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A review of foreign object detection (FOD) for inductive power transfer systems

Yiming Zhang [a], Zhengchao Yan [a, b], Jiaqi Zhu [a, c], Siqi Li [a, d], Chris Mi [a, *]

[a] San Diego State University, San Diego, CA, 92182, USA
[b] Northwestern Polytechnical University, Xi'an, China
[c] University of Electronic Science and Technology of China, Chengdu, China
[d] Kunming University of Science and Technology, Kunming, China

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ABSTRACT

Wireless power transfer (WPT) has a promising application prospect due to its convenience and feasibility to special occasions. Inductive power transfer (IPT) uses the magnetic field for power transfer and it is currently the most popular and mature WPT technology. However, the strong magnetic field will heat up metal objects falling in the charging area due to eddy currents generated in the objects. It can also harm animals or toddlers staying in the charging area. To deal with these issues, foreign object detection (FOD), including metal object detection (MOD) and living object detection (LOD), should be developed for the safe operation of IPT systems. FOD can be divided into system parameter detection methods, wave-based detection methods, and field-based detection methods. System parameter detection methods are normally used in low-power systems for MOD. Wave-based detection methods are suitable for high-power applications, for both MOD and LOD. Field-based detection methods work for both high-power and low-power applications, for both MOD (in an inductive way) and LOD (in a capacitive way). This paper reviews and summarizes the state-of-the-art development of FOD technology in IPT systems.
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1. Introduction

The utilization of electric energy has greatly enhanced the quality of human's life with abundant electric equipment. Normally, power is transferred from the source to the load via the direct contact of metals. This conventional power transfer has caused many problems, such as safety, convenience, reliability, and feasibility. Wireless Power Transfer (WPT) technology is introduced to solve these issues. WPT can be applied where the conventional power transfer is hazardous, inconvenient, unreliable, or even impossible. Typical application scenarios include railway transport [1], electric vehicles (EVs) [2], consumer electronics [3], implantable medical devices [4], and some special occasions like mining and underwater applications [5].

Electromagnetic wave and mechanical wave [6] are two major energy carriers for WPT, of which the former is more popular. The category based on the energy carrier is shown in Fig. 1. Electromagnetic radiation WPT, based on the far field and divided into microwave [7] and laser [8], can achieve long-distance power transfer, but it is costly, low in efficiency, and has safety issues. Capacitive induction WPT, or capacitive power transfer (CPT), uses the electric field between metal plates to transfer power wirelessly [9,10]. Because the electric field does more harm to the human than the magnetic field, CPT is still in study and much work needs to be done before it can be applied commercially.

Magnetic induction WPT, or inductive power transfer (IPT), is the most popular WPT technology that has been extensively researched and applied in both academia and industry due to its relatively long transfer distance, large transfer power, and high transfer efficiency [11–17]. It has been applied commercially in wireless charging for EVs and cellphones. A typical topology for wireless EV charging is depicted in Fig. 2.

A high-frequency AC current flows through the transmitting coil (TX), generating magnetic flux, part of which is linked to the receiving coil (RX). When the load is connected to the RX, power is transferred wirelessly from the TX to the RX. The TX and the RX are normally flat spiral coils and are called charging pads [2]. By utilizing the ferrite plate and the aluminum plate, as shown in Fig. 2, the magnetic field outside the charging pads can be greatly mitigated. However, the magnetic field between the charging pads

* Corresponding author
E-mail address: mi@ieee.org (C. Mi).

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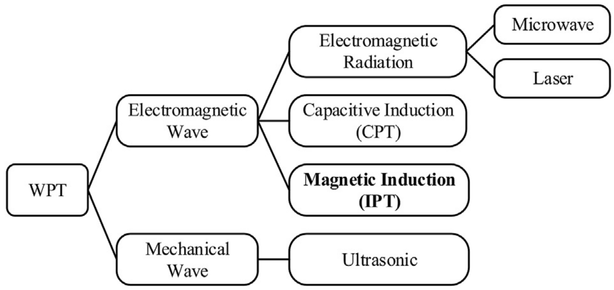

Fig. 1. Category of WPT technology.

during power transfer would still be strong. If some conducting material, such as metal object (MOs) like a key, a clip, a coin, a screw, or a tinfoil, falls between the pads during power transfer, an eddy current will be generated in the conducting material, leading to overheating and potential hazards like fire. Meanwhile, the strong magnetic field can also cause danger to animals staying between the pads, especially for wireless EV charging systems where the charging distance is sufficient for a cat or a dog to enter the charging space. Other possible scenarios include toddlers grabbing a ball rolling under the vehicle or drivers outstretching the arm to pick up the car key that drops in the charging zone [18]. To deal with these problems, the WPT system should be able to detect foreign objects (FOs) between the charging pads, including conducting material like MOs and living objects (LOs). Foreign object detection (FOD) technology, divided into metal object detection (MOD) and living object detection (LOD), is the key to solve these issues. FOD technology is one of the main obstacles that hinder the development and application of IPT. Here MOD can also refer to detecting nonmetal conducting material like graphite.

FOD is not restricted to IPT systems. In fact, FOD exists in many fields, such as food industry [19–21], airport runway [22–26], security inspection (airport, building, event, etc.), and item recovery [27].

In the Qi standard, version 1.1.2, for low-power WPT applications, the power loss across the interface is mentioned as one of the possible methods to limit the temperature rise of FOs. In the common practice of J2954, version 2016–05, for high-power WPT applications from the Society of Automotive Engineers (SAE), no specific methods have been put forward. However, some test conditions of temperature rise test and ignition test have been proposed. In temperature-rise test, the wireless charger should be operated at full power transfer and the debris items being tested should be positioned at the specific locations to determine if there are any unacceptable thermal effects. During this test, the test object should be placed on paper to see if it smokes or catches fire, which is the ignition test.

In this paper, the FOD technology is categorized according to its detecting objects, principle, and applications in Section 2. The MOD technology is described in Section 3 with different detection methods, followed by the LOD technology in Section 4. Section 5 concludes the paper.

