Energy and Power Engineering, 2013, 5, 1072-1076
doi:10.4236/epe.2013.54B204 Published Online July 2013 (http://www.scirp.org/journal/epe)

Research of Magnetic Coupler Array for IPT System

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Received March, 2013

ABSTRACT

The advance of Inducive Power Transfer (IPT) system is capable to transfer large power across an air gap of sufficient distance, but the power level and charging area of receiver are limited by the magnetic coupler of IPT system. This paper analyses the correlative factors which effect maximum output power (P_m), it reveals P_m is inversely proportional with magnetic flux of power receiving coils. New ferrite array structure is proposed as the basic part of magnetic coupler that focusing on enhancing the equilibrium of magnetic flux distribution at charging area and increasing power transfer distance. The method of winding on ferrite array is quite flexible and the power transmission distance can be increased by changing the mode of ferrite array windings while magnetic field uniform is reduced, users can chose the suitable mode of winding for different IPT system. Finally the validity of theory analysis is tested by a 3D finite element modeling tool.

Keywords: Inducive Power Transfer; Ferrite Array; Magnetic Coupler; Finite Element Modeling

1. Introduction

Inductive Power Transfer (IPT) technology is a new power transmission technology which is based on electromagnetic induction principle, wireless power transmission between the power supply by using modern power electronics technology and high frequency converter technology, in addition applying modern control theory [1-3]. IPT technology is much safer, reliable, flexible comparing to traditional mechanical contact power supply, as a result, a research upsurge was set off around the world in recent years [4].

Magnetic coupler is the key part of IPT system, whether the magnetic circuit design is reasonable or not directly affects the power, efficiency and other important parameters of the whole IPT system [5-7]. The receiving coil and transmission coil realize the non-contact transmission via electromagnetic field, electromagnetic conversion efficiency is lower while the transmission distance increases, and IPT technology is generally applied to the wireless power transmission [8].

IPT system can have one or more receivers, the main circuit of IPT system with a plurality of receiver is as shown in **Figure 1**. In order to ensure IPT system can work normally, the magnetic coupler of transmitter can be composed of a large area resonant coil, or a plurality of small area resonant coil array. For IPT system with multiple receiving coils, the single large resonant coil at the transmitter is very difficult to achieve equilibrium magnetic circuit in a plane, while multiple resonant coils produce a relatively one.

Transmission coil array generated IPT system magnetic circuit is appropriate for single receiver, it can flexibly move within the magnetic coupler array of transmitter. Compared with single transmitter resonant coil, a plurality of transmitter resonant coil magnetic coupler array reduces the electromagnetic energy transmission distance, however, relatively gains equilibrium magnetic field distributions.

Paper 9 described a three layers and hexagonal magnetic array structure, the structure of magnetic coupler array is designed by air core, spatial distribution of magnetic field in the space field more uniform, but the three layer structure of magnetic coupler structure of energy

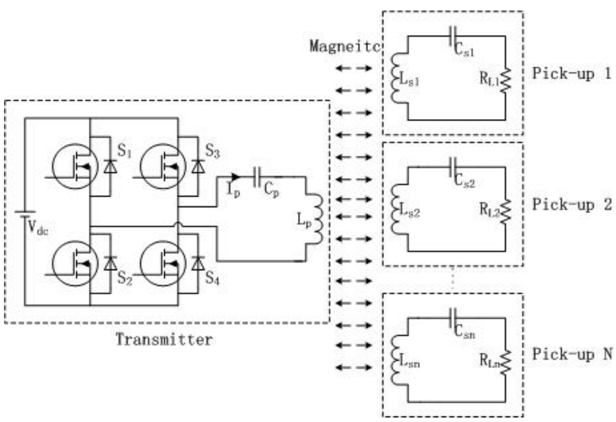

Figure 1. The main circuit of IPT system with several pick-ups.

transmission distance restrictions. In this paper single magnetic array is proposed, taking the ferrite with higher permeability as the core, increasing the energy transmission distance of the magnetic array.

2. Output Power and Efficiency of IPT System

2.1. The Maximum Output Power of IPT System

Output power and efficiency of the resonance mechanism is essential for the selection of resonance coil parameters when designing the IPT system.

The maximum output power P_m of system is:

$$P_m = V_{oc} I_{sc} Q_s = \omega_0 I_p^2 \frac{M^2}{L_s} Q_s \tag{1}$$

where V_{oc} is the open-circuit voltage of receiver, Isc is the short-circuit current of transmitter, Q_s is the quality factor of receiver circuit tuning , ω_0 is the resonant frequency, M is mutual inductance, L_s represents the inductance of transmission coil.

