A new metal detection method based on balanced coil for mobile phone wireless charging system

B Zhou¹, Z Z Liu, H X Chen, H Zeng, T Hei
School of Electrical Engineering, Shandong University, Jinan, 250061, China
E-mail: zhoubo_0524@163.com

Abstract. The wireless charging time of mobile phone will increase greatly if the metal objects mix in the magnetic field coupling area. In addition, the fire may be caused as for the high temperature of metal objects. The paper proposed an improved detecting method based on balance coil for mobile phone wireless charging system according to comparing the advantages and disadvantages of traditional metal detection methods. The circuit model was established, and hardware and software were optimized. At last, experimental results verified the theoretical analysis.

1. The introduction
In recent years, with the popularity of smart phones, our mobile phones possess more and more functions and bigger screen, which leads to larger power consumption and charging frequency. Messy wires, frequent plug, along with interface damage, disgust us deeply for the charging process [1]. We need a more convenient and reliable charging way. As a new charging way, wireless charging gets the favor of most people. Through the space magnetic field coupling, electricity was transmitted to batteries. It enables us to make full use of fragments of time to charge phones, which greatly improve the customer experience.

However, with the development of wireless electricity transmission technology, new problem has emerged. When metal objects enter the power transmission area, part of the energy is consumed on the metal because of the eddy current effect. This may lead to the increase of charging time, and more seriously, the sharply rising temperature of metal may cause a fire. Above all, the metal detection problem needs to be solved urgently.

In this paper, a new detection method based on balance coil was proposed, which can be used in mobile phone wireless charging system to detect metal foreign body.

2. The influence of different metal object in mobile phone wireless charging system

2.1. The influence of metal foreign bodies on mobile phone wireless charging time
As shown in Figure 1, this experiment adopts the mobile phone wireless charging device. It includes transmitting part and receiving part. There are three kinds of metal mediums: ¥1 coins (steel material plated with nickel), ¥0.1 coins (aluminum-magnesium alloy), and a piece of iron.

¹ Address for correspondence: B Zhou, School of Electrical Engineering, Shandong University, Jinan, 250061, China. E-mail: zhoubo_0524@163.com.
In order to ensure that the distance of receiving coil and transmitting coil is consistent for each test, we put a cardboard between the receiving coil and the transmitting coil, which is one centimeter thick. We set the initial charging capacity as 63%, and the end of charge capacity as 73%. Then the charging times of the air medium, mixed with ¥ 1 coin, mixed with ¥0.1 coin and mixed with iron medium are recorded relatively. The physical map of testing system mixed with metal foreign body is shown in the Figure 2.

Then, Figure 3 shows the device of wireless charging system.

Finally, the results of experiment are shown in table 1.

| Coupling area media          | Charging time(min) |
|-----------------------------|--------------------|
| Air medium                  | 38                 |
| Mixed with ¥1 coins         | 66                 |
| Mixed with ¥0.1 coins       | 46                 |
| Mixed with iron             | 54                 |

According to the experimental data, the charging time will increase greatly, and the charging efficiency will decrease obviously when there is metal foreign body in the wireless charging system.

2.2. The introduce of metal heating
Metal objects can not only lead to the increase of charging time, also aggravate its heating situation. Because of the eddy current effect, the temperature of the metal rises sharply, which is easy to cause a fire. The ¥1 coin was placed in the energy exchange area. When the charging time reaches five minutes, the temperature of the coin is shown in Figure 4, which is caught by the infrared temperature measuring instrument.

![Figure 4. The temperature of the coin caught by the infrared temperature measuring instrument](image)

The temperature is raised to 50 degrees after five minutes, so it is indeed a risk for charging system. Above all, it is necessary to carry out the metal detection for the mobile phone wireless charging system.

3. The comparison of traditional metal detection methods

At present, there are three kinds of metal detection methods in practice, which include the LC resonance detection technology, the differential frequency detection technology and the balanced coil detection technology.

The core of the LC resonance detection technology is the LC oscillation circuit. The operating frequency will deviate from the resonance point when metal objects mix in the system. By detecting the output voltage, we can judge the existence of objects. However, the LC oscillation circuit can be greatly influenced by environmental changes, which is easy to cause the circuit out of order [2].

The differential frequency metal detector is composed of two groups of oscillators with the same frequency. One is the reference oscillator, and the other is the detecting oscillator. When there is metal object, the frequency of detection oscillator may change, therefore, the value of frequency may be different from the reference detector. According to the difference, we can detect the presence of metal objects. The obvious advantage is the simplification of its circuit. However, as its unsteadiness of overall performance, the method has eliminated since the 1970’s.

