



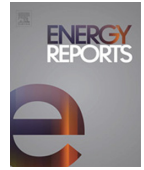
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Research on optimal receiver radius of wireless power transfer system based on BP neural network

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Abstract

In order to improve transmission performance of Wireless Power Transfer (WPT) system, this paper proposes the concept of optimal receiver radius. The planar square transmitter coil WPT system is studied to explore the variation rule of optimal receiver radius with the parameters of WPT system. The key parameters that affect optimal radius are transmitter coil turns, turn spacing, side length and transmission distance. On this basis, by introducing BP neural network to learn the variation rule, the accurate prediction of optimal receiver radius under different parameters is realized. Finally, the finite element simulation proves the existence of optimal receiver radius and the accuracy of the prediction value.

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Keywords: Wireless power transfer; Optimal receiver radius; BP neural network; Transmission performance; Simulation analysis

1. Introduction

With the development of Wireless Power Transfer (WPT) technology, greater transmission power and longer transmission distance have always been the goals pursued by researchers. The Magnetic Resonant Wireless Power Transfer (MR-WPT) makes high-power, long-distance wireless charging possible. Frequency tracking control technology [1], the maximum efficiency tracking technology [2] has been proposed one after another, all in pursuit of the best transmission performance, but these technologies require additional control circuits in addition to the WPT system itself, the implementation methods are relatively complex.

For the research on transmission performance of MR-WPT, many scholars have optimized the structure of WPT. Guo Yugang [3] analyzed the optimal configuration of the LCC-S WPT system based on the multi-objective

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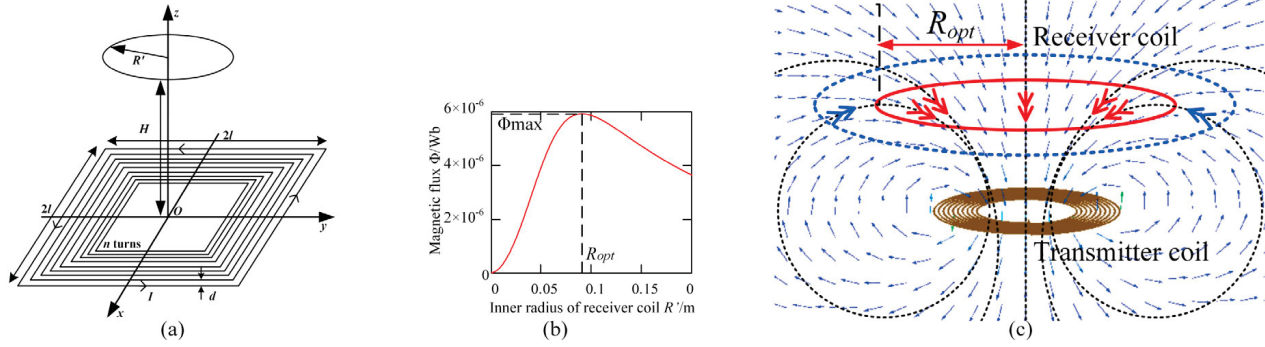


Fig. 1. (a) Model of WPT system; (b) Relationship between magnetic flux and inner radius; (c) Magnetic vector distribution diagram.

genetic algorithm, but only studied the compensation network. Su Yugang [4] proposed an adaptive genetic algorithm optimization method for the electric field coupled WPT system, which configured the parameters of the complementary and symmetrical LCC resonant system. Literature [5] proposed the concept of angle splitting for non-planar receiver coil WPT system, and explained that this phenomenon is caused by the optimal size of receiver coil, but the factors affecting the optimal size are not explored. Therefore, combined with intelligent algorithms to optimize the parameters of WPT system can better improve the transmission performance.

Reasonable configuration parameters for the WPT system are the basis for modeling and optimization, but the current research on the optimal receiver radius, including the reasons for formation, influencing factors and law analysis, has few references. Based on this, the optimal radius is studied deeply in this paper, determines the parameters that affect the optimal radius, and uses BP neural network to predict it accurately.

2. Theoretical analysis of WPT system

The optimal receiver radius proposed in this paper is based on the relationship between magnetic flux of the WPT system and the receiver inner radius. The WPT system with a square transmitter coil is selected for theoretical analysis.

