Research on Detection Method of Metal Foreign Objects in Electric Vehicle Wireless Power Transfer System

Anjie Ran[1](✉), Xiaobo Wu[2], Donglei Sha[2], Zhongping Yang[1], and Fei Lin[1]

[1] School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China
393008317@qq.com, 20121480@bjtu.edu.cn

[2] National Innovation Center of High Speed Train, Chengyang 266111, China

Abstract. The high frequency magnetic field area in the radio energy transmission system (WPT) is an important medium for electric energy transmission. As an open structure, the high frequency magnetic field often inevitably falls into metal foreign matters, leading to a decline in the transmission efficiency of the system, and the heating of the metal itself will also cause potential safety hazards. In this paper, based on the loose coupling model, the detection sensitivity formula of the detection coil method is established. On this basis, combined with the magnetic field characteristics of the square transmission coil surface, a long rectangular interconnection detection coil group and its layout are proposed. Compared with the traditional small coil independent detection method, this method has the advantages of less detection channels, high detection sensitivity, simple control and less blind area. Through electromagnetic field simulation, the advantages of the proposed structure are proved, and experimental verification is carried out on the WPT platform of the square transmission coil to achieve effective detection of ferrite, copper sheet, iron sheet and aluminum alloy sheet.

Keywords: Wireless Power Transfer · Detection Sensitivity Formula · Metal Foreign Object Detection · Detection Coil Interconnection

1 Introduction

Due to the non-contact open structure of the WPT system, metal foreign objects can easily invade the high-frequency AC magnetic field, which is an important medium for energy transmission in the air, resulting in a decrease in the transmission performance of the system and serious heating of the metal itself, cause damage to the coil or even fire, a complete WPT system must have the auxiliary function of metal foreign object detection. Regardless of whether the metal plate with the size of the transmission coil is located at the transmitting end, the receiving end, the middle of the two coils or the outside of the coil, the operating frequency of the system is changed and the output power of the system is reduced [1]. According to the eddy current loose coupling model, establish the equivalent circuit model between the metal foreign object and the coupling

F. Sun et al. (Eds.): ICEIV 2022, LNEE 1016, pp. 10–21, 2023.
https://doi.org/10.1007/978-981-99-1027-4_2

coil, quantitatively analyze the impact of the metal foreign object on the system transmission performance, and provide the theoretical analysis basis for the metal foreign object invading the wireless charging system [2, 3]. Metal foreign object detection methods are divided into three categories: physical detection method, system parameter detection method and auxiliary coil method [4, 5]. The physical detection method is susceptible to environmental interference, the realization of the detection system is more complicated and costly. The system parameter detection method is to directly use the electrical parameters inside the WPT system as the detection index to complete the high-precision detection system design [6, 7], but it's not suitable for high-power systems, the influence of metal foreign objects on the system parameters is often covered by the fluctuation of the circuit itself, and the system parameter detection method is completely invalid. Due to the limitations of the physical detection method and the system parameter detection method to deal with the intrusion of metal foreign objects in the high-power WPT system, the auxiliary coil method has become the only option. The detection coil method is divided into active excitation [8, 9] and passive excitation [10, 11] according to the different excitation sources.

Compared with the active excitation method, the passive excitation method does not need an external excitation source, and depends on the magnetic field distribution of the primary coil, so the detection is more targeted. In this paper, the detection system is designed for the large-size transmission coil used in the high-power WPT system, and the passive excitation method is selected as the auxiliary coil method. First, according to the loose coupling model, analyze the relationship between the voltage change of the detection coil and the voltage change rate before and after the metal intrusion, and explain the advantages of the long rectangular detection coil. Based on the distribution of the magnetic field intensity of the square primary coil and the direction of the magnetic field lines, the long rectangular coils are interconnected, so that the number of detection channels is reduced, the detection sensitivity is improved, and the detection area is increased. Finally, the effectiveness of the detection system was verified on the 800 mm * 800 mm transmission coil platform.

