ISSN (Print) 1226-1750
ISSN (Online) 2233-6656
Journal of Magnetics 22(3), 491-496 (2017) https://doi.org/10.4283/JMAG.2017.22.3.491

Effect of Distance on Optimum Transfer Efficiency for the Four-coil Magnetic Coupled Resonance System

Lijiao Gong[1,2], Xinheng Li[1], Xuewei Chao[1], Jing Zuo[1], and Yang Li[1]*

[1]*College of Mechanical and Electrical Engineering, Shihezi University, Shihezi, Xinjiang 832003, China*
[2]*State Key Laboratory of Power Transmission Equipment & System Security and New Technology, Chongqing 400044, China*

(Received 30 April 2017, Received in final form 23 June 2017, Accepted 23 June 2017)

As known, the variation of distances between the adjacent coils will affect the transfer efficiency in magnetic coupled resonance system. In order to explore the influence of distance on the optimum transfer efficiency, a four-coil magnetic coupled resonance system is established. Based on the mutual inductance coupling theory, the relationship between the transfer efficiency and coupling coefficient is obtained. Supported by the simulation analysis and experimental evidences, it is found that the coupling coefficient k_{23} (between transmitter and receiver coils) is the most significant factor affecting the transfer efficiency. Under the optimal k_{23}, the transfer efficiency will increase with the coupling coefficient k_{12} (between driver and transmitter coils). Besides, it will firstly increase and then decrease with the coupling coefficient k_{34} (between receiver and load coils). Moreover, the theoretical calculation formula of k_{23} is deduced, which can make a contribution to the optimization of parameters and improvement of transfer efficiency for the four-coil magnetic coupled resonance system.

Keywords : wireless power transfer, planar spiral coil, magnetic coupled resonance, coupling coefficient

1. Introduction

With the rapid development of various low power mobile appliances such as cell-phones, laptops and hand-held equipment, there is substantial interests in the wireless power charging. In view of the drawbacks of traditional induction charging, the wireless power transmission (WPT) via magnetic coupled resonance displays its superiority due to its higher efficiency, longer range and greater power output [1, 2].

As a new WPT technology, the magnetic coupled resonant is based on the near-magnetic field coupling concept, which is the principle that two or more objects with the same resonant frequency can exchange energy efficiently and the coupled energy between non-resonant objects is very weak [3, 4]. The magnetic coupled resonance between coils is not only related to the position and direction [5-9], but also relates to the relay coil and the structures [10-15]. For instance, it was demonstrated that a high efficiency wireless power transfer system can be achieved by adjusting the coupling factors between the source and the internal resonator [6]. It was also verified that the change of addition of the relay coil between transmitter and receiver coils can affect the transfer distance and efficiency [13]. Besides, the size and structure of the resonant coils has an impact on the coupling coefficient, by comparing the three different structures (planar spiral, spherical and solenoid) coils, it is pointed out that the coil structure determines the coupling resonance frequency and the distribution of magnetic field, affecting the effective coupling between coils [14].

Although many studies have been carried out in the relevant aspects mentioned above, but there are still few researches on the relationships between the optimum transfer efficiency and distances for the four-coil magnetic coupled resonance system. Thus, this article will be interesting and meaningful.

In this paper, the magnetic resonance coupled WPT system is established based on four single-layer planar spiral coils. Through the equivalent circuit, the relationship between the transfer efficiency and coupling coefficient between the adjacent coils is analyzed. Moreover, the expressions of transfer efficiency and optimum coupling coefficient have been derived. The simulation analysis and experiments are carried out, which indicate that the coupling coefficient k_{23} (between transmitter and receiver

*Corresponding author: Tel: +86-188-9959-7887
Fax: 0993-2057219, e-mail: liyang328@shzu.edu.cn

coils) is the key factor affecting the transfer efficiency of the system. In addition, the influence of other coupling coefficients on the transfer efficiency has also been investigated.

2 System Model and Transfer Characteristics Analysis

2.1. System model

The wireless power transmission (WPT) is mainly achieved by the magnetic coupled resonance between coils. For the four-coil WPT system, its electrical model is shown as Fig. 1, in which the coupling coefficients are also denoted.