2.1. Optimal receiver radius

Fig. 1(a) shows a WPT system with a square transmitter coil and a round receiver coil. The outer length of the transmitter coil is $2l$, the number of turns is n , the turn spacing is d , the innermost side length is $2l-2(n-1)d$, the input current is I . The radius of the single-turn receiver coil is R' . The transfer distance is H . The vacuum permeability is μ_0 . According to Biot–Savart Law [6], the magnetic flux expression [7] through single-turn receiver coil can be obtained:

$$\left\{ \begin{aligned} \Phi &= \sum_{i=1}^n \int_0^{R'} \left\{ \frac{\mu_0 r I [l - (i-1)d] [l - (i-1)d - r]}{\sqrt{H^2 + [l - (i-1)d - r]^2 + [l - (i-1)d]^2}} E(r) + \frac{\mu_0 r I [l - (i-1)d] [l - (i-1)d + r]}{\sqrt{H^2 + [l - (i-1)d + r]^2 + [l - (i-1)d]^2}} F(r) \right\} dr \\ E(r) &= \frac{1}{H^2 + [l - (i-1)d - r]^2} + \frac{1}{H^2 + [l - (i-1)d]^2}, F(r) = \frac{1}{H^2 + [l - (i-1)d + r]^2} + \frac{1}{H^2 + [l - (i-1)d]^2} \\ \text{s.t. } l - (n-1)d &> 0 \end{aligned} \right. \quad (1)$$

Fig. 1(b) indicates that the receiver coil has an optimal radius R_{opt} to achieve the maximum magnetic flux. Fig. 1(c) shows magnetic vector distribution. Within the optimal receiver radius R_{opt} , all magnetic flux lines penetrate into coil. Once the optimal radius is exceeded, part of the flux is negative, total magnetic flux will decrease.

2.2. Influencing factors of optimal receiver radius

The change rules of optimal receiver radius with single variable of system are explored under the default parameters. We can conclude from Fig. 2 that R_{opt} is positively correlated with the transfer distance H and transmitter

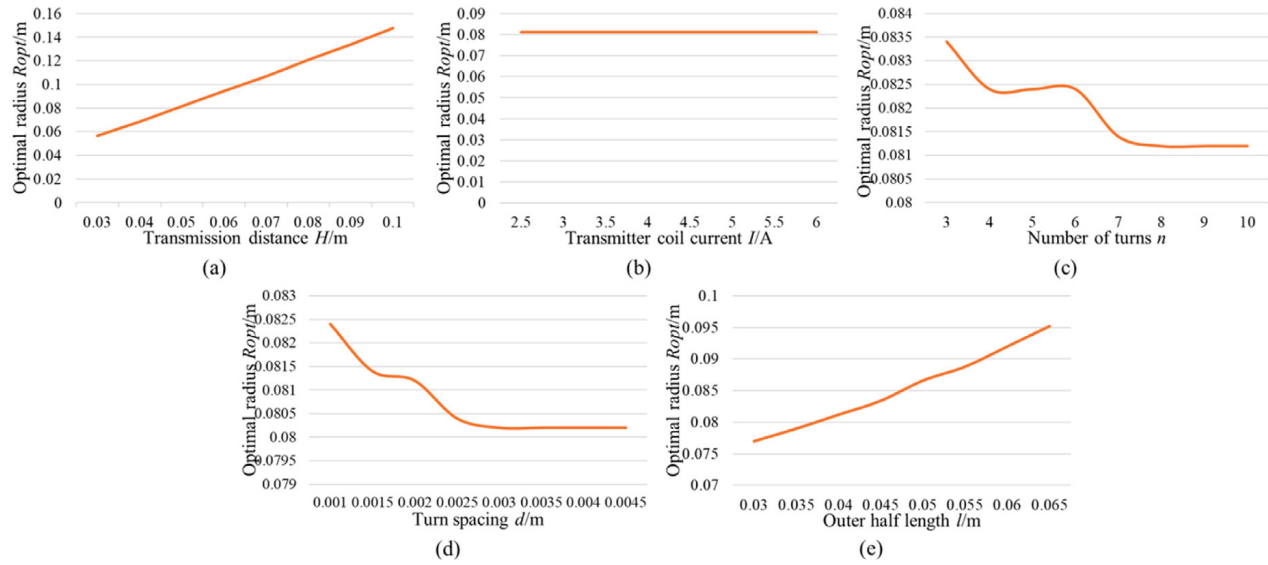


Fig. 2. (a) Relationship between R_{opt} and H ; (b) Relationship between R_{opt} and I ; (c) Relationship between R_{opt} and n ; (d) Relationship between R_{opt} and d ; (e) Relationship between R_{opt} and l .