2. Category of FOD

According to the difference in the detecting objects, FOD can be divided into MOD and LOD, as shown in Fig. 3. LOD only exists in high-power applications, such as wireless charging for EVs, where the charging space is large enough for animals to enter. As for MOD, both high-power applications and low-power applications encounter the issue of overheating MOs, including small objects like coins.

According to the difference in principle, FOD technology can also be divided into different detection types, as shown in Fig. 4.

In system parameter detection methods, there are two kinds of system parameters, namely electrical parameters and non-electrical parameters. There is no need for extra equipment by using the detection method based on electrical system parameters. The impact of an FO on the electrical system parameters is large in low-power applications but small in high-power applications. Therefore, it is only suitable for low-power applications for MOD. The detection method based on non-electrical system parameters requires some extra sensors to obtain these parameters. It can be employed in both high-power and low-power applications for both MOD and LOD. Wave-based detection methods and field-based detection methods both need extra equipment to detect an FO. Wave-based detection methods, also referred to as optical detection methods [28], are normally used in high-power applications as the detection methods for MOD and LOD. Field-based detection methods can be used in both high-power and low-power applications, also for both MOD and LOD.

The comparison of different detection methods is illustrated in Table 1.

3. MOD

System parameter detection methods, wave-based detection methods, and field-based detection methods can all be applied to MOD. Electrical system parameter detection methods are suitable

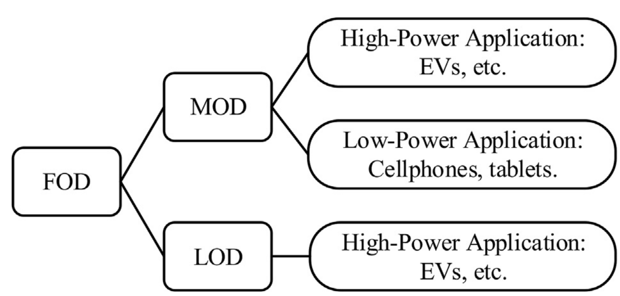

Fig. 3. Category of FOD technology in IPT systems.

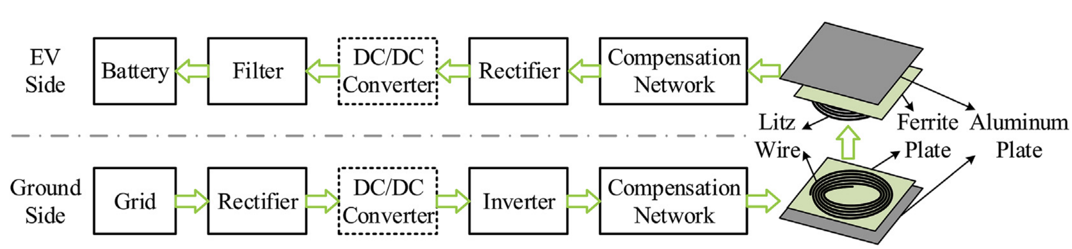

Fig. 2. Typical topology of wireless charging for EVs.

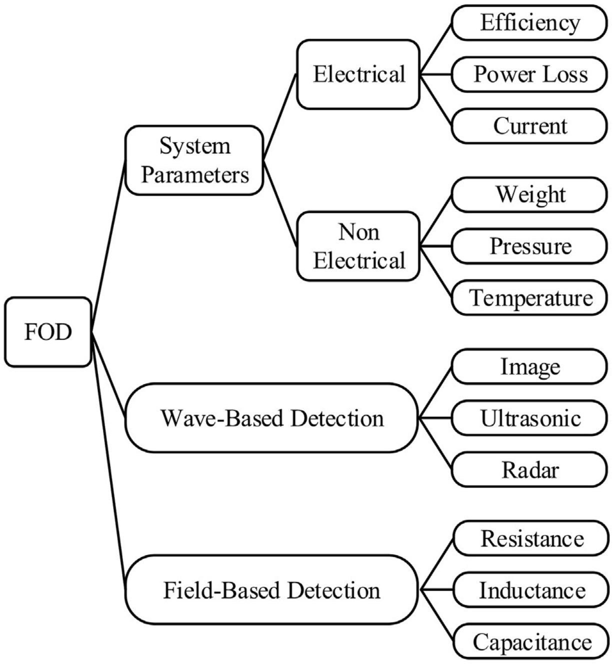

Fig. 4. Category of FOD detection methods.

for low-power applications, wave-based detection methods are mainly for high-power applications, and non-electrical system parameter detection methods and field-based detection methods work for both high-power and low-power applications.

3.1. System parameter detection methods

For non-electrical system parameter detection methods, the parameters including pressure [29] and temperature-rise because heat can be an indicator for the existence of an MO. Pressure sensors are employed to detect the change in pressure but they cannot distinguish the difference between metal and nonmetal objects. Thermal sensors are used to detect the temperature-rise caused by an MO [30,31]. In Ref. [31], a sheet of thermally conductive and electrically nonconductive material is placed on top of the transmitting coil to transfer the heat. Thus, fewer thermal sensors are needed to detect the temperature rise.

The detection methods based on electrical system parameters rely on the electrical parameters to detect an MO, such as power loss, the efficiency, current, and transmitting coil inductance/quality factor. Due to the fact that eddy currents are induced in the MO in the charging zone, extra power is extracted from the transmitter. When the transferred power is small, the extra power loss in the MO is significant and can be detectable. Thus, this kind of method is only suitable for low-power applications, such as wireless charging for consumer electronics.

With the existence of an MO, the power loss of the transfer system is increased. Thus, the power loss can be an indicator to distinguish the MO [32,33]. With a fixed output power, the input power [34,35] or the transmitter current [36,37], varying with the existence of an MO, can also be used to detect an MO. The efficiency also changes with the existence of an MO [38]. A part of the flow chart of the detecting algorithm using the input power in Ref. [34] is shown in Fig. 5. When the input power exceeds the threshold, it is determined that there is an MO and actions will be taken to handle the MO.