The traditional balanced coil metal detection technology contains three circular coils, which possess equal diameter. And also, their central axes keep in a straight line, as shown in Figure 5. With the transmitting coil is in middle, two receiving coils are symmetrically placed on both sides. When the transmitter is coupled with sinusoidal signal, the two receiving coils induce the same electromotive force. However, when there are metal objects, voltages of the two receiving coils are different[3]. By comparing the difference of these two voltages, we can detect the presence of undesirable metal objects. In view of the excellent anti-interference and high sensitivity, the balance coil detection technology has widely used in precise metal detection at home and abroad.
4. A new balance coil metal detection method used for mobile phone wireless charging system

4.1. The introduction of the improved balanced coil

Taking into account the magnetic field of mobile phone charging system, this paper proposes an improved balance coil structure. As is shown in Figure 6, the receiving coil is composed of two parallel symmetrical half circle coils.

![Figure 6. An improved balanced coil structure](image)

Different from the traditional structure, the detection coil is placed close to the launch coil. In order to increase the signal variation caused by metal object, we increase the turn number of the coil. The position of the detecting coil in the charging system is shown in Figure 7.

![Figure 7. The diagram of detection system](image)

Ideally, the electromagnetic field of the left and the right semicircle are the same when there is no metal. According to the principle of electromagnetic induction, the electromotive force induced in the left and right coils are equal, but the direction is opposite [4]. So the voltage of the balanced coil is almost zero after offsetting. However, when the charging system is mixed with metal object, the original magnetic field can be changed, which leads to the changes of coil terminal voltage. Then we can determine the existence of metal object in the magnetic field coupling region.
4.2 The equivalent circuit model of the system
The eddy current effect of the metal in magnetic field can be equivalent to a circuit that consists of an inductance and a resistance [5]. The equivalent circuit model of wireless charging system after mixing with metal foreign body is shown in Figure 8.

![Figure 8. The equivalent circuit model of wireless charging system](image)

The system’s equivalent circuit is composed of four circuits, including the launching loop, the receiving loop A, the receiving loop B, and the eddy current loop. \( R_1, R_2, R_3, R_4 \) are the equivalent resistance; \( L_1, L_2, L_3, L_4 \) are the coefficient of self-inductance; \( M_{12}, M_{13}, M_{14}, M_{23}, M_{24}, M_{34} \) are the coefficient of mutual induction; \( I_1, I_2, I_3, I_4 \) are the current of the four loops; \( U_0 \) is the excitation voltage of the transmitting coil; \( U_A, U_B \) are the terminal voltage of the receiving coil A and B. According to the Kirchhoff’s law, the voltage equations of circuits are established as equation (1).

\[
\begin{align*}
(R_1 + j\omega L_1) I_1 - j\omega M_{12} I_1 - j\omega M_{13} I_3 - j\omega M_{14} I_4 & = U_0, \\
-j\omega M_{23} I_2 + (R_2 + j\omega L_2) I_2 - j\omega M_{24} I_4 & = U_A, \\
-j\omega M_{34} I_3 - j\omega L_3 I_3 + (R_3 + j\omega L_3) I_3 & = U_B, \\
-j\omega M_{13} I_1 - j\omega M_{24} I_2 - j\omega M_{34} I_3 + (R_4 + j\omega L_4) I_4 & = 0 \\
\end{align*}
\]

(1)

According to the special structure of the balance coil in this paper, it has the following equation (2).

\[
I_1 = -I_3 \quad \text{(2)}
\]

The output voltage of the balanced coil is:

\[
U = U_A - U_B \quad \text{(3)}
\]

4.3 Hardware components of the detection circuit
Usually, the voltage signals obtained from the balanced coil are relatively weak, and are always mixed with harmonic component. Firstly, we use the amplifier to amplify the signal, using low-pass filter to eliminate the higher harmonics. The frequency of detection signal is so high that the MCU can’t deal with. By using peak detection circuit, the peak value of AC signal is obtained [6]. At last, the A/D collecting system sends the signal to the microcontroller. Figure 9 is the structure of the hardware circuit.
4.4 Software Process

The system software is responsible for the setting of discharge time of the peak detection circuit, the sampling frequency of the A/D conversion, and the warming voltage.

Actually, the balance coil can’t be completely symmetrical, and there are some factors such as temperature drift and external vibration [7]. All above may lead to a fluctuation in the terminal voltage of the balance coil, which has great influence on the fine metal detection. In order to eliminate the influence, a self-balancing algorithm is adopted in the program. When the power is on, the microcomputer records the initial voltage of the balance coil. Then, the subsequent detection voltage value is modified with the initial voltage value, which can effectively reduce the influence of external factors, and improve the accuracy of detection.

