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A GA-BASED DESIGN AND ANALYSIS OF TRANSMITTING COIL FOR WIRELESS POWER TRANSFER

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Abstract. *For the coupling coils of wireless power transfer (WPT) system based on near-field magnetic coupling, constant mutual inductance helps improve the efficiency, stability of system and simplifies its design. This paper proposes a genetic algorithm (GA) based design method of transmitting coil, which makes the mutual inductance constant and irrelevant to lateral movement of receiving coil. The coil design is treated as optimization model and worked out by genetic algorithm. It is more flexible, effective and simpler than the conventional methods. The parameter constraint of charging plane is also got, and helps maximize the use ratio of coil area. The examples show that the fluctuation of axial magnetic field on the charging plane is less than 3% when the turns of transmitting coil are more than 10, and the mutual inductance keeps constant when the receiving coil moves laterally. Finally, a prototype is built to verify the GA-based method proposed.*
Keywords: Wireless power transfer, Coupling coils, Uniform magnetic field, Mutual inductance, Genetic algorithm

1. **Introduction.** Wireless power transfer (WPT) system based on near-field magnetic coupling is a safe and convenient way to transfer electric power. In WPT systems, coupling coils with constant mutual inductance, which can be achieved by creating a uniform distribution of axial magnetic field on the charging plane, help improve the efficiency, stability of system and simplify the control. Essentially, axial magnetic field distribution is determined by the conductor arrangement of transmitting coil. Several approaches were proposed to make the mutual inductance constant and irrelevant to lateral movement of receiving coil [1-4]. However, the present methods lack flexibility and further optimization. Coil design based on one-dimensional equivalent model and curve fitting methods in [1] and [2] will cause some error, and the error will enlarge with increasing the turns and wire diameter in the practical coil. Coil array in [3] is more practical, but the coil losses are higher due to the complex stack of sub coils. In [4], a bowl-shaped transmitting coil is proposed to realize free-positioning system, but the volume is not suitable for saving space. This paper proposes a design method of transmitting coil based on genetic algorithm, which is more flexible, effective and simpler. The design of transmitting coil is treated as optimization model and worked out by genetic algorithm. Firstly, a coil structure, which is more flexible for conductor arrangement, is defined. Secondly, the criterion of transmitting coil for evaluating the uniformity of the axial field distribution on the charging plane is defined and verified. Finally, the parameter constraint of charging plane is also got, and helps maximize the use ratio of coil area. The method proposed is verified by prototype experiment.

2. **Structure Definition of Transmitting Coil.** The axial magnetic strength distribution on the charging plane is decided by the wire arrangement. Therefore, the uniform

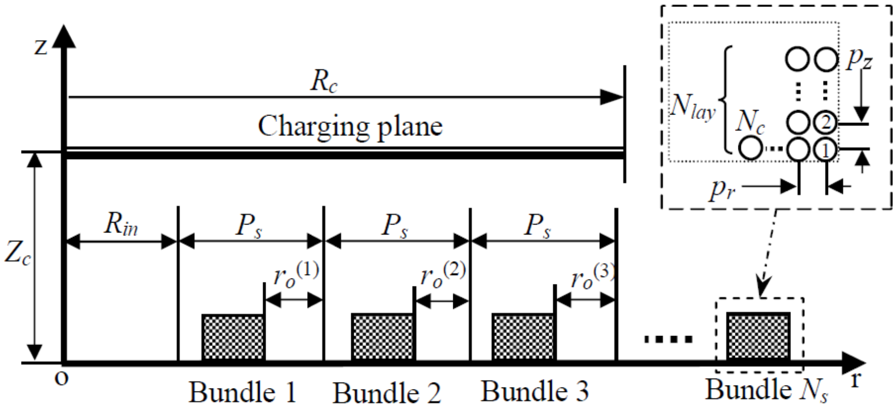

FIGURE 1. The definition of transmitting coil and charging plane

axial field distribution can be easily got by defining a criterion for evaluating the uniformity and optimizing the wire arrangement. Figure 1 shows the definition of circular transmitting coil and its charging plane for placing receiving coils. The wires are arranged in bundles and each bundle contains several wires or none. According to the definition, the radius, R, and axial coordinates, Z, of the mth wire in the nth bundle are calculated by:

$$R^{(n,m)} = {R_b}^{(n)} - p_r \cdot \text{trunc}\left((m-1)/N_{lay}\right) \tag{1}$$