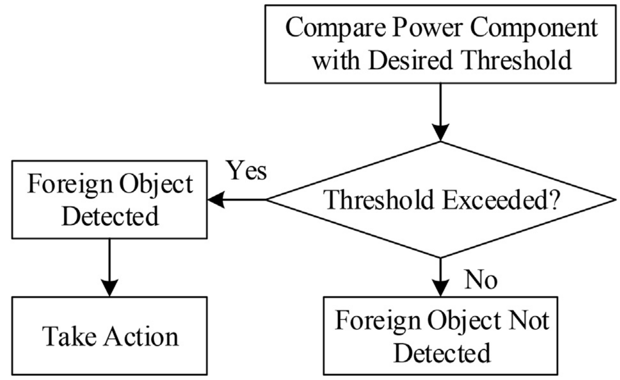

Fig. 5. Flow chart of detecting algorithm [34].

Also, in low-power applications where the TX and RX coils are both small, the presence of an MO affects coil parameters, such as the inductance [39], the quality factor [40,41], the complex resistance [42], and the coupling coefficient between the transmitting coil and the receiving coil [43]. All these electrical parameters can be the indicator for the FOD system.

The reason for the reduced coil inductance and quality factor is explained as follows. The presence of a nonferrous MO on the surface of a coil and its equivalent circuit are shown in Fig. 6. L_{coil} is

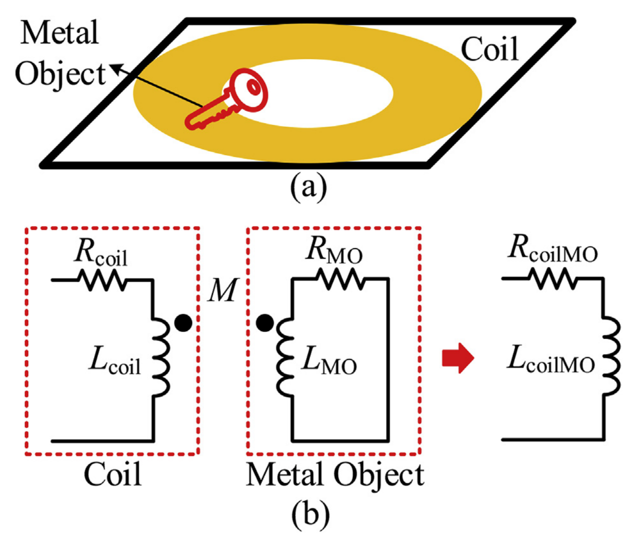

Fig. 6. Model of coil with an MO. (a) Schematic. (b) Equivalent circuit.

Table 1
Comparison of detection methods.

Methods	Power Level of Application	Type of Application	Cost	Precision
Electrical System Parameter	Low-Power	MOD	Low	Low
Non-Electrical System Parameter	High-Power and Low-Power	MOD and LOD	Low	Low
Wave-Based	High-Power	MOD and LOD	High	High
Field-Based	High-Power and Low-Power	MOD and LOD	Medium	Medium

the coil inductance, R_{coil} is the coil equivalent resistance, L_{MO} is the inductance of the MO, R_{MO} is the equivalent resistance of the MO, M is the mutual inductance between the coil and the MO, L_{coilMO} and R_{coilMO} are the equivalent inductance and the equivalent resistance of the coil with the MO, respectively.

The MO can be regarded as an inductance with its equivalent resistance, coupled with the coil. The input impedance of the coil with the MO can be expressed as

$$\begin{aligned} Z_{in} &= R_{coil} + j\omega L_{coil} + \frac{(\omega M)^2}{R_{MO} + j\omega L_{MO}} \\ &= \left(R_{coil} + \frac{(\omega M)^2 R_{MO}}{R_{MO}^2 + (\omega L_{MO})^2}\right) + j\omega\left(L_{coil} - \frac{(\omega M)^2 L_{MO}}{R_{MO}^2 + (\omega L_{MO})^2}\right) \end{aligned} \tag{1}$$

Therefore,

$$L_{coilMO} = L_{coil} - \frac{(\omega M)^2 L_{MO}}{R_{MO}^2 + (\omega L_{MO})^2} \tag{2}$$

$$R_{coilMO} = R_{coil} + \frac{(\omega M)^2 R_{MO}}{R_{MO}^2 + (\omega L_{MO})^2} \tag{3}$$

We can see from (2) and (3) that with an MO, the coil equivalent inductance decreases and the coil equivalent resistance increases, compared with the case without an MO. It is worth mentioning that with the misalignment of the receiving coil, the coil inductance also varies due to the different positions of the receiver ferrite. The FOD system should be able to distinguish the difference between the existence of an MO and coil misalignment.

For a ferrous MO, it can be regarded as a ferrite on the coil. Thus, the equivalent inductance may be increased.

3.2. Wave-based detection methods

In wave-based detection methods, extra sensing equipment is needed to detect the existence of an MO. Sensors, such as imaging cameras, thermal cameras, ultrasonic sensors, and radar sensors, can be employed to detect the presence of an MO. Image identification technology can be used for imaging cameras to identify an MO. Thermal cameras use the heat generated by an MO for detection. Ultrasonic and radar sensors measure the distance to the target point that may be obstructed by an MO for detection.

Frequency-modulated continuous-wave (FMCW) radar is a short-range radar capable of determining a distance. The working principle of FMCW radar sensor is illustrated in Fig. 7 [18].

The transmit signal can be expressed as

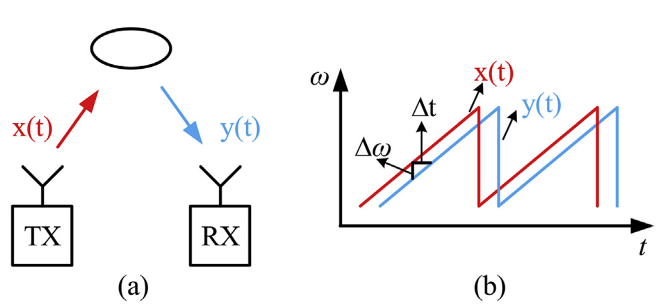

Fig. 7. Principle of FMCW radar sensors. (a) Block diagram. (b) Frequency varying with time [18].

$$x(t) = \cos(\varphi(t)), \qquad \varphi(t) = \varphi_0 + \omega_0 t + \frac{K_r}{2}t^2 \tag{4}$$

where φ_0 is the initial phase, ω_0 is the start frequency, and K_r is the bandwidth-duration ratio.

