides a reference for analysis of the WPT system characteristics of a magnetically coupling resonator system [6]. For the sake of simplicity the crossing mutual inductance between the transmitter and the secondary coil of the receiver are neglected in the following analysis. Then the current in each resonant circuit is determined from (2) to (7) by using Kirchhoff's voltage law.

$$\dot{I}_{t1}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp}\, j\omega M_{t1\_2} = \dot{U}_s \tag{2}$$

$$\dot{I}_{t2}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp}\, j\omega M_{t2\_2} = \dot{U}_s \tag{3}$$

$$\dot{I}_{t3}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp}\, j\omega M_{t3\_2} = \dot{U}_s \tag{4}$$

$$\dot{I}_{t4}\left(R_t + j\omega L_t + \frac{1}{j\omega C_t}\right) - \dot{I}_{rp}\, j\omega M_{t4\_2} = \dot{U}_s \tag{5}$$

$$\begin{aligned}&\dot{I}_{rp}\left(R_{rp} + j\omega L_{rp} + \frac{1}{j\omega C_{rp}}\right) - \dot{I}_{t1}\, j\omega M_{t1\_2} - \dot{I}_{t2}\, j\omega M_{t2\_2}\\ &-\dot{I}_{t3}\, j\omega M_{t3\_2} - \dot{I}_{t4}\, j\omega M_{t4\_2} - \dot{I}_{rs}\, j\omega M_{2\_3} = 0\end{aligned} \tag{6}$$

$$\dot{I}_{rs}\left(R_{rs} + j\omega L_{rs} + \frac{1}{j\omega C_{rs}} + R_L\right) - \dot{I}_{rp}\, j\omega M_{2\_3} = 0 \tag{7}$$

The efficiency of WPT system model is calculated in Equation (8). It is obvious that the efficiency is related to mutual inductance between the primary coil and the secondary coil, the secondary coil and the load coil. Rt, Rrp, Rrs, RL and system angular frequency ω also have an import effect on the efficiency. The value of M_{t1_2}, M_{t2_2}, M_{t3_2}, M_{t4_2} and M_{2_3} give the index of strength of coupling between the primary coil and the secondary coil, the secondary coil and the load coil, which have an important effect on the efficiency of the system. The mutual inductance is in relationship with the shape of the coil, number of turns and relative position of two coils. The transmitter structure in this paper has a positive effect on the strength of coupling between the transmitter and the receiver. According to theoretical analysis, efficiency is in proportion to the operation angular frequency, mutual inductance and load resistance, but in an inverse ratio to inner resistance of the primary coil, the secondary coil and the load coil. The efficiency will increase square times over the increase of angular frequency. What should be pay attention to is load resistance should match the inner resistance well to get the maximal power of the receiver. Therefore, the best way to increase the efficiency is to raise the coupling strength as much as possible between the transmitter and the receiver. So it is effective way to increase the number of turns of the coil and its radius to increase the mutual inductance. But the number of turns and radius should not be too large. One reason is the design of the coils should fit the size of the portable devices. The other reason is the resistance of the coil will also get large which will lead to waste of energy.

$$\begin{aligned}\eta &= \omega^4 M_{tot}^2 M_{2\_3}^2 R_L Z_t \Big/ \Big\{\left(Z_t Z_{rp} Z_{rs} + Z_{rs}\omega^2 M_{tot} + Z_t\omega^2 M_{2\_3}^2\right)\cdot\\ &\qquad \left[4\left(Z_t Z_{rp} Z_{rs} + Z_{rs}\omega^2 M_{tot} + Z_t\omega^2 M_{2\_3}^2\right) - \omega^2 M_{tot}^2 Z_{rs}\right]\Big\}\\ M_{tot} &= M_{t1\_2} + M_{t2\_2} + M_{t3\_2} + M_{t4\_2}\\ Z_t &= R_t + j\omega L_t + \frac{1}{j\omega C_t}\\ Z_{rp} &= R_{rp} + j\omega L_{rp} + \frac{1}{j\omega C_{rp}}\\ Z_{rs} &= R_{rs} + j\omega L_{rs} + \frac{1}{j\omega C_{rs}} + R_L\end{aligned} \tag{8}$$