$$Z^{(n,m)} = p_z \cdot \text{mod}\left(m, N_{lay}\right) \tag{2}$$

$${R_b}^{(n)} = R_{out} - (n-1)P_s - {r_o}^{(n)} \tag{3}$$

$$P_s = \text{trunc}\left(R_{out}/\left(N_s p_r\right)\right) \cdot p_r \quad (N_s \leq N_t) \tag{4}$$

where P_s is the pitch of wire bundles. ${r_o}^{(n)}$ is the radius offset of the nth wire bundle, which contains ${N_c}^{(n)}$ turns. There are N_s wire bundles, and N_s is equal to the coil turns N_t. The wires are arranged in N_{lay} layers with axial pitch p_z and radial pitch p_r between the turns. The function trunc(x) means the integral part of x, and mod(x, y) means the remainder of x/y.

As mentioned above, the uniformity of axial field on the charging plane, which is R_c radius and Z_c above the coil plane, is decided by ${N_c}^{(n)}$ and ${r_o}^{(n)}$. Therefore, uniform axial field distribution on the charging plane can be achieved by optimized values of ${N_c}^{(n)}$ and ${r_o}^{(n)}$, which will be got by genetic algorithm.

3. **Evaluation Criterion of Axial Field Uniformity.**

The criterion function F_{mag} is introduced to evaluate the uniformity of axial field distribution.

$$F_{mag} = \sum_{n=1}^{N_{test}} \left(\frac{H^{(n)} - H_{avg}}{H_{avg}}\right)^2 \tag{5}$$

$$H_{avg} = \frac{1}{N_{test}} \cdot \sum_{n=1}^{N_{test}} H^{(n)} \tag{6}$$

where $H^{(n)}$, which is calculated by (7), is the axial magnetic field strength of the nth sample point. There are N_{test} discrete sample points evenly located along the charging plane. The accuracy improves with increasing N_{test}, but too many points will be time consuming. The axial field strength is calculated by (8), where R is the radius of source wire with I amperes, and r, z are the radial and axial coordinates, respectively.

$$H^{(n)} = \sum_{s=1}^{N_s} \sum_{c=1}^{N_c{}^{(s)}} H_z\left(R^{(s,c)}, R_{test}{}^{(n)}, Z_c - Z^{(s,c)}, 1\right) \tag{7}$$

$$H_z(R, r, z, I) = \frac{I \cdot z}{2\pi r\sqrt{(R+r)^2 + z^2}}\left[K(m) + \frac{R^2 - r^2 - z^2}{(R-r)^2 + z^2}E(m)\right] \tag{8}$$

$$R_{test}{}^{(n)} = R_c(n-1)/(N_{test} - 1) \tag{9}$$

$$K(m) = \int_0^{\frac{\pi}{2}} \frac{1}{\sqrt{1 - m \cdot \sin^2(\alpha)}} d\alpha \tag{10}$$

$$E(m) = \int_0^{\frac{\pi}{2}} \sqrt{1 - m \cdot \sin^2(\alpha)} d\alpha \tag{11}$$

$$m = 4 \cdot R \cdot r / \left[(R+r)^2 + z^2\right] \tag{12}$$

where $K(m)$ is the complete elliptic integral of the first kind, and $E(m)$ is the complete elliptic integral of the second kind. $R_{test}{}^{(j)}$ is the radial coordinate of the jth sample point on the charging plane. The uniformity of axial field distribution is improved with the decrease of F_{mag}. Hence, the transmitting coil design is considered as an optimization problem to get the minimum of F_{mag} with the optimized variables of $N^{(n)}$ and $r_o{}^{(n)}$.

Genetic algorithm provides an effective way to solve the optimization problem whose searching space is too big for enumeration [5]. This paper focuses on the solutions of transmitting coil design by using genetic algorithms but not the improvement of algorithm themselves. The fitness function F_{mag} is defined above. For simplifying the constraints, the turns of the nth bundle $N^{(n)}$, which is limited by the total number of turns N_t, are mapped to variable a with value domain of $[0, 1]$ as

$$N_c{}^{(n)} = \begin{cases} \left(N_t - \sum\limits_{s=n+1}^{N_s} N_c{}^{(s)}\right) \cdot a^{(N_s - n + 1)} & n > 1 \\ N_t - \sum\limits_{s=2}^{N_s} N_c{}^{(s)} & n = 1 \end{cases} \tag{13}$$

where $a^{(1)} \sim a^{(Ns-1)}$ are the optimization variables for genetic algorithm. In addition, the offset values of wire bundles, $r_o{}^{(n)}$, are also mapped to variable b with domain of $[0, 1]$ as

$$r_o{}^{(n)} = w_{free} \cdot b^{(n)} \tag{14}$$

$$w_{free}{}^{(n)} = p_s - \text{trunc}\left(1 + N_c{}^{(n)}/N_{lay}\right) \cdot p_r \tag{15}$$

With the definitions above, $\boldsymbol{a}$ and $\boldsymbol{b}$ are the actual variables for genetic algorithm. There are $2N_s - 1$ variables in total.