The angular frequency can be calculated as

$$\omega(t) = \frac{d\varphi(t)}{dt} = \omega_0 + K_r t \tag{5}$$

There is a time delay Δt between the transmit signal and the receive signal. Also, there is a frequency difference $\Delta\omega$ between the transmit signal and the receive signal at the same time. This frequency difference can be extracted by the multiplication of the transmit signal and the receive signal followed by a low-pass filter, resulting in a cosine with the frequency difference. Once $\Delta\omega$ is obtained, Δt can be calculated by

$$\Delta t = \frac{\Delta\omega}{K_r} \tag{6}$$

The time delay indicates the measured distance. Once an MO obstructs the signal path, the time delay would be shortened. Thus, the MO can be detected.

There are two ways to install these sensors, either on the ground side or on the EV side. If the sensors are installed on the ground side, it helps reduce the cost and volume of the vehicle. However, multiple sensors may be needed since there is no good viewpoint on the ground side to cover the whole charging area. If the sensors are installed on the EV side, they can be combined with the advanced driver assistance system for positioning and other purposes. Sensors can be installed outside the covering area of the receiver to avoid the influence of power transfer. Moreover, only one sensor may be needed since there is a good view if installed on the EV side.

In Ref. [44], either one of a thermistor, a thermal camera (eg. infrared sensors), a radar sensor, or an imaging camera can be installed on the ground side to detect the existence of an MO, as shown in Fig. 8. The thermistor can provide temperature-related information to the controller. The thermal camera can provide a thermal image and may provide visual detection of an MO as the image camera does. The radar sensor can provide an electronic means to detect an MO.

By sending radar signals from radar transmit antennas to radar receive antennas, the distance between them can be known. If an MO blocks in the way, there would be no signal or the measured distance would change. In this way, the existing MO in the sensing area can be detected. Different arrangements of radar sensors were proposed to detect the existence of MOs in Ref. [45]. One stated arrangement is that a transmit antenna is placed on the center and multiple receive antennas are placed on the periphery, as shown in Fig. 9.

In Ref. [46], the temperature sensor is combined with the light camera to detect the existence of an MO. In Ref. [47], the thermal

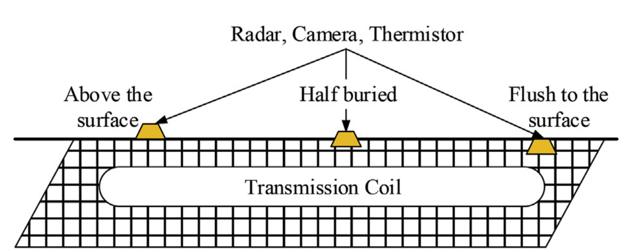

Fig. 8. Function block diagram of a wireless charging system with FOD [44].

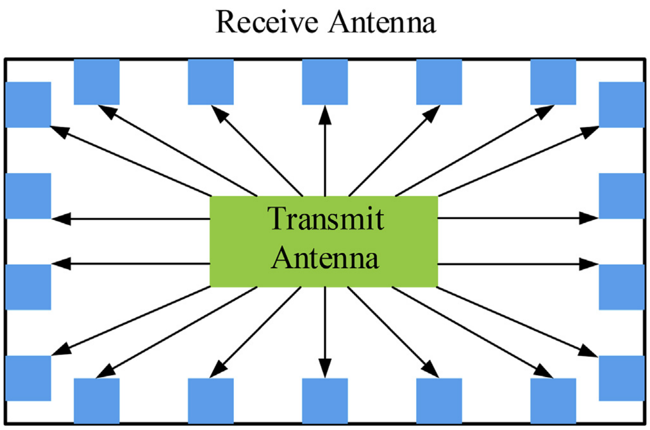

Fig. 9. One radar antenna arrangement [45].

camera and the ultrasonic transducer together perform the function of MOD.

Patent [48] shows the arrangement of the detectors installed on the EV side, placed in the front, in the rear, and on the side.

3.3. Field-based detection methods

Field-based detection methods are the most popular detection methods among these three kinds of methods. An MO item can affect the magnetic field distribution around it. Thus, the field-based detection methods via inductive coupling can be employed for MOD. A detection coil or coil array should be placed on the top of the TX to detect MOs, as shown in Fig. 10. The inductances and the quality factors of the detection coils change with an adjacent MO, the same as shown in Subsection 3.1 Large MOs are easier to be detected than small MOs. Thus, detecting small MOs is of primary importance. If the dimension of the detection coil is much larger than the MO, the parameter variation of the detection coil would not be significant to distinguish the existence of an MO. Therefore, a detection coil array with a size small enough is normally adopted to detect MOs.

It is worth to note that the receiving coil misalignment can also cause the inductance variation of the detection coils due to the different positions of the receiver ferrite. However, this impact is limited because the transfer distance is normally large and the receiver ferrite has a limited impact on the inductances of the detection coils. Moreover, the coil misalignment has impacts on all the detection coils while the existence of an MO with a small size can only affect the adjacent detection coils. By using this characteristic, the coil misalignment and the existence of an MO can be distinguished.

The inductance variation of the detection coil is used to detect the existence of an MO [49–53]. In Ref. [52], the detection coil consists of multiple loop coil sets mounted on the TX. Series resonance and parallel resonance are compared. It is found that the parallel-resonant circuit is more sensitive to MOs and less sensitive to noise than the series-resonant circuit due to its large input impedance. The detection system is operated off the resonant

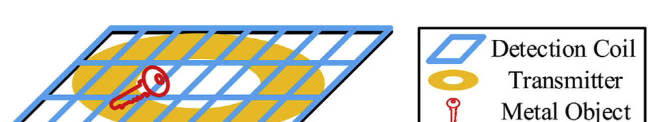

Fig. 10. Schematic of detection coil with an MO.