Because the system works on the resonant frequency, then the efficiency can be modified as Equation (9).

$$\eta = \omega^4 M_{\mathrm{tot}}^2 M_{2\_3}^2 R_{\mathrm{L}} R_{\mathrm{t}} \Big/ \left\{ \left(R_{\mathrm{t}} R_{\mathrm{rp}} R_{\mathrm{RL}} + R_{\mathrm{RL}} \omega^2 M_{\mathrm{tot}} + R_{\mathrm{t}} \omega^2 M_{2\_3}^2 \right) \cdot \left[4\left(R_{\mathrm{t}} R_{\mathrm{rp}} R_{\mathrm{RL}} + R_{\mathrm{RL}} \omega^2 M_{\mathrm{tot}} + R_{\mathrm{t}} \omega^2 M_{2\_3}^2 \right) - \omega^2 M_{\mathrm{tot}}^2 R_{\mathrm{RL}} \right] \right\}$$

$$R_{\mathrm{RL}} = R_{\mathrm{rs}} + R_{\mathrm{L}} \quad (9)$$

For the sake of simplicity the crossing mutual inductance between the transmitter and the secondary coil of the receiver are neglected in the following analysis. Then the power of WPT system model is calculated in equation (10) by using Kirchhoff's voltage law.

$$P = V_s^2 \omega^4 M_{\mathrm{tot}}^2 M_{2\_3}^2 R_{\mathrm{L}} \Big/ \left(4 R_{\mathrm{t}} R_{\mathrm{rp}} R_{\mathrm{rsL}} + R_{\mathrm{rsL}} \omega^2 M_{\mathrm{tot}}^2 + 4 R_{\mathrm{t}} \omega^2 M_{2\_3}^2 \right)^2 \quad (10)$$

It is noticed that if the radius of the coil is increased, then the distance between the transmitter and the receiver can be larger which guarantees the high efficiency. Because the radius of the coil increases, the efficiency will also be raised.

5. Parameters Optimization and Simulation

As is used for the wireless devices, the specific application requirements of WPT system in coal mine constrain the design parameters. The diameter of transmitter is no more than 60 cm and the diameter of receiver is no more than 4cm. By testing and simulating many times, the proper and optimized parameters are given for the WPT system is shown in Table 1.

Table 1. Optimized Coil Parameters of Coal Mine WPT System

Parameter	Valve
Number of Litz Wire Turns (*N*t)	400
Number of Litz Wire Turns (*N*p)	400
Number of Litz Wire Turns (*N*s)	320
Load Resistance	50 ohm
88KHz, AC Current Sauce	0.5A

The receiver is assumed to be placed from -300mm to 300mm in both x axis and y axis. The distance between receiver and transmitter is 400 mm. The simulation defines the transmitter overlap a 600mm × 600mm area.

In Figure 4, the contour map describes the area which the receiver can get more efficiency. The area over 50% is a circular with radius of 0.05m.

From the results, we can conclude that 4 Coil structure transmitter is able to generate over 5 W energy and over 50% efficiency when the receiver is at a 0.2m height.