In Fig. 1(b), U_S is the amplitude of the voltage source that is applied to the driver coil, R_S is the internal resistance of the power supply, R_L is connected to the load coil and regarded as the load. According to the classical circuit theory techniques, the current in each coil can be calculated as:

$$\begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & 0 & 0 \\ Z_{21} & Z_{22} & Z_{23} & 0 \\ 0 & Z_{32} & Z_{33} & 0 \\ 0 & 0 & Z_{43} & Z_{44} \end{bmatrix}^{-1} \begin{bmatrix} Us \\ 0 \\ 0 \\ 0 \end{bmatrix} \tag{1}$$

$$Z_{ij} = Z_{ji} = \begin{cases} R_i + j\omega L_i + \dfrac{1}{j\omega C_i}(i = j) \\ j\omega M_{ij}(i \neq j),\ k_{ij} = M_{ij}/\sqrt{L_i L_j} \end{cases} \tag{2}$$

In equation (2), R_i stands for the equivalent resistance of the resonator, L_i and C_i are the equivalent inductance and external tuning capacitor of the coil, respectively. M_{ij} and k_{ij} represent the mutual inductance and coupling coefficient between resonant coils (i and j), respectively. The mutual inductance M between two coils can be expressed by a function of the transfer distance between coils [16], shown as:

$$M = \frac{\pi\mu_0 (N_1 N_2)^{0.5} (r_1 r_2)^2}{2D^3} \tag{3}$$

Where μ_0 is the vacuum permeability, N_1, N_2 is the number of turns of the coils, r_1, r_2 is the average radius and D is the axial distance between coils.

Keep the same resonant frequency for each loop, and then the circuit impedance will satisfy that $Z_{ij} = R_{ij}$ ($i = j$, $i \in \{1, 2, 3, 4\}$). As the distance between coils (1and 4, 1and 3, 2 and 4) are relatively large, the coupling coefficients k_{13}, k_{14} and k_{24} can be neglected. Based on the equation (2), the current in coil 1 and 4 is:

$$\begin{cases} I_1 = \dfrac{(1 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4) Us}{R_1[(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + k_{23}^2 Q_2 Q_3]} \\ I_4 = \dfrac{k_{12} k_{23} k_{34} \sqrt{Q_1 Q_2}\sqrt{Q_2 Q_3}\sqrt{Q_3 Q_4}}{\sqrt{R_1 R_4 [(1 + k_{12}^2 Q_1 Q_2)(k_{34}^2 Q_3 Q_4) + k_{23}^2 Q_2 Q_3]}} \end{cases} \tag{4}$$

Where Q_i is the loaded quality factor of coil, the power transfer efficiency of the four-coil magnetic coupled resonance system can be computed as:

$$\eta = \frac{|I_4|^2 R_L}{|Us||I_1|} = \frac{k_{12}^2 k_{23}^2 k_{34}^2 Q_1 Q_2^2 Q_3^2 Q_4 R_L}{[(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + k_{23}^2 Q_2 Q_3][(1 + k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4)] R_4} \tag{5}$$

At the resonant frequency, the quality factor of each coil is determined. So it can be found that the coupling coefficients k_{12}, k_{23} and k_{34} are the main factors affecting the transfer efficiency.

2.2. Analysis of coupling coefficient

2.2.1. Effect of coupling coefficient k_{12} on the transfer performance

The partial derivative of the k_{12}^2 for the equation (5) can be obtained as:

$$k_{12\text{opt}}^2 = \frac{k_{23}^2 k_{34}^2 Q_1 Q_2^2 Q_3^2 Q_4 R_L}{[(1 + k_{12}^2 Q_1 Q_2)(1 + k_{34}^2 Q_3 Q_4) + k_{23}^2 Q_2 Q_3]^2 R_4} > 0 \tag{6}$$

It is shown that the transfer efficiency is a monotonic function about k_{12}, which means the transfer efficiency increases with the coupling coefficient k_{12}.

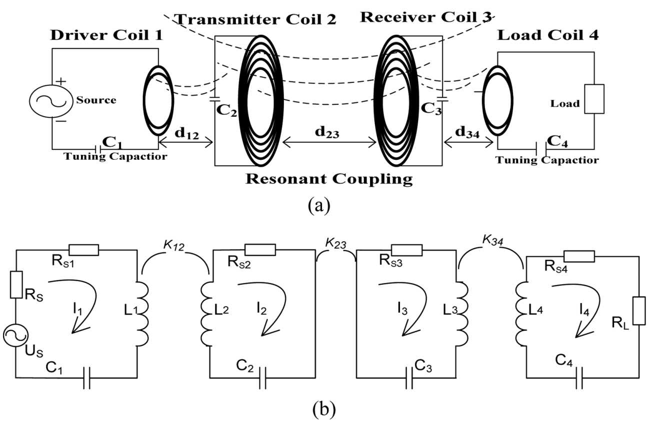


Fig. 1. (a) The four-coil WPT system (b) The equivalent circuit.