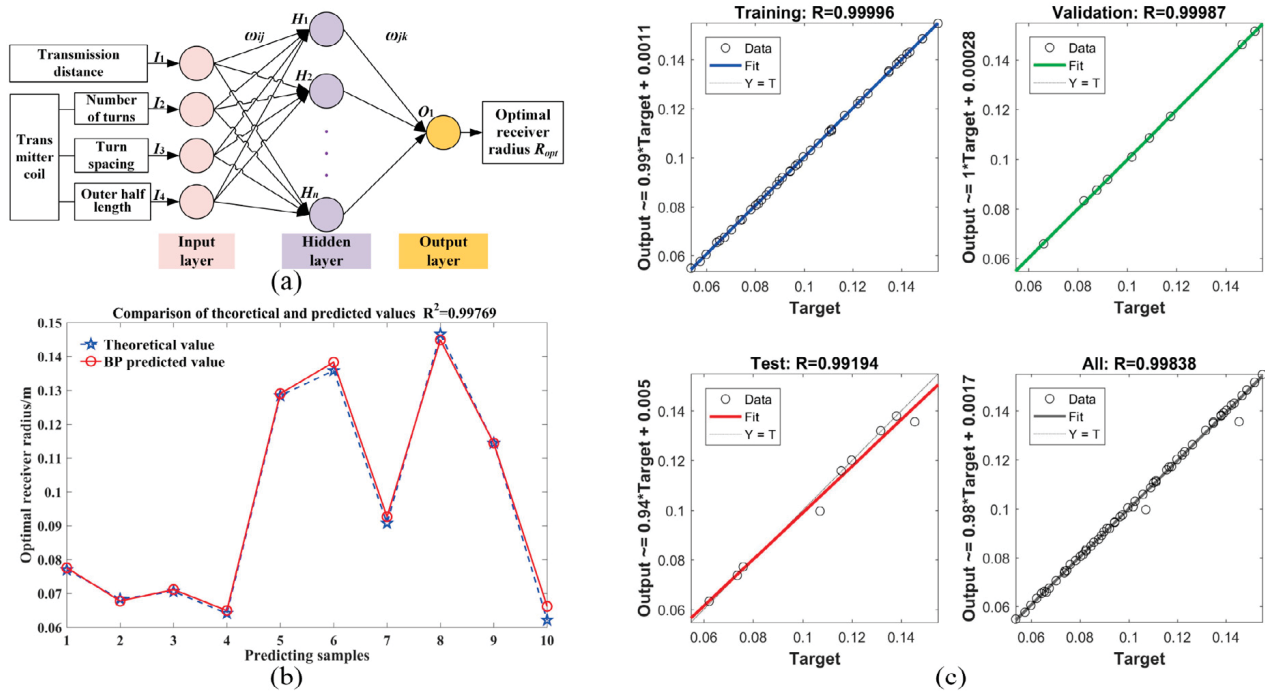


Fig. 3. (a) Model of BP neural network; (b) Comparison of BP predicted value and theoretical value; (c) Regression analysis of data.

coil out half length l . It is unrelated to the transmitter coil's current, and decreases slowly with the increase of the transmitter coil turns n and turn spacing d . In summary, the transmission distance, number of turns, turn spacing, and side length of transmitter coil of WPT system are all important parameters that affect the change of optimal receiver radius (see Table 1).

Table 1. Transmitter coil and transmission distance parameter default values.

Parameter	Current I	Number of turns n	Turn spacing d	Outer half length l	Transmission distance H
Default values	5 A	9	0.002 m	0.04 m	0.05 m

Table 2. Neural network model parameters.

Network parameters	Number of input layer nodes	Number of hidden layer neurons	Number of output layer nodes	Learning rate λ	Maximum number of iterations M	Learning accuracy ε
Value	4	10	1	0.01	1000	1×10^{-7}

Table 3. Neural network model parameters.

Parameters	1	2	3	4	5	6	7	8	9	10
H/m	0.046	0.04	0.042	0.035	0.082	0.087	0.059	0.097	0.072	0.031
n	4	4	4	9	8	9	3	8	7	7
d/m	0.0018	0.0015	0.0016	0.0029	0.0036	0.002	0.0041	0.0025	0.0031	0.0027
l/m	0.038	0.035	0.036	0.045	0.056	0.054	0.033	0.049	0.051	0.047
Predictive	0.0776	0.0678	0.0712	0.0650	0.1290	0.1383	0.0927	0.1449	0.1144	0.0662
Theoretical	0.077	0.0684	0.0706	0.0642	0.1284	0.1358	0.0908	0.1466	0.1144	0.0622
Error%	0.78%	0.88%	0.83%	1.27%	0.48%	1.84%	2.09%	1.18%	0%	6.49%

3. BP algorithm prediction of optimal receiver radius

3.1. Model of BP neural network

BP neural network algorithm [8] is applied to predict the optimal receiver radius. Fig. 3(a) shows a three-layer BP neural network. The input layer contains four input nodes: transmission distance, turns, turn spacing and outer half length of transmitter coil. The hidden layer adopts S-type transfer function *tansig* and contains n neurons. The output layer adopts a linear transfer function *purelin*, the output is optimal receiver radius R_{opt} . To ensure that network can achieve better prediction results, the network parameters are set as shown in Table 2.