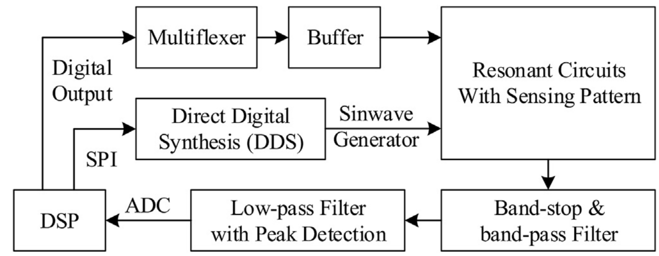

Fig. 11. Overall circuit configuration of the FOD system [52].

frequency to avoid the blind zone and achieve higher sensitivity. The overall circuit configuration of the FOD system is shown in Fig. 11.

In Ref. [53], different detection coil geometries are compared including a conventional rectangular coil, a rectangular double loop coil, a hexagonal coil, a double-D coil, a quadruple-D coil, and some clover leaf-shaped coils, as shown in Fig. 12. A five euro cent coin with a diameter of 21.25 mm and a thickness of 1.67 mm is placed 3 mm above the detection coil along different traces. The inductances are measured and compared with the conventional rectangular coil. It is discovered that compared with the conventional rectangular coil, all the other coils provide “a higher, more uniform sensitivity over the cross section of the respective sense coils without substantially decreasing peaks in that sensitivity”.

The equivalent resistance of the detection coil changes with the presence of an MO. Thus, for a given pulse excitation on the detection coil, the response would be different for the case with and without an MO [54], as shown in Fig. 13. By counting the number of pulses or measuring the amplitude of the response, the presence of an MO can be detected.

Patent [55] uses the variation of the electrical characteristics such as the equivalent resistance, the equivalent inductance, the equivalent impedance, and the impulse response of the detection coil as the indicator for the presence of an MO. The relative motion between the detection coil and an MO will induce a change in these electrical characteristics and Patent [56] employs this principle to determine the presence of an MO. The heat generated by the eddy currents in an MO will result in temperature rise. The electrical characteristics, such as the equivalent resistance, the equivalent inductance, the equivalent impedance, and the impulse response of the detection coil, vary with the temperature and this can be used as a detection method [57]. The MO affects the electrical characteristics of the detection coils in different positions differently. Patent [58] takes advantage of this principle and investigates the difference in the electrical characteristics of adjacent detection coils

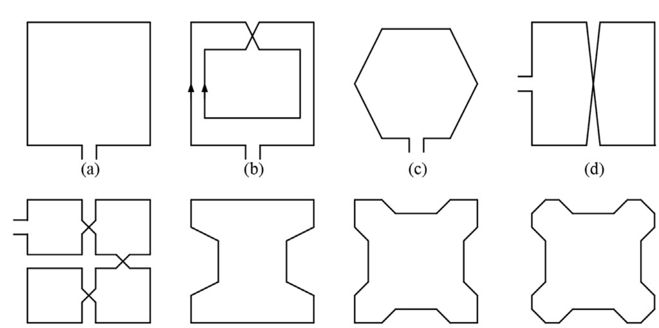

Fig. 12. Different coil shapes. (a) Conventional rectangular coil. (b) Rectangular double loop coil. (c) Hexagonal coil. (d) Double-D coil. (e) Quadruple-D coil. (f) Clover leaf-shaped coil 1. (g) Clover leaf-shaped coil 2. (h) Clover leaf-shaped coil 3 [53].

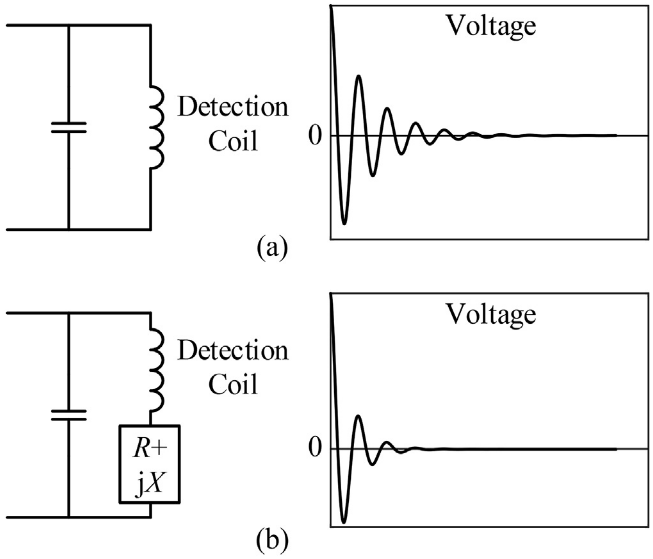

Fig. 13. Response of pulse excitation in the detection coil. (a) Without an MO. (b) With an MO [54].

to determine the presence of an MO. Patent [59] senses the electrical characteristics at harmonics to determine the presence of an MO.

Resonant circuits are necessary for the MOD system to amplify the impedance variation. For small MOs, the inductance variation of the detection coil can be within several percentage. With the amplification of the resonant circuit, the impedance variation of the resonant circuit can be dozens of percentage. Basically there are two kinds of resonant circuits: series resonance and parallel resonance, as shown in Fig. 14.

With the presence of an MO, assume the coil inductance $L_{det}' = \alpha \times L_{det}$ and the coil resistance $R_{det}' = \beta \times R_{det}$ (α<1 and β>1). Without resonance, the impedance amplitude ratio of the detection coil with and without an MO can be calculated as

$$\frac{|j\omega L_{det}' + R_{det}'|}{|j\omega L_{det} + R_{det}|} = \frac{\sqrt{(\alpha\omega L_{det})^2 + (\beta R_{det})^2}}{\sqrt{(\omega L_{det})^2 + (R_{det})^2}} \approx \alpha \tag{7}$$

where normally the coil reactance is much larger than its equivalent resistance.