2.2.2. Effect of coupling coefficient k_{23} on the transfer performance

Through the equation $\partial \eta / \partial k_{23}^2 = 0$, the optimum transfer coefficient k_{23} can be obtained as:

$$k_{23\text{opt}}^2 = \frac{(1 + k_{34}Q_3Q_4)\sqrt{1 + k_{12}Q_1Q_2}}{Q_2Q_3} \tag{7}$$

From equation (7) and (5), the maximum transfer efficiency can be obtained as:

$$\eta_{\text{opt}\_k23} = \frac{k_{12}^2 k_{34}^2 Q_1Q_2Q_3Q_4}{(1 + \sqrt{k_{12}Q_1Q_2})^2(1 + k_{34}^2Q_3Q_4)} \tag{8}$$

2.2.3. Effect of coupling coefficient k_{34} on the transfer performance

Similarly, the optimum transfer coefficient k_{34} can be obtained as:

$$k_{34\text{opt}}^2 = \sqrt{\left(\frac{1 + k_{23}^2Q_2Q_3}{Q_3^2}\right)\left(\frac{1 + k_{12}^2Q_1Q_2 + k_{23}^2Q_2Q_3}{Q_4^2 + k_{12}^2Q_1Q_2Q_4^2}\right)} \tag{9}$$

From equation (9) and (5), the maximum transfer efficiency can be obtained as:

$$\eta_{\text{opt}\_k34} = \frac{k_{12}^2 k_{23}^2 Q_1 Q_2^2 Q_3}{\sqrt{(1 + k_{12}^2Q_1Q_2)(1 + k_{23}^2Q_2Q_3)} + \sqrt{1 + k_{12}^2Q_1Q_2 + k_{23}^2Q_2Q_3}} \tag{10}$$

3. Simulation Analysis

The electromagnetic simulation modeling and analysis could be executed based on the finite element method [17-19]. All the geometry parameters of the coils are shown in Table 1. Select AC/DC module, magnetic field and frequency domain, the coil model is established according to that adopted in the experiment. The resonant frequency is set as f = 4.60 MHz, set up the boundary conditions such as the external circuit and excitation source.

The two-dimensional screen shot of the simulation model and the generation of magnetic flux density is shown in Fig. 2, where d_{12} = 5 mm, d_{23} = 20 mm, d_{34} = 5 mm.

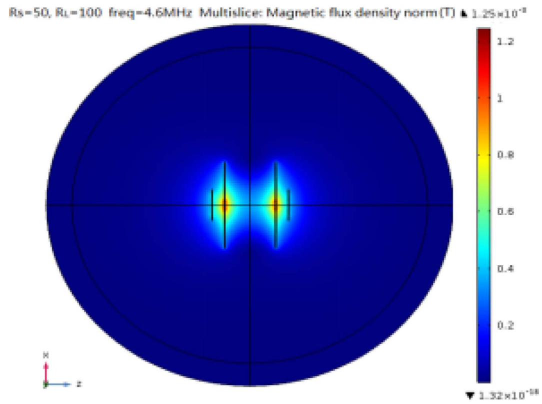


Fig. 2. (Color online) The distribution of the magnetic flux density.

3.1. Relationship between transfer efficiency, k_{12} and k_{23}

When d_{34} is fixed, for example 5 mm, by the parametric sweep of d_{12} and d_{23}, the relationship between transfer efficiency, d_{12} and d_{23} can be described as Fig. 3.

It is indicated that the transfer efficiency increases firstly and then decreases with the d_{23} under different d_{12}. Moreover, the distance d_{23} is fixed corresponding to the maximum transfer efficiency, in this simulation it is 20 mm, which can be regarded as the optimum transfer distance of the transmitter coil and receiver coil. According to equation (2) and (3), it can be calculated that the optimum coupling coefficient k_{23opt} is 0.0208. Besides,

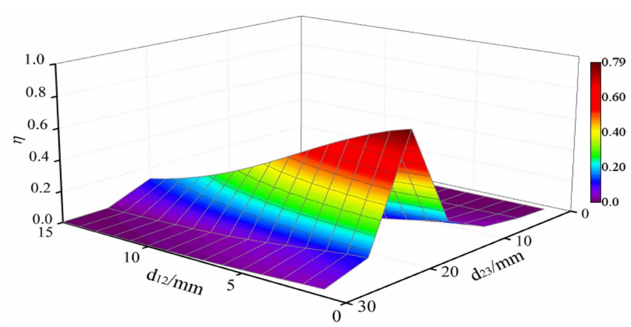


Fig. 3. (Color online) The relationship between η, d_{12} and d_{23}.