Based on theoretical calculation in Section 2, 70 sets of data are obtained, among which 60 training sets are generated from random functions, and the remaining 10 sets as test set.

3.2. Analysis of the prediction result of optimal radius

A. Evaluation index

In order to verify the prediction effect of BP neural network model, the relative *error* is first introduced:

$$error = \frac{|f - y|}{y} \times 100\% \quad (2)$$

where f is predicted value and y is actual value. The smaller the *error*, the higher the credibility of the prediction.

The coefficient R^2 which is used to evaluate the generalization ability of model is determined. Where f_i is predicted sample, y_i is real sample, l is the number of samples, the closer R^2 is to 1, the better the performance will be.

$$R^2 = \frac{\left(l \sum_{i=1}^l f_i y_i - \sum_{i=1}^l f_i \sum_{i=1}^l y_i \right)^2}{\left(l \sum_{i=1}^l f_i^2 - \left(\sum_{i=1}^l f_i \right)^2 \right) \left(N \sum_{i=1}^l y_i^2 - \left(\sum_{i=1}^l y_i \right)^2 \right)} \quad (3)$$

B. Analysis of prediction results

It can be seen from Fig. 3(b) that theoretical value and predicted value in the 10 predicted samples almost coincide, and determination coefficient R^2 is as high as $0.99769 \approx 1$, indicating that the model has a better generalization ability. As shown in Table 3, relative error is distributed between 0% and 6.49%, and the error is within an acceptable range.

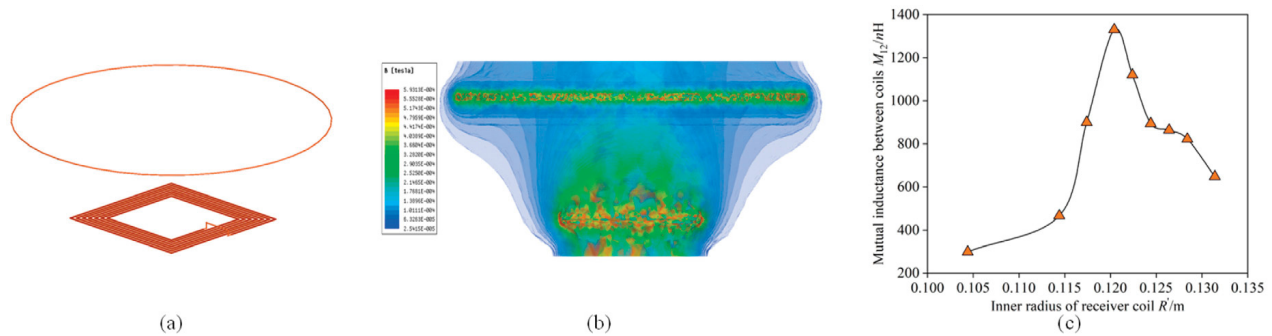


Fig. 4. (a) Ansys simulation model; (b) System magnetic field strength distribution; (c) Relationship between M_{12} and R .

In Fig. 3(c), regression analysis of training, verification, test, and all samples are presented. All data points are basically scattered on regression line, and R are close to 1, indicating that the model achieve high prediction accuracy.

4. Simulation analysis

Finally, the existence of the optimal receiver radius and the accuracy of BP prediction results are verified by finite element simulation software.

4.1. Simulation parameter settings

Fig. 4(a) shows a simulation model based on ANSYS Electronics. Fig. 4(b) shows the system's magnetic field intensity distribution, it can be seen that the distribution is relatively concentrated. The 9th group of data in Table 3 is selected as the parameter setting of simulation model.

4.2. Analysis of simulation results

Within the variation of inner radius is (0.1, 0.135), 9 values are randomly selected to obtain the mutual inductance under corresponding radius, as shown in Fig. 4(c). The variation rule is basically consistent with the theoretical analysis results. Moreover, When M_{12} takes the maximum value, the optimal radius is about 0.1204m. There is a certain deviation from BP predicted value, but the error is only 5.43%. Also, under optimal receiver radius, the mutual inductance is significantly improved, which can make system itself maintain the best transmission performance.

5. Conclusion

Based on the model analysis of MR-WPT system, this paper proposed the concept of optimal receiver radius. The variation rule of optimal radius with each parameter was analyzed, and the influencing factors of optimal radius were determined: turns, turn spacing, outer radius of transmitter coil and transmission distance. To accurately quantify the optimal receiver radius, BP neural network algorithm is introduced, R^2 is as high as 0.99769, and relative error is basically distributed at about 1% in the test. Finally, in the simulation model, the deviation between simulated result and BP predicted value of the optimal radius is only 5.43%. That is, by predicting the optimal receiver radius of the designed WPT system through BP algorithm, the transmission performance can reach the best state.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

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