4. **Examples of Transmitting Coil with Uniform Axial Field Distribution.** The transmitting coil design has been transformed to a sample optimization problem. Design examples are finished with the parameters in Table 1. The population size of genetic algorithm is set to 50. The algorithm procedure stops if the average relative change in the best fitness function values over 50 generations is less than or equal to 0.0001.

Table 1. Parameters of examples

Transmitting coil				Charging plane		
R_{out}/mm	N_s	p_r/mm	p_z/mm	R_c/mm	Z_c/mm	N_{test}
100	N_t	1	1	75	15	21

Figure 2 shows the optimal results with $N_t = 5, 10, 15, 20$ and 25 respectively. The wire arrangements are illustrated below the legends. When $N_t = 5$, the coil turns are too less to create uniform axial field distribution, and F_{mag} is relatively high. It means that uniform enough field distribution cannot be achieved with too few turns. When the number of turns is more than 10, the fluctuation of the fields is lower than 3% on the charging plane, and the F_{mag} decreases one order of magnitude compared to $N_t = 5$. And the fluctuation decreases with increasing coil turns.

In the examples, R_c is chosen to verify the method proposed, but it is not the best option. For maximizing the use ratio of coil area in practical designs, R_c should be maximum with allowed uniformity of axial field distribution. In our designs, for meeting the required limit of mutual inductance fluctuation, F_{mag} should be less than 0.05. Figure 3 shows the charging plane parameters sweep results of F_{mag}. As the bold line in Figure 3, the parameter constraint of charging plane with proper margin is: $R_c + Z_c \leq R_{out}$.