2 Theoretical Analysis

2.1 Detection Sensitivity Analysis

In the high-power WPT system, the air gap of the primary and secondary coil is about 20cm, and the coil itself is large in size, and small-sized foreign objects fall on the surface of the primary coil, which has minimal impact on the secondary coil. In order to simplify the analysis model, only the three circuits of the primary coil, the detection coil and the metal foreign object are analyzed here.As shown in Fig. 1, I_{p} is the primary coil current, M_{kp} is mutual inductance between primary coil and detection coil, M_{pm} is the mutual inductance between the primary coil and metal foreign object, M_{km} is the mutual inductance between detection coil and metal foreign object, I_{k} is the detection coil current, R_{k} is the internal resistance of the detection coil, L_{k} is self inductance of detection coil, I_{m} is the equivalent induced current generated by metal foreign object, R_{m} is the equivalent internal resistance of metal foreign object, L_{m} is the equivalent internal resistance of metal foreign object, R is the external resistance of detection coil, V_k is detection coil induced voltage, ω is the resonant frequency of the system.

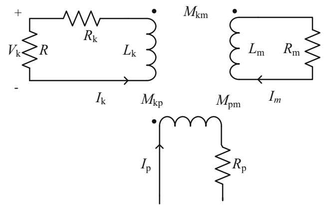

Fig. 1. Modeling of primary coil, metal foreign body and detection coil

When there is no foreign object intervention, deduce the detection coil voltage:

$$V_k = \frac{I_p j\omega M_{kp}}{R_k + j\omega L_k + R} R \tag{1}$$

The voltage difference caused by foreign objects is obtained:

$$\Delta V_k = \frac{I_m j\omega M_{km}}{R_k + j\omega L_k + R} R \tag{2}$$

Substituting the expression of I_m into (2), and the detection coil of passive excitation method can be regarded as open circuit treatment, and the detection coil current is very small, so $I_k \approx 0$, $R \gg j\omega L_k + R_k$. Finally, the voltage change rate is the sensitivity expression:

$$\frac{\Delta V_k}{V_k} = \frac{j\omega \frac{M_{pm} M_{km}}{M_{kp}}}{R_m + j\omega L_m} \tag{3}$$

2.2 Long Rectangular Detection Coils

As shown in Formula (3), the detection sensitivity is positively correlated with M M_{km}. Taking the common single turn rectangular detection coil as an example, the foreign object can be equivalent to a sheet with a surface area of S, and the distance between the foreign object and the four sides of the rectangular detection coil is a_1, a_2, b_1 and b_2, the relationship between these parameters and M_{km} is derived (Fig. 2).

The magnetic field generated by the rectangular detection coil in the plane is in the same direction, which can be superposed with each other to obtain the mutual inductance expression between the detection coil and foreign object. Similarly, formula (4) of N

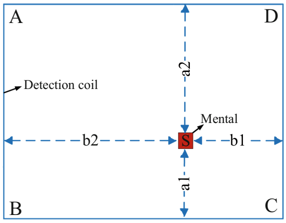

Fig. 2. Metal foreign object and detection coil

turn coil M is obtained. It can be seen that M_{km} is related to a_1, a_2, b_1, and b_2.

$$M_{km} = \frac{NBS}{I_k} = \frac{\mu NS}{4\pi}\left(\begin{array}{l} \frac{a_2}{b_1\sqrt{a_2^2+b_1^2}} + \frac{a_1}{b_1\sqrt{a_1^2+b_1^2}} \\ + \frac{a_2}{b_2\sqrt{a_2^2+b_2^2}} + \frac{a_1}{b_2\sqrt{a_1^2+b_2^2}} \\ + \frac{b_2}{a_2\sqrt{a_2^2+b_2^2}} + \frac{b_1}{a_2\sqrt{a_2^2+b_1^2}} \\ + \frac{b_1}{a_1\sqrt{a_1^2+b_1^2}} + \frac{b_2}{a_1\sqrt{a_1^2+b_2^2}} \end{array}\right) \tag{4}$$

When a foreign object invades, the four parameters a_1, a_2, b_1, and b_2 all tend to be extremely small, and the detection sensitivity is the highest. As shown in Fig. 3, when the metal foreign object moves inside the long rectangular detection coil, it can ensure that the two parameters in a_1, a_2, b_1, and b_2 are close to zero. Therefore, the long rectangular detection coil has a higher detection sensitivity while ensuring a wider detection area, which is suitable for the detection of small metal foreign objects on a large platform.