Table 1. Dimensions parameter of coils.

	driver Coil	Transmitter Coil	Receive Coil	Load Coil
Inner Diameter d_1/mm	8	3	3	8
Outer Diameter d_2/mm	13.35	35.05	35.05	13.35
Wire Diameter a/mm	0.28	0.28	0.28	0.28
Layers	1	1	1	1
Turns	10	62	62	10
Material	Copper	Copper	Copper	Copper

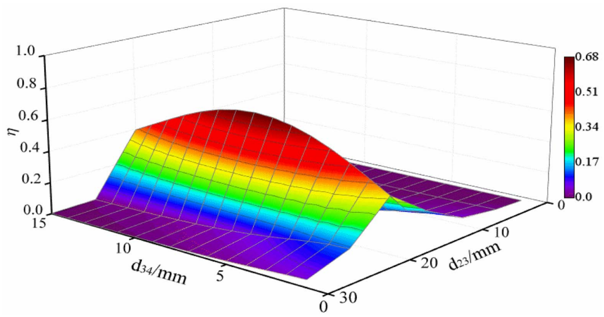


Fig. 4. (Color online) The relationship between η, d_{23} and d_{34}.

under the optimum d_{23}, the transfer efficiency decreases with the d_{12}.

3.2. Relationship between transfer efficiency, k_{23} and k_{34}

When d_{12} is fixed, for example 5 mm, by the parametric sweep of d_{23} and d_{34}, the relationship between transfer efficiency, d_{23} and d_{34} can be described as Fig. 4.

It is found that the distance d_{23} corresponding to the maximum transfer efficiency is also 20 mm under different d_{34}. And the transfer efficiency increases firstly and then decreases with the d_{34} under the optimum d_{23}, the largest transfer efficiency is 67.60 % when d_{34} is 8 mm. From equation (2) and (3), it can be calculated that the optimum coupling coefficient k_{34opt} is 0.0269.

A common feature can be found from Fig. 3 and Fig. 4, the transfer efficiency is not varied obviously with the increase of d_{12} and d_{34} when $d_{23} \neq 20$ mm, but all those efficiencies are significantly lower than that when $d_{23} = 20$ mm. It can be concluded that the coupling coefficients k_{12} and k_{34} have a strong dependence on k_{23}.

4. Experimental Verification

In order to verify the effect of distance on optimum transfer efficiency, a magnetic coupled resonance WPT system is constructed as Fig. 5.

The high frequency supply for the system is composed by the signal generator and power amplifier. The impedance analyzer (LCR-8110G) is used to measure the equivalent circuit parameters, which are shown in Table 2. The voltage U_L of the load is detected by oscilloscope and then the load power $P_L = U_L^2/R_L$ can be obtained. One resistance (1 Ω) is used in series with the driver coil to sense the current, and the input voltage value U_S is measured by oscilloscope. So the input power can be obtained.

In order to verify the influence of k_{23} on the transfer efficiency, the distances d_{12} and d_{34} are both set as 5 mm in experiment, the transfer efficiency with the change of

Table 2. Components of the system parameters.

	driver Circuit	Transmitter Coil	Receive Coil	Load Circuit
L_i/uH	1.46	59.89	59.91	1.46
C_i/nF	0.82	0.02	0.02	0.82
R_i/Ω	0.22	14.05	14.02	0.23
Q_i	0.84	122.95	123.42	0.42
f/MHz	4.60	4.60	4.60	4.60

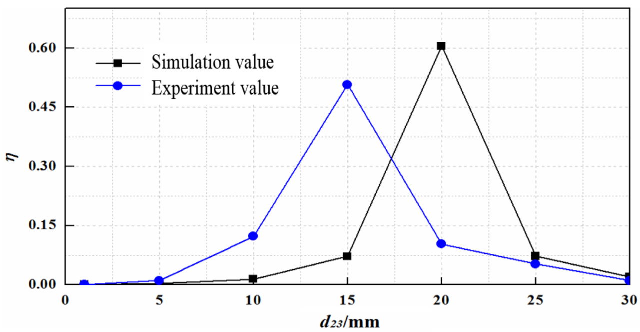


Fig. 6. (Color online) The relationship between η and d_{23}.