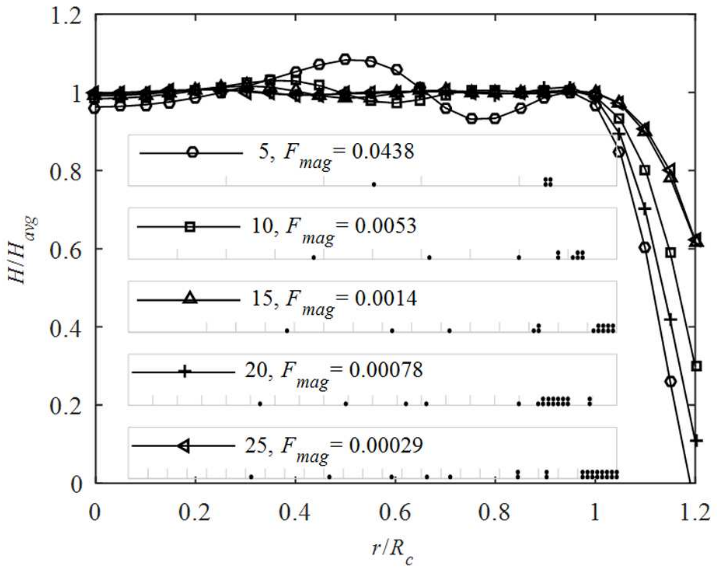

FIGURE 2. Normalized axial field and wire arrangement

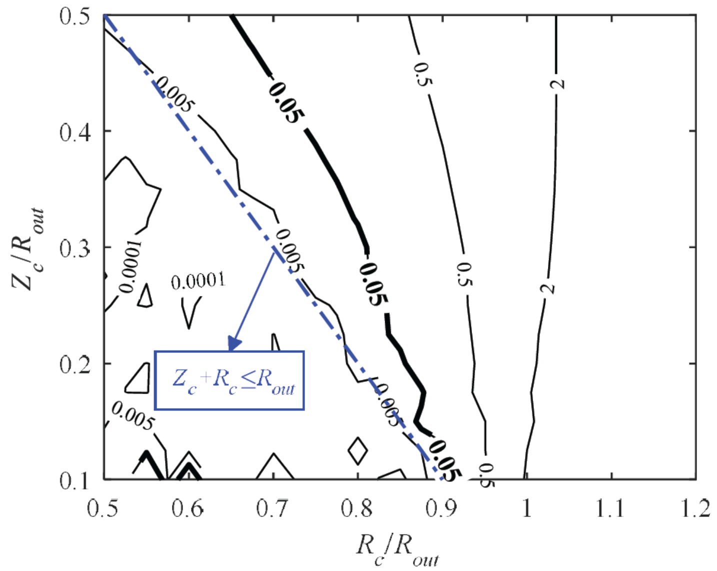

FIGURE 3. Optimal F_{mag} with the variation of charging plane parameters

5. **Experiment of Coupling Coils.** As the examples above, a uniform axial field distribution can be created on the charging plane of transmitting coil. It is the final goal that the mutual inductance of coupling coils is irrelevant to lateral move of receiving coil within charging plane range. A prototype with parameters in Table 2 is built as shown in Figure 4. The mutual inductance is measured by open-voltage method. The alternating current excitation of 1 ampere amplitude was applied to the transmitting coil by a high-frequency inverter. The open circuit voltage, V_o, of the receiving coil was measured, and the mutual inductance was got by $V_o/(2\pi f)$, where f is the excitation frequency. As shown in Figure 5, moving the receiving coil from place A to C, the 40mm radius receiving coil will exclude the edge of 85mm radius charging plane when r is greater than 45mm. Mutual inductance variates from 3.6 to 3.7μH, and the fluctuation is small enough for most of WPT systems.

Table 2. Parameters of experiment coil

Transmitting coil					Charging plane		
R_{out}/mm	N_s	N_t	p_r/mm	p_z/mm	R_c/mm	Z_c/mm	N_{test}
100	N_t	15	2	2	85	15	21

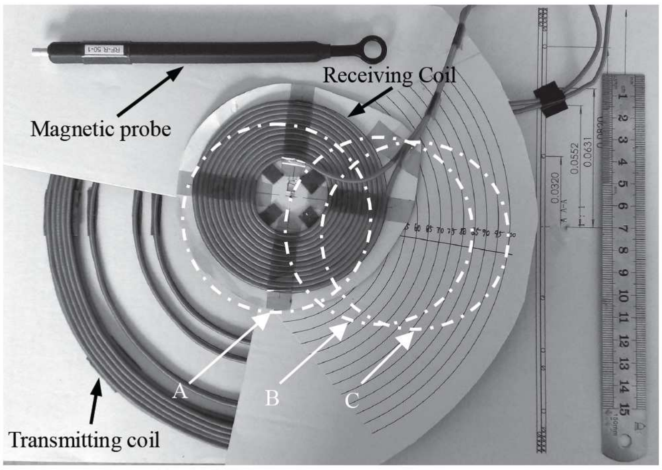

Figure 4. Coupling coils and the magnetic probe

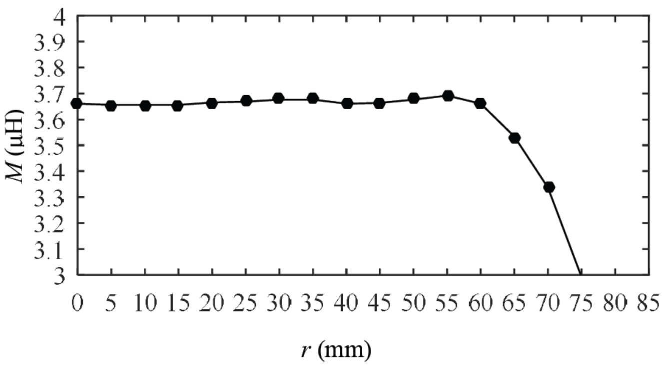

Figure 5. Mutual inductance measurement of coupling coils

6. **Conclusions.** A GA-based design and analysis of transmitting coil for wireless power transfer is proposed in this paper. The structure model of transmitting coil and its optimization method are proved efficient and suitable for the coil design. A uniform axial magnetic field distribution on the charging plane is got by the optimization method, and then the mutual inductances keep constant with the lateral move of receiving coil. The design is verified by experiments, and the fluctuation of axial field strength is lower than 3% when the turns of transmitting coil are greater than 10. For maximizing the use ratio of coil area in practical designs, the parameter constraint of charging plane with proper margin is also got. The transmitting coil deign method proposed in this paper is suitable for a lot of wireless charger applications, such as laptop computer, electric vehicles, and smart phone. In these applications, the lateral movement of receiving coil will not cause mutual inductance variation with the transmitting coil proposed, so the wireless power transfer is more stable and easy to control.

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