Take series resonance as an example. The operating frequency is set at the original resonant frequency of the resonant circuit. The input impedance amplitude ratio of the resonant circuit with and without an MO can be calculated as

$$\frac{\left|j\omega L_{det}' + \frac{1}{j\omega C_S} + R_{det}'\right|}{\left|j\omega L_{det} + \frac{1}{j\omega C_S} + R_{det}\right|} = \frac{\sqrt{[(1-\alpha)\omega L_{det}]^2 + (\beta R_{det})^2}}{R_{det}} = \sqrt{\left((1-\alpha)\frac{\omega L_{det}}{R_{det}}\right)^2 + \beta^2} > (1-\alpha)Q_{det} \tag{8}$$

where Q_{det} is the quality factor of the detection coil.

We can see from (8) that the input impedance is amplified by the quality factor of the detection coil. When Q_{det} is large enough, the amplitude ratio can be large to have a high sensitivity. Therefore, the quality factor of the detection coil should be large. Similar derivation can be obtained for parallel resonance. The difference between the series resonance and parallel resonance is that the parallel resonance has a large input impedance so that it is more insensitive to noise than the series resonance [52].

Based on the same principle of inductance variation, Patent [60] further utilizes various coupling circuits to sense the variation induced by an MO, including inductive coupling and capacitive coupling, as shown in Fig. 15.

Besides affecting the inductance and the equivalent resistance, the existence of an MO will also affect the mutual inductance between the transmitting coil and the detection coil. In other words, the induced voltage will be affected by an MO. There are two kinds of detection methods that are based on the induced voltage variation. The first one uses the magnetic field of power transfer to induce a voltage on the detection coil, i.e., the TX acts as the source coil for the induced voltage. This method is called the passive method since it utilizes the magnetic field of the power transfer and no extra source is employed. The other one is that an extra coil set is introduced to generate the magnetic field for the induced voltage, i.e., the extra detection coil acts as the source coil for the induced voltage. This method is called the active method since it has an independent source coil to generate the magnetic field that is different from the one of power transfer. The passive method is simple and low in cost, but it cannot conduct off-line MOD. Also, the magnetic field of the power transfer varies during different charging stages and this affects the precision of MOD. The active method can achieve an independent MOD method, but it is complex and high in cost, and may be influenced by the magnetic field of power transfer.

The passive detection methods can be found in Refs. [61–65]. Two detection coils are connected in reverse directions, forming balanced coils, to cancel out the induced voltage. If an MO is placed on the balanced coils, the induced voltage would no longer be zero. Thus, the MO can be detected. Patent [64] shows different coil shapes to achieve decoupling between the TX and the detection coil, illustrated in Fig. 16. However, there are blind spots using this detection method. At particular positions, the MO may have the same impact on the detection coils so that the induced voltage

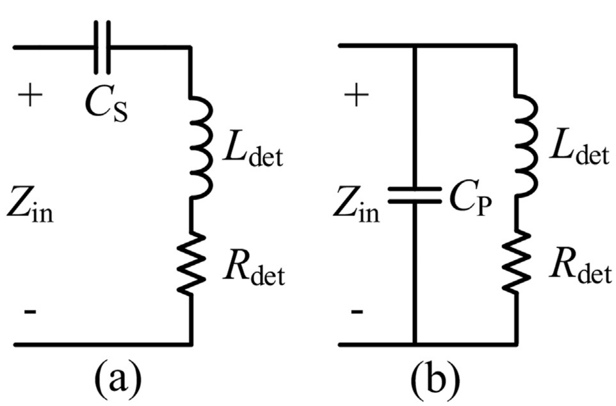

Fig. 14. Resonant circuits. (a) Series resonance. (b) Parallel resonance.

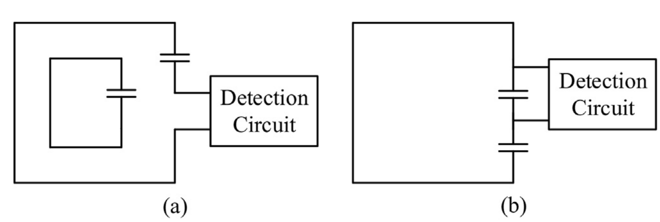

Fig. 15. Coupling circuits. (a) Inductive coupling. (b) Capacitive coupling [60].

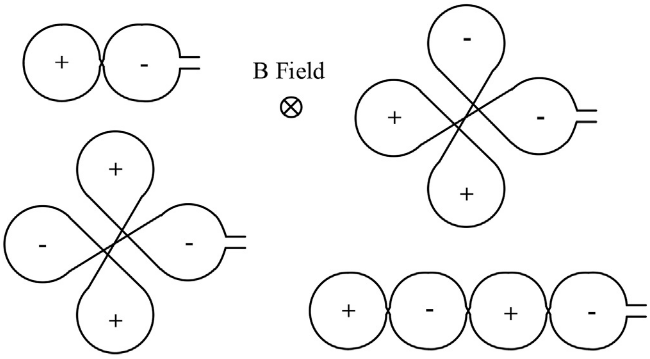

Fig. 16. Four different detection coils to decouple with the TX [64].

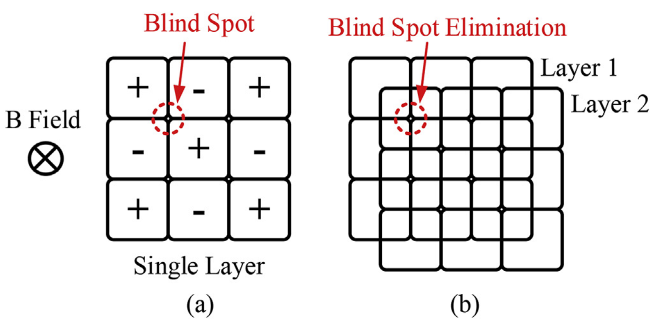

Fig. 17. Detection coil array. (a) Single-layer detection coil array with blind spots. (b) Double-layer detection coil arrays to eliminate blind spots [64].

remains close to zero, as shown in Fig. 17(a). A solution for this problem is to add another detection coil array with an offset, as shown in Fig. 17(b).

