Abstract—The successful commercialization of wireless power transfer (WPT) technology in mobile phones, laptops, and electric vehicles (EV), requires a safe, reliable, and efficient charging infrastructure. A metal object, such as a coin, a key, or a nail, however, may be inadvertently exposed, by close proximity, to the magnetic fields generated by the WPT coupler, creating a potential safety hazard and affecting the electrical characteristics of the WPT system. In addition, the magnetic fields may produce adverse symptoms, such as dizziness and breathlessness, in living objects near the charging systems. This paper provides a current state of the art review of all available designs for detecting metal and living objects in WPT systems. Working principles and qualitative comparisons in terms of sensitivity, accuracy, and cost of major detection methods are presented to reveal their inherent limitations and available applications. Finally, a number of research topics on foreign object detection (FOD) are suggested to encourage more researchers to make contributions to the development and commercial application of wireless charging systems.

Index Terms—Foreign object detection, living object protection, metal object detection, wireless power transfer.

I. INTRODUCTION

RECENT developments in wireless power transfer (WPT) technology [1]–[3] mean that the technology has gained wide acceptance in a range of applications, including electronic devices [4], [5], implantable electronics [6]–[8], automatic guided vehicles (AGV) [9]–[11] and electric vehicles (EV) [12]–[18]. WPT technology has some outstanding advantages compared with conventional plug-in chargers, for example, with these systems charging can be performed automatically and without user intervention or manipulations, thereby significantly improving the user experience. These systems also include no exposed electrical and mechanical contacts, which improves the safety and reliability of the charging infrastructure.

However, when one or more metallic foreign objects, such as coins, keys, paper clips, nuts, or bolts, are present on the transmitter (Tx) coil in a WPT system, they will dramatically affect the distribution of the magnetic fields between the Tx and receiver (Rx) coils [19], [20]. Consequently, some electrical characteristics of the WPT system, including the system transfer efficiency, output power, and quality factors of the Tx and Rx coils, inevitably change. Further, metallic foreign objects provide a path upon which eddy currents and hysteresis losses can be generated. This can cause the temperature of these objects to rise significantly [21]–[23], which may melt the plastic surface of the Tx coil. This is not an uncommon issue, either, as any users may inadvertently put their keys next to a wireless charging device that is charging a mobile phone or laptop computer. The generated eddy currents and hysteresis losses might also heat the keys and cause injuries to the user who picks up the keys. In addition to the issues regarding the metal objects, some physical symptoms, such as dizziness, breathlessness, and blood pressure change may occur in living foreign objects, such as cats, dogs, birds, and humans, that are exposed to the magnetic field generated by the WPT coupler [24]. Thus, to ensure the safety and reliability of WPT systems, it is mandatory that special precautions and designs are adopted to 1) prevent foreign objects (including conducting materials like metallic and magnetic objects and living objects) from being exposed to the charging system, 2) detect the inadvertent presence of foreign objects, and 3) take corresponding measures, such as sounding an audible alarm, actuating a visual alarm, or halting power provision to the load.

The method of designing a movable shield surrounding the WPT coupler, as shown in Fig. 1, is an effective solution to prevent foreign objects from being exposed to the charging area. However, the high cost and difficulty in installation are the drawbacks of this method and limit its application. Past research efforts on metal object detection (MOD) and living object detection (LOD, can also be referred to as living object protection) in WPT systems can be categorized as shown in Fig. 2. There is no doubt that both metal and living objects