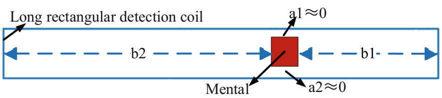

Fig. 3. Metal foreign object and detection coil.

3 Long Rectangular Interconnection Coil Group

3.1 Direct Connection and Reverse Connection of Detection Coil

Reasonable coil interconnection can reduce M_{kp} while increasing M_{km}, which is finally manifested as a larger voltage difference ΔV_{k} generated by the detection coil caused by metal intrusion, so as to improve sensitivity. The difference in the connection of the two coils will lead to two results: the induced potentials superimpose each other after the positive connection, and the induced potentials cancel each other after the reverse connection. as shown in Fig. 4, increasing the number of turns and sequential connection can improve M_{km}, and the latter can eliminate the blind area in adjacent areas. The voltage difference caused by the metal foreign object is increased, and the ΔV_{kc} after interconnection is close to the ΔV_{ka} when the metal foreign object is completely inside the coil, which realizes the elimination of the detection blind zone.

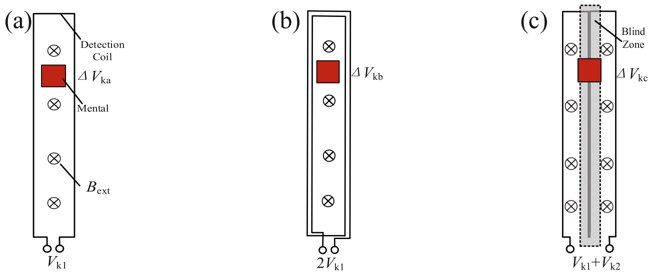

Fig. 4. Method of increasing detection coil M_{km}. **a** Metal intrusion detection coil. **b** Increase turns. **c** Positive connection

However, the two methods mentioned above increase the mutual inductance M_{kp} between the primary coil and the detection coil. It can be seen from Formula (3) that the increase of M leads to the decrease of detection sensitivity. Remote reverse connection is also required. As shown in Fig. 5, M_{km} is increased by increasing the number of turns and adjacent sequential connection. Then, through the remote reverse connection of coil groups 1 and 2, the M_{kp} is reduced. Because the 2 coil group is weakly coupled with A and B, the voltage change caused by A and B will not be affected by the 2 coil group The induced voltage of the final coil group drops from V_1 to $V_1 - V_2$. Finally, the coil set not only increases M_{km}, but also decreases M_{kp}. While improving the sensitivity, the number of voltage to be processed is reduced, and the sampling circuit is simplified.

3.2 Magnetic Field Distribution and Magnetic Line of Force Direction

For high-power WPT platform, this paper uses equivalent model to build square primary side transmission coil and ferrite core simulation model in Maxwell software. As shown in Fig. 6, the side length of primary side square transmission coil is 800 mm, the number of turns is 10, the wire diameter is 7.3 mm, the side length of square ferrite core is 900 mm, and the coil excitation current is selected as 85 kHz effective value 24A. The distribution of magnetic induction intensity is shown in Fig. 6. It can be seen that the distribution of magnetic field presents a downward trend from the coil to the outer ring. The stronger the magnetic induction intensity is, the greater the hysteresis loss and eddy current loss of metal are, and the more serious the heating is. The metal foreign matters in the weak magnetic field area have low coupling with the transmission coil, and the M_{pm} is small and difficult to detect. However, the metal foreign matters in this area have

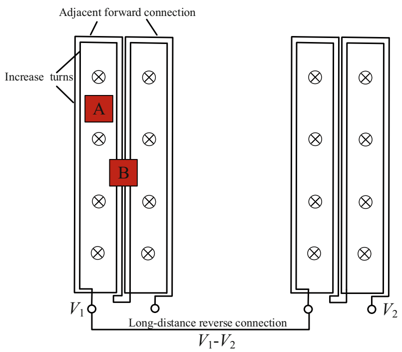

Fig. 5. Interconnect coil group after positive and reverse connection

little impact on the system, and there is no obvious heating itself, so the detection can be omitted. The magnetic field lines of the square transmission coil at a certain moment is shown in Fig. 6. The position where metal foreign objects may invade is divided into areas A and B with a dashed line. In the front view, the magnetic field lines of area B are perpendicular to the paper surface outward, the magnetic field lines of area A are perpendicular to the paper surface inward, and the magnetic field lines near the dotted line are approximately parallel to the paper surface.