The resonant circuit can be divided into four resonant networks: SS, SP, PS, PP (S represents series resonant and P stands for parallel resonance) according to the compensation system [10]. For high power IPT system, transmitter needs to be set to S type resonant network, so this paper will analyze the SS, SP resonant network of IPT system, in this condition, the current of transmission coil (I_p) is described as:

$$I_P \cong 4V_{dc} \big/ (\sqrt{2} p Z_r) \tag{2}$$

where V_{dc} is the DC input voltage of IPT system, Z_r is the reflection impedance. When receiver resonance network are S and P network respectively, Q_s and Z_r are as follows:

$$Re\, Z_r = \begin{cases} \omega_0^2 M^2 / R_L & \text{(S)} \\ M^2 R_L / L_s^2 & \text{(P)} \end{cases} \tag{3}$$

$$Q_s = \begin{cases} \omega_0 L_s / R_L & \text{(S)} \\ R_L / (\omega_0 L_s) & \text{(P)} \end{cases} \tag{4}$$

Equation (2), (3), (4) are substituted in Equation (1), the maximum output power of SP, SS system can be expressed as:

$$P_m \cong \begin{cases} 8R_L^2 V_{dc}^2 / (p^2 M^2 \omega_0^2) & \text{(SS)} \\ 8L_s^2 V_{dc}^2 / (M^2 p^2 R_L) & \text{(SP)} \end{cases} \tag{5}$$

According to Equation (5), when the resonance frequency and input voltage are constants, there are two factors for P_m of SS IPT system will be influenced by R_L and M, two factors for P_m of SP IPT system will be influenced by R_L, M and L_s. The design of M, L_s is closely related to the resonance coil, the magnetic field distribution of different structure of coils and inductance, mutual inductance can be calculated by using magnetic field simulation software when the index of maximum output power and system operation at rated load are given.

2.2. The Efficiency of IPT System

Coupled mode equation for the receiver is shown as Equation (6) [11]

$$\frac{\mathrm{d}a_s}{\mathrm{d}t} = i\omega a_s - \Gamma_w a_s - \Gamma_e a_s + \kappa a_p \tag{6}$$

where a_p and a_s are energy amplitudes of transmitter and receiver respectively. The power of receiver got from the transmitter is dependent on κa_p, where κ is coupling coefficient. Γ_w is power decay rate of load and Γ_e is other power attenuation rate (mainly the attenuation rate of electromagnetic radiation). Then the power amplitudes of transmitter and receiver can be expressed as:

$$s_p = A_p e^{ikt}, \tag{7}$$

$$s_s = A_s e^{i(\Gamma_e + \Gamma_w)t} \tag{8}$$

where A_p and A_s are power coefficient of transmitter and receiver respectively. The energy consumption of receiver is mainly in the load and other energy, namely sp = ss, then

$$A_s / A_p = k / (\Gamma_e + \Gamma_w). \tag{9}$$

The load power consumption P_w can be expressed as

$$P_w = 2\Gamma_w |A_s|^2, \tag{10}$$

Total power P_t of receiver can be expressed as

$$P_t = 2\Gamma_p\ |A_p|^2 + 2(\Gamma_w + \Gamma_e)|A_s|^2 \tag{11}$$

where Γ_p is the energy decay rate of transmitter, then efficiency of system can be described as:

$$\eta = \frac{P_w}{P_t} = \frac{2\Gamma_w |A_s|^2}{2\Gamma_p |A_p|^2 + 2(\Gamma_w + \Gamma_e)|A_s|^2} = \frac{\frac{\Gamma_w}{\Gamma_e} \frac{k^2}{\Gamma_e \Gamma_p}}{(1+\frac{\Gamma_w}{\Gamma_e}) \frac{k^2}{\Gamma_e \Gamma_p} + (1+\frac{\Gamma_w}{\Gamma_e})^2} \tag{12}$$

According to Equation (12), the system will achieve maximum efficiency when $\Gamma_w / \Gamma_e = \sqrt{1 + k^2 / \Gamma_e \Gamma_p}$. If $\kappa > \Gamma_e$, $\kappa > \Gamma_p$, then effect of energy transmission from transmitter to receiver is the best, which means the coupling structure is in the state of strong coupling status.

The value of κ can be expressed as Equation (13) when the state of the resonant mechanism is resonance.

$$k = \mathrm{i}M / \left(2\sqrt{L_p L_s}\right) \tag{13}$$

According to Equation (6) and Equation (13), the efficiency of IPT system is related to the value of M, in other words, it is related to the magnetic induction intensity produced by transmitting coil.

3. Design of Magnetic Coupler Array

From the analysis of energy efficiency, transmitter under the excitation source will emission electromagnetic energy to space, receivers get electromagnetic energy. When the resonant parameters, mutual inductance of transmitter and receiver is reasonable, magnetic coupler can realize high efficiency, high power energy transmission. At this time, the energy emission ability of transmitter will determine the wireless transmission parameters of the power efficiency.