In Ref. [65], non-overlapped balanced coils are utilized. The null voltage area is tuned to achieve the same induced voltage on the D coil and the Q coil, as shown in Fig. 18. When there is an MO, the induced voltage difference would no longer be zero. To be able to detect the position of an MO and the vehicle, longitudinal and lateral coil sets are combined to fully cover the whole charging area. Similar to Ref. [64], there are also blind spots and another coil array with an offset is added to eliminate the blind spots.

The active methods can be found in Refs. [60,66–68]. Two detection coil sets are adopted as a transmitter loop (indicated with solid lines) and a receiver loop (indicated with dashed lines), shown in Fig. 19 [68]. The transmitter loop and the receiver loop are decoupled by using a unipolar coil and a bipolar coil or two perpendicular bipolar coils. The transmitter loop is driven with a signal at a frequency between 1 MHz and 10 MHz. The induced voltage on the receiver loop would be zero with the absence of an MO, and it would not be zero in the presence of an MO. Thus, when the induced voltage on the receiver loop is not zero, it can be known that an MO exists. Similar to the passive method, there are also blind spots by using this method.

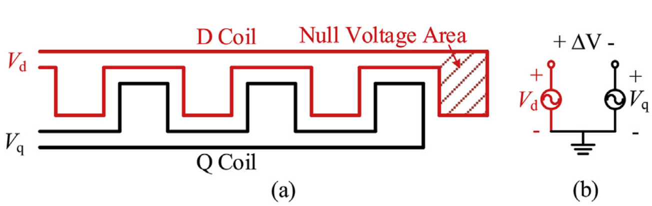

Fig. 18. Non-overlapped coil set. (a) Configuration. (b) Principle to obtain the induced voltage difference [65].

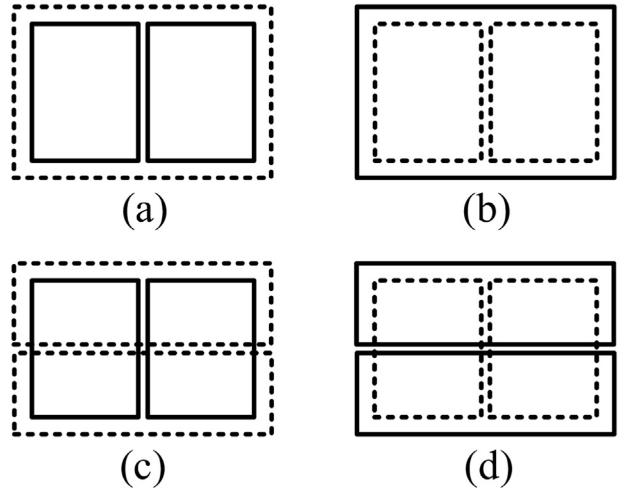

Fig. 19. Schematic diagram of transmitter loop and receiver loop. (a) A bipolar coil as transmitter loop and a unipolar coil as receiver loop. (b) A unipolar coil as transmitter loop and a bipolar coil as receiver loop. (c) and (d). Two perpendicular bipolar coils as transmitter loop and receiver loop.

4. LOD

The detection for LO is mainly for high-power applications where animals or toddlers can stay in the charging area. Wave-based detection methods and field-based detection methods are two major detection methods for LOD.

4.1. Wave-based detection method

Ultrasonic or radar sensors can be utilized to measure the distance. An existing or a moving LO changes the measured distance. Thus, the distance variation can be an indicator for LOD.

The working principle of radar used for LOD is similar to that for MOD. There are also two ways to install the sensors: on the ground and on the vehicle.

Radar antennas are utilized to detect the LO [18,69–71]. In Ref. [71], the antenna transceivers are integrated into the base pad of a WPT system, as shown in Fig. 20.

Patent [46] combines the thermal sensor and light camera to detect the possible LO in the charging area, as shown in Fig. 21.

4.2. Field-based detection method

The LO has a negligible impact on the inductance and equivalent

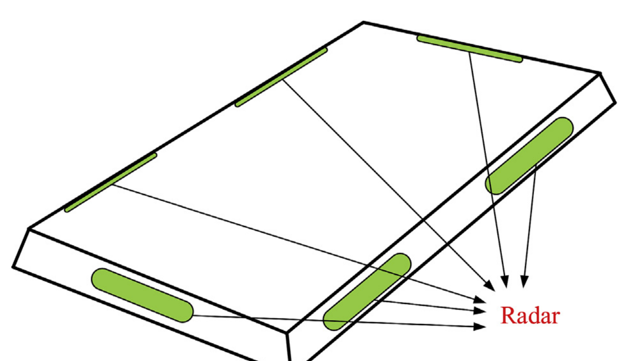

Fig. 20. Schematic of LOD system with integrated antenna transceivers [71].

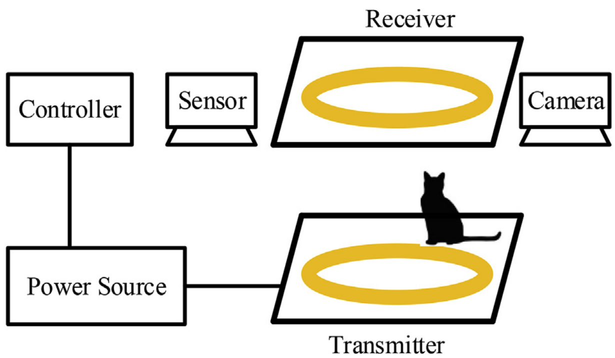

Fig. 21. LOD system with thermal sensor and light camera [46].

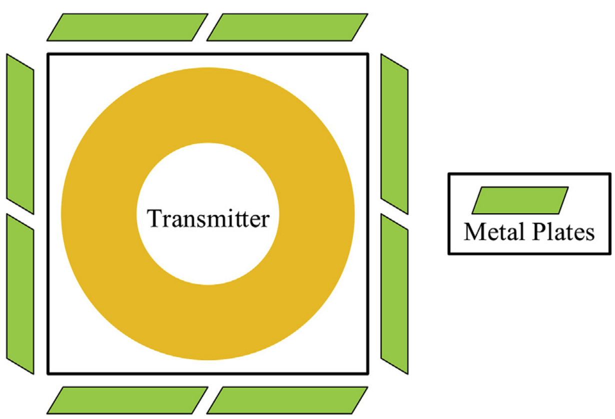

Fig. 22. LOD system with capacitive detection [72].