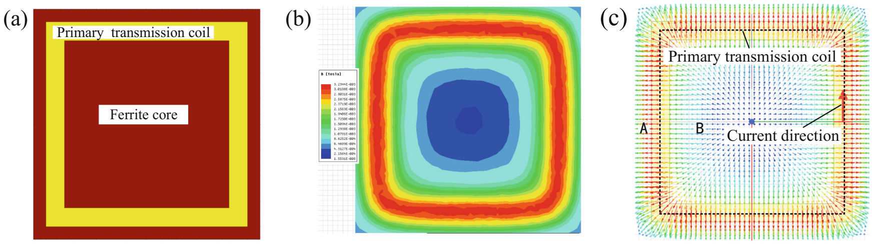

Fig. 6. Simulation of Magnetic Induction Intensity Distribution of Square Coil. **a** Square transmission coil platform. **b** Magnetic field distribution. **c** Magnetic line of force distribution

The detection coil is arranged in area A or B, and the direction of the internal magnetic field line is consistent. When metal invades, the detection coil voltage changes. When the arrangement of the detection coil is at the dotted line position shown in Fig. 6, the direction of the internal magnetic line is different, and the voltage of the detection coil does not change when the metal invades the surface, the detection system fails.

As shown in Fig. 7, when the detection coil is arranged at the dotted line, the left and right magnetic force lines on the coil surface are reversed. When the metal foreign matters invade the detection coil, they have the same effect on the magnetic force lines in the opposite direction. If it is arranged on both sides of the dotted line and the magnetic force lines inside the detection coil are in the same direction, this problem can be avoided. Therefore, when the detection coil is arranged above the transmission coil, the latter shall be located on both sides of the transmission coil as far as possible.

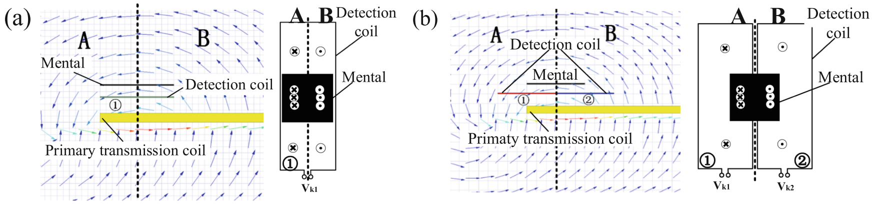

Fig. 7. Distribution of metal foreign matters, detection coils and magnetic lines of force. **a** Double view of the detection coil arranged at the dotted line. **b** Double view of the detection coil arranged on both sides of the dotted line

3.3 Long Rectangular Interconnecting Coil Group

Figure 6 shows that the center of the square transmission coil belongs to the weak magnetic field area. Since the harm of metal foreign matters invading this area is low, it can not be detected when unnecessary. In this paper, it is considered that the detection can be omitted when the magnetic field drops to 0.2 times of the strong magnetic field area. As shown in Fig. 8, the unnecessary detection area is determined to be a square area 120 mm away from the inner edge of the transmission coil, and the long rectangular detection coil structure is designed. Design principle: Unless necessary detection area, the transmission coil platform shall cover the detection coil; The detection coils shall be arranged on both sides of the transmission coil directly above the transmission coil, that is, the area where the magnetic line of force is reversed; On the inner and outer sides of the transmission coil, that is, the area where the magnetic lines of force are in the same direction, the detection coils are arranged side by side; If the detection coil part is located in the unnecessary detection area, the size can be adjusted as required to achieve the purpose of small M_{kp} between the final interconnection coil group and the primary coil and save the coil consumption, while ensuring that the detection coil can be covered in the strong magnetic field area.