Fig. 1. A movable shield surrounding the WPT coupler.
that present in the charging area cause the variation of some physical properties in the area. This means that physical sensors, such as temperature sensors, infrared cameras, pressure sensors, and radar sensors, can be configured to detect foreign objects [25]–[32], [35]–[39]. In addition, as described above, metal objects affect the magnetic fields between the Tx and Rx coils and thus the electric characteristics of the WPT system [19]–[21], [40]–[67]. These characteristics may include the self-inductances and quality factors of the Tx and Rx coils, currents on the Tx and Rx coils, coupling coefficient, input/output powers, and efficiency. These variation of electric characteristic can also be used to indicate the presence of metal objects. Furthermore, the sensing pattern-based method [23], [32]–[34], [68]–[92] is alternatively an effective solution for detecting metal objects. This method measures variations in induced voltage or impedance of a detection coil set mounted on the Tx coil. For LOD, in addition to the sensor-based methods, the capacitive detection method, in which capacitance variation is detected, is another alternative solution [24], [35], [70], [93]. Even though some MOD and LOD methods have been proposed for a variety of applications and Zhang et al. [22] has reviewed the widely-used FOD methods, it is still worth a comprehensive analysis of the working principle of the widely-used FOD methods, because it can illustrate the essential effect of the foreign object on the WPT systems and can provide more possible detection methods. And there is a lack of quantitative analysis and comparisons of all alternative detection methods in terms of their accuracy, sensitivity, and cost, which can reveal their inherent limitations in applications. In addition, which method is the most promising solution is an open question for either/both MOD or/and LOD.

In order to gain a thorough knowledge of both MOD and LOD, this paper qualitatively analyzes the influence of foreign objects on all electrical and non-electrical characteristics of WPT systems. In theory, all variation in measurable parameters can be used to detect the presence of foreign objects. Based on the analysis, the latest achievements in FOD research are reviewed, categorized, and compared. Moreover, the limitations inherent in the available applications of major detection methods are presented. A number of suggested FOD research topics are put forward, all sharing the aim of promoting its accuracy, sensitivity, and cost-effectiveness. More specifically, Section II analyzes the working principles, features, limitations, and available applications of three different MOD methods, i.e., sensor-based detection method, system parameter detection method, and sensing pattern-based detection method. The LOD technology is given in Section III, followed by the conclusion in Section IV.

II. METAL OBJECT DETECTION

A. Sensor-based detection method

According to Faraday’s law of induction, when a metallic foreign object is placed in close proximity to a time-varying magnetic field, eddy currents will be generated in the metal object, inevitably causing its temperature to rise. In addition, hysteresis losses may be generated in some metal objects as well which will further increase the temperature of the metal objects. Table I presents our experiment results of a number of metal objects present in a 3.3-kW WPT system. The results show that temperatures of all metallic objects have increased...
dramatically in just 2 minutes, especially that of the screw, which increase to approximately 102.1 °C. Thermal cameras (e.g., infrared sensors) [25]–[29], temperature sensors [27], and thermistors [28] are able to sense temperature rise and provide temperature-related information to their controller to indicate the presence of metallic foreign objects.

In addition, metal objects falling on the Tx coil inevitably cause its surface to deform, which means that pressure sensors [27] can detect their presence. Besides these, radar sensors [28], [30] and image cameras [28], [31] can also be applied to identify the presence of metal objects by measuring the distance-related information between the radar transmission and reception signals and providing visual detection, respectively.

Some of these sensors, such as infrared and radar sensors as well as image cameras, can be mounted, not only the Tx side, but also the Rx side [27], [28], [30]. On the Rx side, relatively fewer sensors are needed to protect the whole charging area, as there is a clear view of the whole charging area. Sensors mounted on the Rx side are also protected from the risk of vandalism or weather-inflicted damage.

Overall, the sensor-based method has the following advantages: (1) it is not limited by the WPT operating frequency and power level, especially in high power applications like EVs, electric bikes, etc; (2) it operates independent of misalignment between the Tx and Rx coils; (3) it can detect any metallic foreign objects; and (4) it has high sensitivity to small metal objects. However, this type of method is not free of issues. It is still the case that some non-conductive materials (e.g., wood, glass and plastic), which will not create a potential safety hazard and influence the electrical characteristics of the WPT system, may affect the detection accuracy. For example, it is difficult for a temperature sensor to detect a nail embedded in wood, and a piece of glass debris can falsely trigger a pressure or radar sensor. Additionally, some metal objects, for example, the coin and the key, exhibit insignificant temperature rise in low power WPT systems operating at 6.78 MHz and higher frequencies [67]. It means that the temperature sensor is not suitable for detecting metal objects in these applications. Further, the relatively high cost and difficulty in installation limit the potential application of the sensor-based detection method [23], [68], especially in wireless mobile phone and laptop computer charging systems.