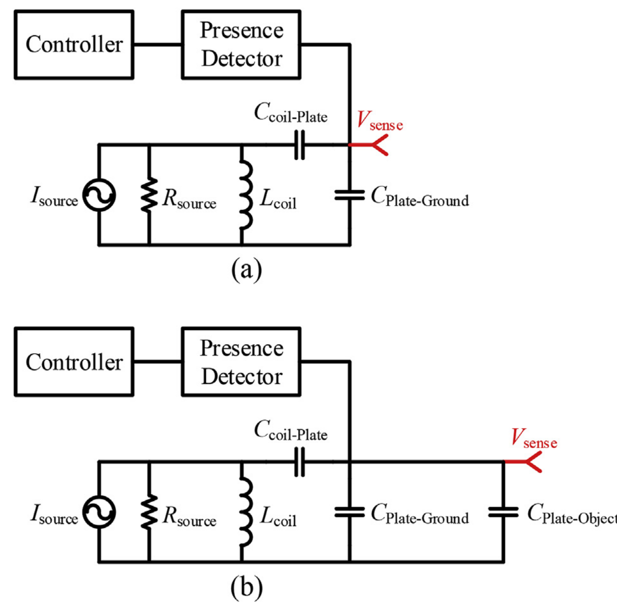

Fig. 23. Equivalent circuit of LOD system. (a) Without an LO. (b) With an LO [72].

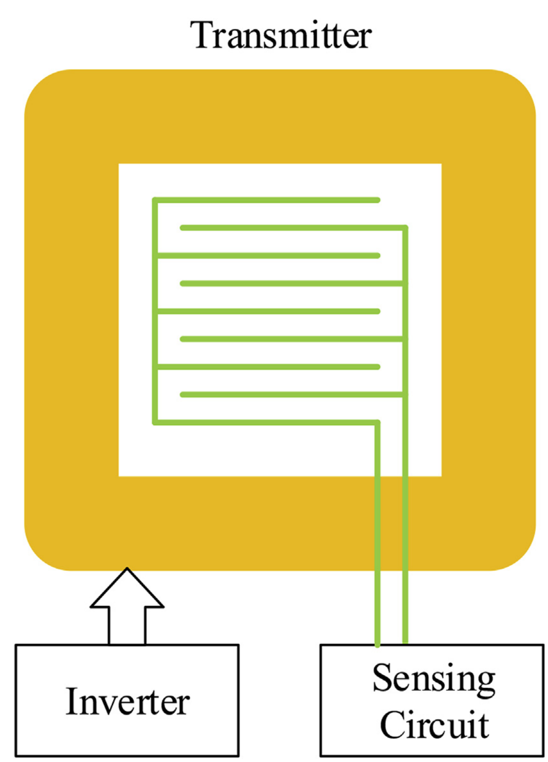

Fig. 24. Overall configuration of the LOD system [74].

resistance. However, it can affect the capacitance around it. Patent [72] adds eight metal plates around the charging pad, as shown in Fig. 22. The equivalent circuits of the LOD systems without and with an LO are depicted in Fig. 23. I_{source} is the source current, R_{source} is the source internal resistance, L_{coil} is the inductance of the transmitting coil, $C_{Coil\text{-}Plate}$ is the equivalent capacitance between the transmitting coil and the metal plates, $C_{Plate\text{-}Ground}$ is the equivalent capacitance between the metal plates and the ground, $C_{Plate\text{-}Object}$ is the equivalent capacitance between the metal plates and the LO, and V_{sense} is the sensing voltage of the metal plates. Compared with Fig. 23(a), there is an extra capacitance $C_{PLATE\text{-}OBJECT}$, formed by the presence of an LO in Fig. 23(b). The sensing voltage V_{SENSE} would be different from the case without an LO. Thus, the LO can be detected.

Patent [73] also adopts the capacitive detection method, but the location and the metal shape are different from Ref. [72].

In Ref. [74], a comb pattern capacitive sensor for LOD is proposed, as shown in Fig. 24. When an LO approaches the charging pad, the capacitance of the comb pattern sensor would vary and the LO can be detected. A multiple comb-pattern capacitive sensor is further proposed to improve the sensitivity [75].

5. Conclusion and future trends

This paper reviews and summarizes the state-of-the-art development of the FOD technology in IPT systems. The MO and the LO are the two major detecting objects in the FOD technology. FOD can thus be categorized into MOD and LOD. Moreover, based on the working principles, the FOD technology can be divided into system parameter detection methods, wave-based detection methods, and field-based detection methods.

System parameter detection methods based on electrical parameters use electrical parameters such as power, current, and efficiency of the transfer system to detection objects. They can be used in MOD, mainly for low-power applications and no extra equipment is needed. Thus, they are cost effective but the accuracy is low.

System parameter detection methods based on non-electrical parameters use non-electrical parameters such as pressure and temperature of the system to detection objects. They can be used in both MOD and LOD, and for low-power and high-power applications. Only some sensors are required. Thus, it is low in cost but the accuracy is also low.

Wave-based detection methods use sensors that are based on electromagnetic wave, mechanical wave, and other waves, such as imaging cameras, thermal cameras, ultrasonic sensors, and radars, to detect FOs. They are normally used in high-power applications for MOD purposes. Extra equipment is needed. Thus, it is high in cost but the accuracy is high.

Field-based detection methods, which are the most popular, use the near field of the electromagnetic field to detect FOs. They can be divided into inductive coupling and capacitive coupling. They work for both high-power and low-power applications, and for both MOD and LOD. Similar to the wave-based detection methods, extra equipment is needed. Thus, the cost is in a medium level, and so is the accuracy.

Presently the field-based detection methods are the most popular method for MOD and wave-based detection methods are widely used for LOD. The future development of the FOD technology lies in the combination of wave-based detection methods and field-based detection method to achieve the targets of MOD, LOD, and positioning.

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