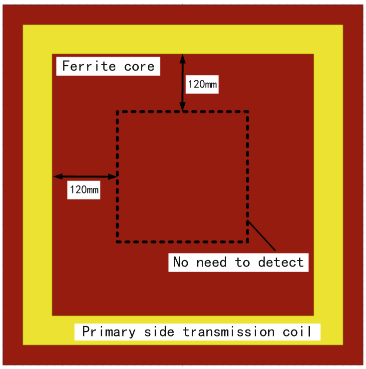

Fig. 8. Unnecessary detection area of square transmission coil

Taking the metal foreign object with a side length of 40 mm as the detection target, according to the design principles obtained from the previous analysis, the coil structure as shown in Fig. 9 is finally obtained. All long rectangular coils are coaxial and connected in sequence with the inner and outer rings. The 1 and 2 (A and B) detection coils are distributed on both sides of the primary coil, and the 3, 4, and 5 (C, D, E) detection coils are arranged close to each other. 4, 5 The part of (D, E) detection coil in the unnecessary detection area can be flexibly adjusted in size. In order to ensure that the strong magnetic field area covers the detection coil, the width of the outer loop coil is appropriately expanded to 100 mm, and the inner loop coil is also expanded to 60 mm. The inner and outer ring coils are connected in coaxial sequence to ensure that the coupling between the metal foreign matters inside the detection coil and the detection coil is high. 1, 2 (A, B) are connected in adjacent sequence, and 3, 4, 5 (C, D, E) are connected in adjacent sequence to ensure that the coupling between the metal foreign matters at the edge of the detection coil and the detection coil is high. Finally, 12 (AB) coil groups and CDE (345) coil groups are connected in reverse from a long distance to complete the design.

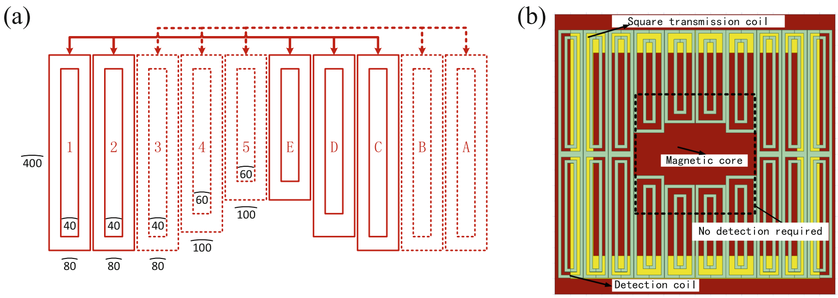

Fig. 9. Long rectangular interconnection coil group. **a** Structure of long rectangular detection coil group. **b** The long rectangular detection coil group is arranged on the surface of the square transmission coil

Combined with Maxwell software to verify the detection effect, take the thin iron sheet with side length of 40 mm as the simulation object, compare the three detection coil structures, and obtain the change rate of induced voltage at each point of the iron sheet intrusion detection area (Fig. 10).

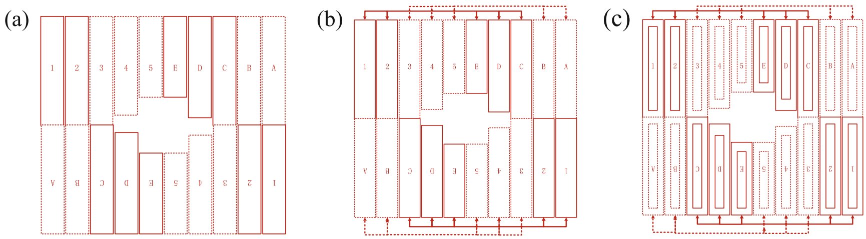

Fig. 10. Comparison of three detection coil schemes. **a** Independent long rectangular detection coil. **b** Double layer interconnected long rectangular detection coil. **c** Inner and outer ring interconnected long rectangular detection coil

The horizontal and vertical movement gradient of 40 mm square iron sheet is 40 mm, and the induced voltage change rate of the three cases is summarized. The results are shown in Fig. 11. The heat map shows the results. The darker the color, the higher the sensitivity. The detection sensitivity of the two schemes with interconnection is obviously higher than that of the scheme with non interconnection independent detection coil. In this paper, the sensitivity of structure detection is more than 5%. When metal invades the strong magnetic field area, the sensitivity basically reaches above 30%, and some weak magnetic field areas can also reach above 10%. To sum up, the designed rectangular interconnect coil group with long inner and outer rings has the best detection effect.