B. System parameter detection method

Figs. 3(a) and 3(b) show the magnetic fluxes of a 15-W WPT system based on the Qi standard [94], without and with the presence of a US one-cent coin (diameter = 19.05 mm; thickness = 1.55 mm) on the Tx coil, respectively. From Fig. 3(b), it can be seen that the coin dramatically distorts the distribution of the magnetic fluxes between the Tx and Rx coils, which consequently changes the electrical characteristics of the magnetic couplers. These variations in electrical parameters can then be used to detect the presence of metal objects. We will next present generic circuit models of a WPT system without and with the presence of a metal object and comprehensively analyze the effect of the metal object on the WPT system parameters. Based on the mathematical models of the parameters, a quantitative analysis of a US one-cent coin in two WPT systems with different power levels is presented to show the limitations and available applications of this type of method.

Fig. 4(a) shows the equivalent circuit of a series-series (SS) compensated WPT system [1], [12], [95]. The self-inductances of the WPT coupler are represented by $L_{Tx}$ for the transmitter and $L_{Rx}$ for receiver. $M_{TR}$ is the mutual inductance between the Tx and Rx coils. $R_{Tx}$ and $R_{Rx}$ denote the resistances of the Tx and Rx coils, respectively. $C_{Tx}$ and $C_{Rx}$ are the compensation capacitances on the Tx and Rx sides. $V_{AB}$ and $I_{Tx}$ are the phasor forms of the input voltage and current of the charging area. $V'_{AB}$ and $I'_{Tx}$ are the input variables. $R_{ab}$ is the equivalent ac load resistance.
TABLE 1

<table>
<thead>
<tr>
<th>Metal objects</th>
<th>Key US one-cent coin</th>
<th>US quarter dollar coin</th>
<th>Screw</th>
<th>Nail</th>
<th>Spring washer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature rise (°C)</td>
<td>52.3</td>
<td>46.5</td>
<td>61.7</td>
<td>102.1</td>
<td>89.2</td>
</tr>
</tbody>
</table>

Also, by applying KVL to Fig. 4(b), the following equations can be obtained,

\[ V'_{AB} = \left( \frac{1}{R_{MO} + j\omega L_{MO}} \right) \cdot V_{AB} \]  
\[ V'_{ab} = \left( \frac{1}{R_{MO} + j\omega L_{MO}} \right) \cdot V_{ab} \]  
\[ I'_{MO} = \frac{1}{R_{MO} + j\omega L_{MO}} \cdot V'_{AB} \]  

Here, \( V'_{AB} \) and \( V'_{ab} \) are the phasor forms of the input voltage and current when an MO is placed in the charging area, and \( V_{ab} \) and \( I_{Rx} \) are the corresponding output variables. \( I_{MO} \) represents the eddy current on the metal object. Under the resonant condition of (2), equation (10) can be simplified to

\[ V'_{AB} = \left( \frac{1}{R_{MO} + j\omega L_{MO}} \right) \cdot V_{AB} \]  
\[ V'_{ab} = \left( \frac{1}{R_{MO} + j\omega L_{MO}} \right) \cdot V_{ab} \]  
\[ I'_{MO} = \frac{1}{R_{MO} + j\omega L_{MO}} \cdot V'_{AB} \]

And one can then obtain,

\[ I'_{Tx} = \frac{1}{R_{Tx} + j\omega L_{Tx}} \cdot V'_{AB} \]  
\[ I'_{Rx} = \frac{1}{R_{Rx} + j\omega L_{Rx}} \cdot V'_{ab} \]  
\[ I'_{MO} = \frac{1}{R_{MO} + j\omega L_{MO}} \cdot V'_{AB} \]

where,

\[ A = j\omega R_{Tx} L_{MO} + R_{Tx} R_{MO} + (\omega M_{TM})^2 \]  
\[ B = j\omega R_{MO} M_{TR} - \omega^2 L_{MO} M_{TR} + \omega^2 M_{TM} M_{RM} \]  
\[ C = j\omega (R_{Rx} - R_{ab}) L_{MO} + (R_{Rx} - R_{ab}) R_{MO} + (\omega M_{RM})^2 \]  