Electromagnetic energy in the plane is related to the decay rate of magnetic flux, which can be defined as:

$$\frac{d\phi}{dt} = BS\frac{\mathrm{d}\theta}{dt} + B\theta\frac{\mathrm{d}S}{dt} + S\theta\frac{\mathrm{d}B}{dt} \tag{14}$$

where B is the magnetic induction intensity, S is the area of magnetic flux, θ stands for angle between receiver and transmitter. Receiver in IPT system is invariant under normal circumstances, therefore, the value of $\mathrm{d}\theta / dt$, $\mathrm{d}S / dt$ is zero. The decay rate of the magnetic flux is related to $\mathrm{d}B / dt$, which means P_m is inversely proportional with magnetic flux of power receiving coils when the frequency and I_p is fixed.

Magnetic coupler structure of IPT system is as shown in **Figure 2**:

Magnetic coupler is composed of a plurality of independent coil windings by ferrite array, the adjacent coil windings are connected by series connection, and the current of windings are same. In addition, each magnetic core coil has the same winding turns, core size and all of the other parameters.

In short-distance wireless power transmission, each core coil generates large magnetic induction intensity in the upper space, as the core reducing the reverse the weakened degree around magnetic field. In long-distance wireless power transmission, magnetic field of all coil windings gathers to at the upper center of the magnetic coupler. Within certain height, the equilibrium of magnetic is well, assuming the area of magnetic coupling mechanism is large enough, then the magnetic field area with good equilibrium will also be enough for providing energy for a plurality of pick-up structure.

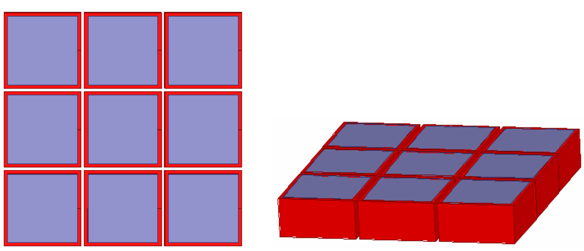

Figure 2. The structure of magnetic coupler array.

4. Simulation of Magnetic Coupler Array

A 9 ferrite array is taken as the example for analyzing magnetic coupler array, the model is built by 3D finite element modeling tool. **Figure 3** and **Figure 4** are magnetic induction intensity distribution of short-distance, long-distance respectively, short-distance plane is at the height of 2cm from the magnetic coupler and long-distance plane is at the height of 15cm.

As shown in **Figure 3**, magnetic field of adjacent core coils exist interaction reverse weakened on the short –distance plane, which result the magnetic induction intensity near the ferrite winding is relatively small comparing to other regions. Center ferrite winding and other ferrite windings are adjacent in magnetic coupler array, thus the magnetic induction intensity above the central region is relatively small compared with the other ferrite windings.

Long-distance wireless power transmission is more extensively used, and then magnetic induction intensity area is concentrated in the center area. The magnetic induction intensity in the region determines whether the receiving coil can obtain sufficient electromagnetic power,

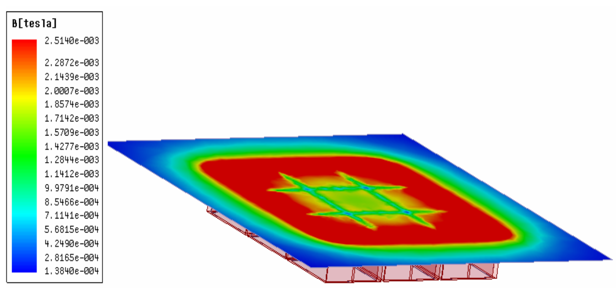

Figure 3. Magnetic induction intensity distribution on the short-distance plane.

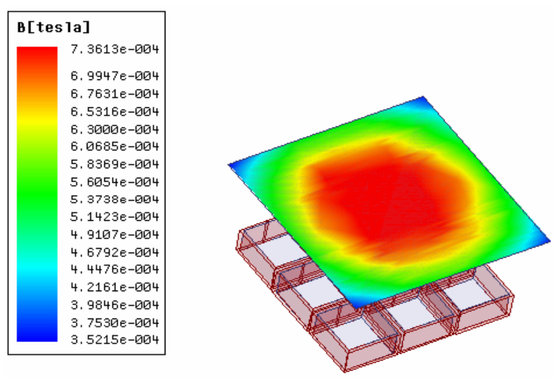

Figure 4. Magnetic induction intensity distribution of on long- distance plane.

equilibrium of magnetic in central region determines how much energy area can be obtained in the receiving coil, namely the operating range of receiver side.