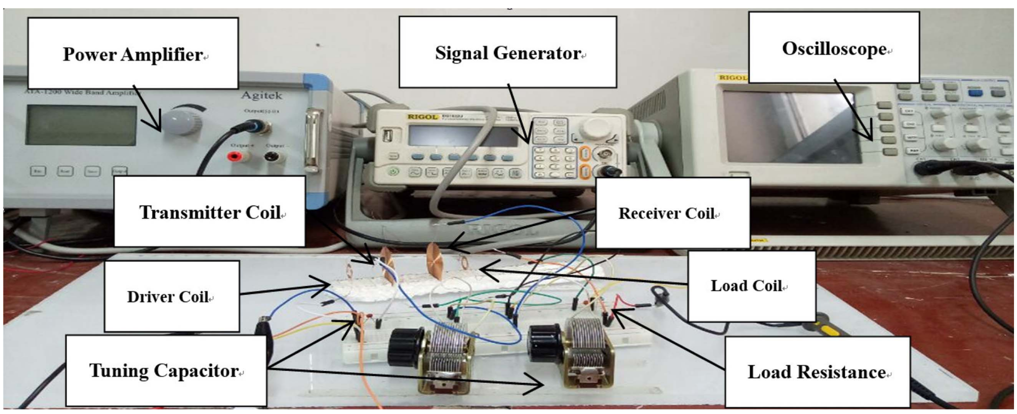
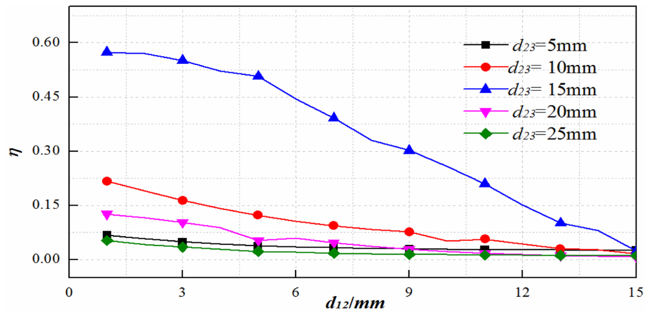
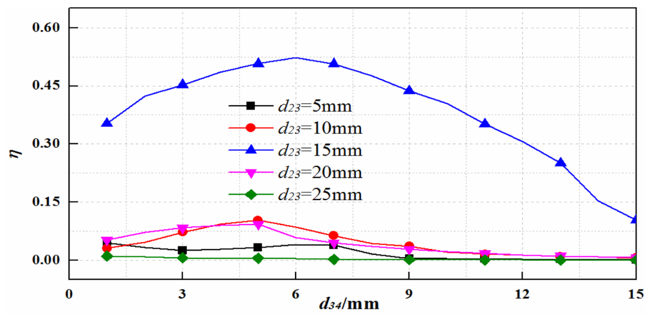


Fig. 5. (Color online) The experimental setup.



(a)



(b)

Fig. 7. (Color online) (a) The relationship between η and d_{12} (b) The relationship between η and d_{34}.

d_{23} is measured as shown in Fig. 6.

The experimental results show that the transfer efficiency increases first and then decreases with d_{23}, the largest transfer efficiency η = 50.72 % appears when d_{23} = 15 mm. The variation law of experimental results is basically consistent with the simulation analysis.

In order to verify the influence of k_{12} and k_{34} on the transfer efficiency, other five groups of experiment are carried out. The distance d_{23} is set as 5, 10, 15, 20 and 25 mm, the relationships between transfer efficiency, d_{12} and d_{34} are shown in Fig. 7.

It can be found that under different d_{12} and d_{34}, the maximum transfer efficiency all appears when d_{23} = 15 mm. Besides, the transfer efficiency decreases with d_{12}, increases first and then decreases with d_{34}. All these features are consistent with the simulation analysis, which verifies each other.