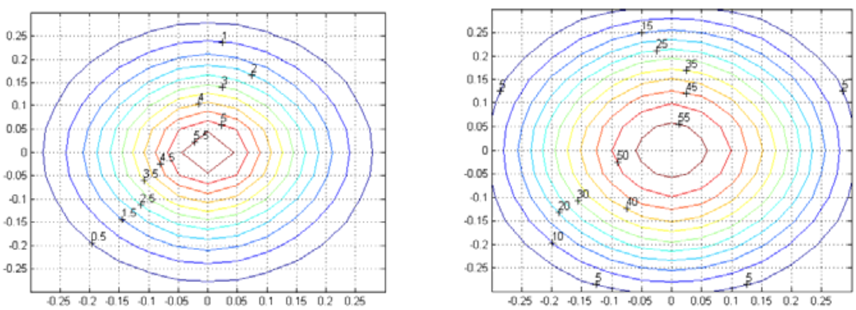
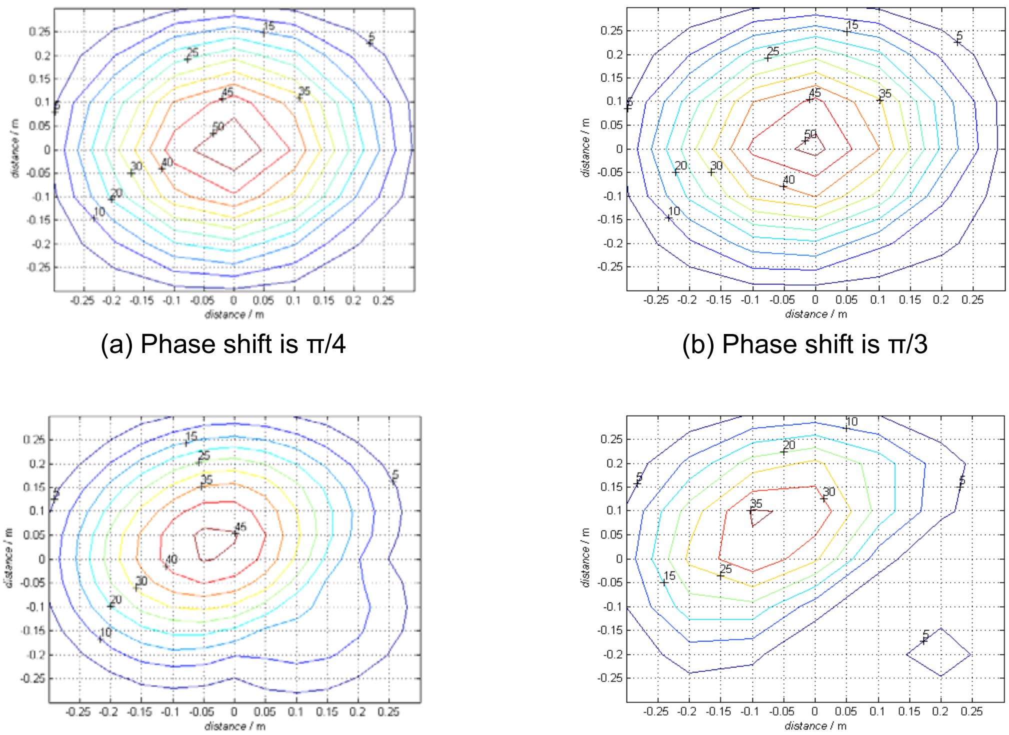


Figure 4. Received Power (Unit W) and Efficiency (Unit %) at 200mm Height

The phase shift of AC input signal should be considered when using 4 Coil structure. In this part, different input signals (with same frequency and amplitude, different phase shift) will be given to different coil of the 4 Coil structures, while the other simulation parameters are not changed.When give one of the 4 coils π/4, π/3, π/2 and π phase shifts, the received power and efficiency contour map is shown in Figure 5.



(a) Phase shift is π/4

(b) Phase shift is π/3

(c) Phase shift is π/2

(d) Phase shift is π

Figure 5: Efficiency when Coil 2 given Different Phase Shift (Unit %)

Comparing Figure 5(a) to Figure 5(d) with Figure 4, it can be found that when the signal with phase shift is given to one coil of the 4 coil structure, the efficiency will decrease. The larger value of the phase shift is, the smaller of the efficiency is at the center of the transmitter.

6. Conclusion

In this paper, the design and optimization MISO model for WPT system are described. Simulation results show that significant advantages of multiple input transmitter in receiving efficiency. The four coil transmitter model provide a large range, which can receiving high power efficiency, comparing to the single coil model. When using 4 coils model with a 600mm × 600mm transmitting area, 400mm receiving distance and no phase shift input signal, the power transfer efficiency over 60% is achieved for 88KHz. The results confirm the robustness of the multi-coils model based on WPT which is well adapted for charging the coal mine IOT nodes.

Acknowledgements

This work was financially supported by the national science and technology support program of China, under Grant No. 2012 BAH12B01.

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