Magnetic coupler in the paper is designed to be a symmetrical structure, if a length of 20cm line above the center area for 15cm exists, magnetic induction intensity distribution along the line is as shown in **Figure 5**. The magnetic induction intensity within the circular area with a diameter of 20cm achieve between 718 μT to 764 μT, the magnetic induction intensity within circular area with a diameter of 15cm is 748 μT~764 μT. Accordingly, the structure in this paper can provide an effective field area for long-distance wireless power transmission with larger area, better equilibrium, and longer transmission distance.

Suppose a size of 20 cm × 20 cm plane which is located above the coils about 15cm. **Figure 6** shows distribution of Φ above ferrite windings array and air windings array. When the abscissa is 0, the plane is located right above the winding array.

According to **Figure 6**, it is obvious that Φ above the ferrite windings array is bigger than air windings array which means the magnetic coupler can effectively increase the transmission power and distance.

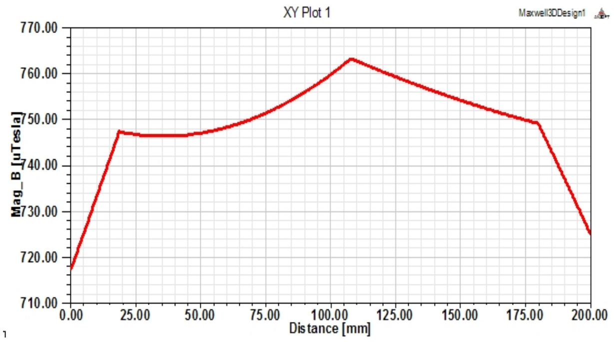

Figure 5. Magnetic induction intensity distribution curve on the long-distance plane.

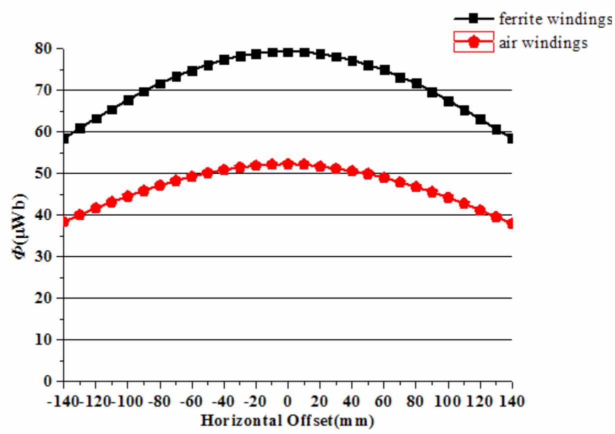

Figure 6. Distribution of Φ above ferrite windings array and air windings array.

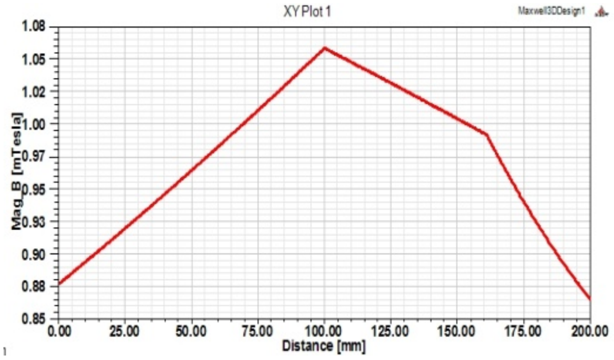

Figure 7. Magnetic induction intensity distribution curve on the long- distance plane when winding turns increased.

Under long-distance wireless power transmission, winding number of magnetic coupler array center ferrite has greatly affected the magnetic induction intensity at specified height, winding turns of central magnetic core coil was increased double, other parameters remain the same. Magnetic induction intensity distribution of a line which is above the coil for 15cm with a length of 20cm is as shown in **Figure 7**.

According to **Figure 6** and **Figure 7**, when excitation current of each coil is unchanged, magnetic induction intensity above the center coin is obviously increased by increasing the turns of winding at center ferrite of the magnetic coupler. In the proposed model, the magnetic induction intensity within diameter of 20cm region is 870 μT~1060 μT, the maximum magnetic induction intensity is increased by 39%, but the equilibrium of magnetic is decreased.

If the charging area is not so important in practical application, winding turns of the center ferrite can increased to achieve longer distance for wireless power transmission, in other hand, if charging area is pursued, the symmetric parameter of magnetic coupler can be chosen.

5. Conclusions

This paper proposed a new magnetic coupler which is composed of a plurality of ferrite winding array. The kind of magnetic coupler can produce magnetic field with good equilibrium, provides higher power transmission, and increases the transmission distance. In long-distance power transmission, longer power transmission distance was achieved by doubling the winding turns of the center ferrite, while the charging area was reduced. Parameters of the magnetic coupler array can be designed according to the actual application of receivers, the flexible modes of windings for magnetic coupler provided reference for the design of IPT system.

6. Acknowledgements

The author would like to thank the National Natural Science Foundation of China (Grant No. 51277192) for financial support.

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