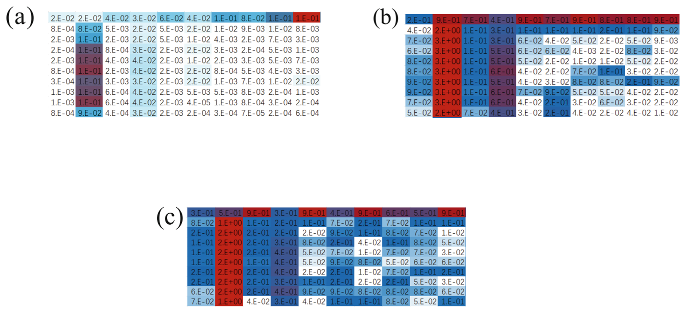

Fig. 11. The sensitivity thermogram of the last three schemes when the sheet iron intrudes into each position in the dotted line frame coil. **a** Independent long rectangular detection coil. **b** Double layer interconnected long rectangular detection coil. **c** Inner and outer ring interconnected long rectangular detection coil

4 Experimental Result

In order to verify the detection effect of the designed detection system, experimental verification is carried out. In this paper, PCB is used to make the interconnect detection coil to avoid errors that may be caused by manual winding. Place the long rectangular detection coil group on the surface of the primary coil, the effective value of the primary coil current is 5A, and the working frequency is 85 kHz. The final experimental platform is shown in Fig. 12.

The final test results show that when the four metals shown in Fig. 13 are thrown into the strong magnetic field area, the output voltage of the detection circuit changes as shown in Fig. 14, and the smallest 50 mm thin iron sheet in the strong magnetic field area reaches 98% detection sensitivity.

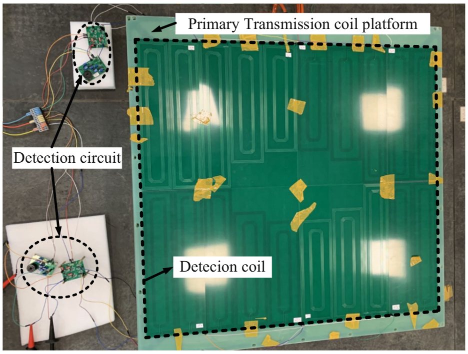

Fig. 12. Primary coil platform and detection system

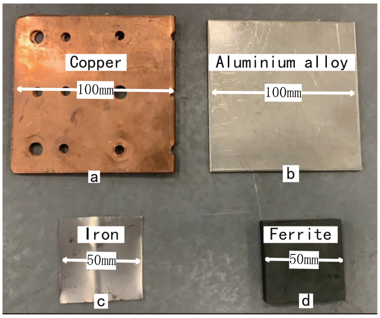

Fig. 13. Four kinds of metal foreign bodies

5 Conclusion

In this paper, the detection coil method is theoretically analyzed, and the advantages of the long rectangular detection coil are explained after the sensitivity formula is obtained. Then, taking the square transmission coil as an example, the magnetic field is analyzed, and a detection coil group with long rectangular interconnection structure is proposed. The effectiveness of the proposed structure is proved by comparative simulation, and is verified by experiments on the 800 mm * 800 mm wireless charging platform. The final detection system realizes the effective detection of aluminum alloy, ferrite, iron and copper. The minimum size of 50 mm iron sheet in the strong magnetic field area can cause a change rate of more than 90% of the induced voltage of the detection coil.