In addition, the charging process of mobile phone may emerge power fluctuations, which easily lead to false operation of the detection mechanism. In order to eliminate the influence of power fluctuation, we continuously collect five voltage signals in the experiment and obtain the average value. Comparing the mean value with the threshold voltage, we can judge whether there is a metal foreign body. This method can avoid the error caused by accidental power fluctuations, and increase the reliability of the detection system. The flow chart of software system is shown in Figure 10.

5. Experiment

Figure 9. The structure of hardware circuit

Figure 10. The flow chart of software system
In order to verify that the proposed balance coil can be used to detect metal, we use a wireless charging device with a coil. The radius of transmitting coil is 25mm as well as the number of turns is 5. The physical diagram of the balance coil is shown in Figure 11.

![Figure 11. The physical diagram of the balance coil](image)

The experimental device comprises a transmitting coil, a receiving coil and a balanced detecting coil. The transmitting coil is a litz wire with the radius of 25mm, the wire diameter of 0.5mm and the turn number of 10. The receiving coil is a copper enameled wire with the radius of 20mm, the wire diameter of 0.1mm, the turn number of 20. The height of the energy exchange area is 5mm. The input signals of transmission coil in the frequency of 155 kHz, and the peak value of voltage is 10.4V. Figure 12 shows the waveform of terminal voltage.

![Figure 12. The terminal voltage waveform of the transmitting coil](image)

5.1. The measured voltage waveform of each link in the experiment

In this experiment, we use ¥1 coin as a sample of metal foreign body. As shown in Figure 13, the paper measures the voltage waveform of balanced coil when there is a metal object or not.

![Figure 13. (a) The voltage waveform of balance coil](image) ![Figure 13. (b) The voltage waveform of balance coil](image)

Figure 13. (a) The voltage waveform of balance coil before the metal is placed  
Figure 13. (b) The voltage waveform of balance coil after the metal is placed

![Figure 13. The voltage waveform of balance coil](image)

Although the signal amplitude of output voltage increased significantly after the metal was placed in energy exchanging area, it’s still only 400 mV. In order to detect the changes of signal, we add the amplifying and filtering element. The waveform is shown in Figure 14.
The AC signal frequency is so high that the microcontroller can’t handle with. So, we add the peak detection circuit. The voltage waveform obtained is shown in Figure 15. The magnitude of DC voltage is 3.2V.

### Table 2. The data of experiment

| Metal material | Balance coil voltage /mV | Peak detection voltage /V | Testing number | Alarming number |
|----------------|--------------------------|---------------------------|----------------|----------------|
| ¥ 1 coin       | 400                      | 3.2                       | 10             | 10             |
| ¥ 0.1 coin     | 310                      | 2.3                       | 10             | 9              |
| Iron medium    | 360                      | 2.6                       | 10             | 10             |

From table 2, we can see that the detection system successfully detects metal object of different media and raises the alarm. It is indicated that the balance coil detection system is safe and reliable.

### 6. Conclusion

The improved metal detection technology introduced in this paper, excellently accomplishes the metal detection task. The experiment proves that this scheme is feasible, and possesses high application values. The metal detection device based on balance coil is high precision and high sensitivity. And, the software algorithm adopted in the experiment, perfectly solves the detection problem caused by the unsymmetrical coil and the power fluctuation of wireless charging.

In addition, there are some problems remained to be solved. As we all know, the main obstacle hindering the development of mobile phone wireless charging is the economy. So we should try to reduce the cost of the raw materials of the metal detection system. Then, there is still room for further optimization of the detecting method, including the way to insure the stability of hardware and the sensitivity of software. At last, the security will be more and more important along with the marketable launch of the wireless charging system. So the metal detection method introduced in this paper will get a wide range of applications in future.

### References

[1] Zhou L Y 2014 *Design of the Wireless Charging System for Mobile Phones* (Chongqing: Chongqing University)

[2] Yamazaki S, Nakane H and Tanaka A 2002 Basic analysis of a metal detector *IEEE
Transactions on Instrumentation and Measurement 51 810-4

[3] Wang Q L 2010 Design of metal detector based on balance coil technique (Jinan: Shandong University)

[4] Qu X D, Yang Y, Liu Z Z and Hou Y J 2014 Metal Detection Technology Based on Balance Coil in Application of Wireless Power Transmission Power Electronics 10 61-3

[5] Lan T Y 2009 Design of metal detection system based on DSP (Chengdu: Southwest Jiaotong University)

[6] Fan L Z and Li S H 2006 Design of an intelligent metal detector based on AT89s52 Acta Scientiarum Naturalium Universitatis NeiMongol 02 185-9

[7] Zhang Z X 2009 The Research of Metal Detector Based on ATmega8515 Single-chip (Jinan: Shandong University)