5. Conclusions

In this paper, the relationship between the transfer efficiency and coupling coefficient is analyzed. Supported by the simulation analysis and experimental evidences, it is found that the coupling coefficient k_{23} (between the transmitter coil and receiver coil) is the decisive factor influencing the transfer efficiency. Under the optimum coupling coefficient k_{23opt}, the transfer efficiency increases with k_{12}, and increases firstly and then decreases with k_{34}.

Therefore, for the practical applications, some suggestions can be proposed by this research as follows:

Firstly, adjust the distance d_{23} (between transmitter and receiver coil) to achieve the best coupling state to ensure that the transfer efficiency is a local optimum value.

Then, adjust the distance d_{12} (between driver and transmitter coil) as close as possible on the premise of considering the system structure.

Finally, adjust the distance d_{34} (between receiver and load coil) to an appropriate position, so as to achieve its optimum transfer efficiency.

6. Discussion

There are two very significant parameters in the magnetic coupled resonance WPT system, which are the transfer efficiency and transfer power. In this research, the transfer efficiency determines the amplitude of transfer power on account of the fixed input power. Thus, only one parameter transfer efficiency is analyzed and discussed in this paper.

In theoretical predictions, the optimum transfer efficiency is obtained at d_{23} = 20 mm, but in the case of experimental results it is obtained at d_{23} = 15 mm. The main reasons could be summarized as follows:

The actual experimental coils are tightly wound coils, not same as the ideal plane geometry in simulation. The difference of geometrical structure will affect the transmission characteristics of system.

The input voltage in simulation is ideal and stable, while the actual input voltage is probably not stable due to the loss of front circuit and interference from outside.

Although the values are different, the related conclusion and trends in theoretical predictions are still consistent with those in experiments, which means it can provide the guidelines for other systems.

Acknowledgements

This work was supported by the State Key Laboratory of Power Transmission Equipment, System Security and New Technology Visiting Scholar Program [No. 2007DA10512713407]; Scientific Research Foundation for Distinguished Scholars, Shihezi University [No. RZCX201544]; Applied Basic Research Youth Project, Shihezi University [No. 2015ZRKXYQ05].

References

[1] Z. Zhao, Y. Zhang, and K. Chen, Proceedings of the

CSEE **33**, 3 (2013).
[2] W. Chen and Q. Chen, Advanced Technology of Electrical Engineering and Energy **35**, 9 (2016).
[3] J. Li, P. Zhang, T. Ma, and Y. Zhang, Electric Machines and Control **19**, 11 (2015).
[4] W. Fu, B. Zhang, and D. Qiu, Proceedings of the CSEE **29**, 18 (2009).
[5] H. Huang, X. Huang, and L. Tan, Advanced Technology of Electrical Engineering and Energy **30**, 1 (2011).
[6] T. Phi. Duong and J. W. Lee, IEEE Microwave and Wireless Components Letters **21**, 8 (2011).
[7] W. Junhua, S. L. Ho, and W. N. Fu, IEEE Trans. Magn. **47**, 10 (2011).
[8] X. Zhang, Q. Yang, and H. Chen, Proceedings of the CSEE **32**, 9 (2012).
[9] J. Wang, J. Li. Jiangui, S. L. Ho, and W. Chau, IEEE Trans. Magn. **48**, 11 (2012).
[10] T. Cai and J. Shen, Journal of Power Supply **9**, 5 (2014).
[11] W. Zhong, K. Chi, and S. Y. R. Hui, IEEE Trans. Ind. Electron. **60**, 1 (2013).
[12] F. Zhang, S. A. Hackworth, and W. Fu, IEEE Trans. Magn. **47**, 5 (2011).
[13] L. Chi, W. Zhong, and S. Y. R. Hui, EEE Trans. Power Electron. **27**, 4 (2012).
[14] H. Marques and B. V. Borges, IEEE International Telecommunications Energy Conference (2011).
[15] C. Chen, T. Hu, and C. Lin, IEEE Transactions on Circuits and Systems II: Express Briefs **57**, 7 (2010).
[16] A. Karalisa, J. D. Joannopoulosb, and M. Soljacic, Annals of Physics **323**, 1 (2008).
[17] Y. Li, X. Sheng, M. Lian, and Y. Wang, Nondestructive Testing and Evaluation **31**, 4 (2016).
[18] X. Chao, Y. Li, and J. Nie, J. Magn. **21**, 4 (2016).
[19] X. Sheng, Y. Li, M. Lian, C. Xu, and Y. Wang, Materials Evaluation **74**, 12 (2016).