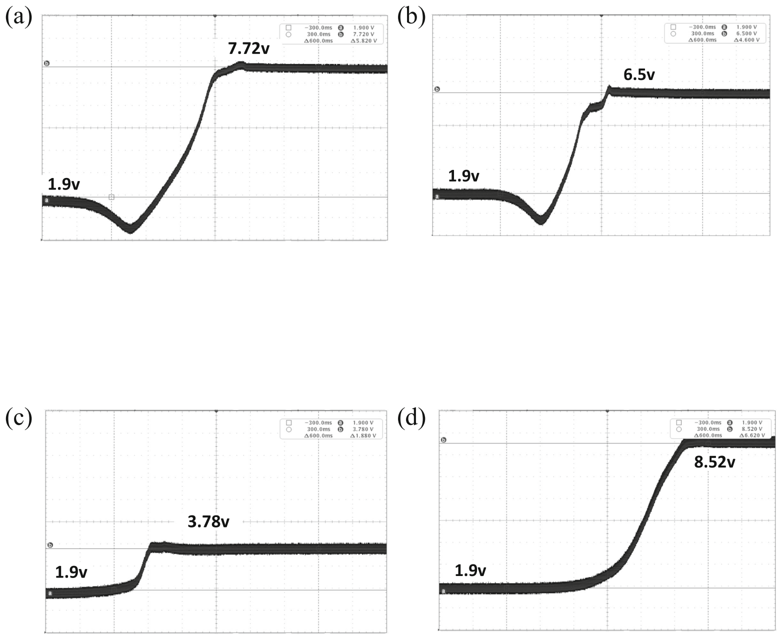

Fig. 14. Variation of Induced Voltage of Coil Filter Rectifier Output When Four Metal Foreign Objects Intrude. **a** 100 mm Copper. **b** 100 mm Aluminium. **c** 50 mm Iron. **d** 50 mm Ferrite

Acknowledgment. This research was partially funded by National Innovation Center of High Speed Train.

References

1. Chen, C., Xueliang, H., Wenhui, S. et al.: The influence of metal obstacles on the magnetic coupling resonance wireless power transfer system. Trans. China Electrotech. Soc. **29**(09), 22–26 (2014). (In Chinese)
2. Liang, H.W.R., Wang, H., Lee, C.-K. et al.: Analysis and performance enhancement of wireless power transfer systems with intended metallic objects. IEEE Trans. Power Electron. **36**(2), 1388–1398 (2021)
3. Changsheng, L., Juan, C., He, Z.: Modeling and analysis of magnetic resonance coupled power transmission system under the influence of non ferromagnetic metals. Autom. Electr. Power Syst. (23), 152–157 (2015). (In Chinese)
4. Yugang, S., Xinyu, H., Xin, D.: Overview of foreign object detection technology in magnetic coupling wireless power transfer system. Chin. J. Electr. Eng. **41**(02), 715–728 (2021). (In Chinese)
5. Xia, J., Yuan, X., Li, J., et al.: Foreign object detection for electric vehicle wireless charging. Electronics **9**, 805 (2020)
6. Jafari, H., Moghaddami, M., Sarwat, A.I.: Foreign object detection in inductive charging systems based on primary side measurements. IEEE Trans. Ind. Appl. **55**(6), 6466–6475 (2019)

7. Fukuda, S., Nakano, H., Murayama, Y., et al.: A novel metal detector using the quality factor of the secondary coil for wireless power transfer systems. In: Proceedings of the 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless power transfer: Technologies, Systems, and Applications, Kyoto, Japan, 10–11 (May); pp. 241–244 (2012)
8. Jeong, S.Y., Thai, V.X., Park, J.H. et al.: Self-inductance-based metal object detection with mistuned resonant circuits and nullifying induced voltage for wireless EV chargers. IEEE Trans. Power Electron. **34**(1), 748–758 (2019)
9. Ying, S., Tian, Z., Kai, S. et al.: High-order composite resonant topology for improving sensitivity of wireless charging foreign object detection system. Trans. China Electrotech. Soc. 1–12 (2022). (In Chinese)
10. Jeong, S.Y., Kwak, H.G., Jang, G.C.: Dual-purpose nonoverlapping coil sets as metal object and vehicle position detections for wireless stationary EV chargers. IEEE Trans. Power Electron. **33**(9), 7387–7397 (2018)
11. Thai, V.X., Jang, G.C., Jeong, S.Y. et al.: Symmetric sensing coil design for the blind-zone free metal object detection of a stationary wireless electric vehicles charger. IEEE Trans. Power Electron. **35**(4), 3466–3477 (2020)