Further, according to (11)-(13), the input impedance, quality factors of the Tx and Rx coils, output power, and efficiency of the SS compensated WPT system with an MO placed on the Tx coil are expressed by the following:

\[ Z_{in} = R_{in} + jX_{in} = R_{Tx} + \frac{(\omega M_{TM})^2}{R_{ab} + R_{Rx}} \]  
\[ Q_{Tx} = \frac{1}{R_{Tx}} \sqrt{\frac{L_{Tx}}{C_{Tx}}} \quad \text{and} \quad Q_{Rx} = \frac{1}{R_{Rx}} \sqrt{\frac{L_{Rx}}{C_{Rx}}} \]  

When an MO is placed in the charging area, it will be coupled with both the Tx and Rx coils. The system equivalent circuit, in a case such as this, is shown in Fig. 4(b). In this figure, the metal object is modeled as an inductance, \( L_{MO} \), with a series resistance, \( R_{MO} \). With a mutual inductance between the Tx coil and metal object defined as \( M_{TM} \), while \( M_{RM} \) represents the mutual inductance between the Rx coil and the metal object.

\[ V_{ab} = j\omega M_{TR} \cdot I_{Tx} + \left(\frac{1}{j\omega C_{Rx}} + R_{Rx}\right) \cdot I_{Rx} \]  
\[ V_{ab} = j\omega M_{TR} \cdot I_{Tx} + \left(\frac{1}{j\omega C_{Rx}} + R_{Rx}\right) \cdot I_{Rx} \]  

Here, \( \omega = 2\pi f \) represents the resonant angular frequency of the WPT system and is usually set to be 2π. When an MO is placed in the charging area, it will be coupled with both the Tx and Rx coils.

\[ \omega^2 = \frac{1}{L_{Tx} C_{Tx}} = \frac{1}{L_{Rx} C_{Rx}} \]  

By substituting (2) into (1), the system can be simplified to

\[ V_{AB} = R_{Tx} \cdot I_{Tx} + j\omega M_{TR} \cdot I_{Rx} \]  
\[ V_{ab} = j\omega M_{TR} \cdot I_{Tx} + R_{Rx} \cdot I_{Rx} \]  

According to (3), the currents on the Tx and Rx coils (\( I_{Tx} \) and \( I_{Rx} \)), input impedance (\( Z_{in} \)), quality factors of the Tx and Rx coils (\( Q_{Tx} \) and \( Q_{Rx} \)), output power, and transfer efficiency are expressed as, respectively,

\[ I_{Tx} = \frac{(R_{Rx} + R_{ab})}{R_{Tx} (R_{Rx} + R_{ab}) + (\omega M_{TR})^2} \cdot V_{AB} \]  
\[ I_{Rx} = \frac{-j\omega M_{TR}}{R_{Tx} (R_{Rx} + R_{ab}) + (\omega M_{TR})^2} \cdot V_{AB} \]  

\[ Z_{in} = R_{in} + jX_{in} = R_{Tx} + \frac{(\omega M_{TR})^2}{R_{ab} + R_{Rx}} \]  

\[ Q_{Tx} = \frac{1}{R_{Tx}} \sqrt{\frac{L_{Tx}}{C_{Tx}}} \quad \text{and} \quad Q_{Rx} = \frac{1}{R_{Rx}} \sqrt{\frac{L_{Rx}}{C_{Rx}}} \]  

\[ P_{out} = I_{Rx}^2 R_{ab} = \frac{(\omega M_{TR})^2}{\left(\frac{1}{R_{Tx} (R_{Rx} + R_{ab}) + (\omega M_{TR})^2}\right)^2} \]  

\[ \eta = \frac{P_{out}}{P_{loss}} = \frac{I_{Rx}^2 R_{ab}}{\omega^2 M_{TR}^2 R_{Rx} R_{L}} \]  

\[ = \frac{R_{Rx} R_{ac} + R_{Rx}^2 + \omega^2 M_{TR}^2 R_{Rx} + R_{L}}{R_{Rx} R_{ac} + R_{Rx}^2 + \omega^2 M_{TR}^2 R_{Rx} + R_{L}} \]
Fig. 5. (a) A 15-W WPT coupler based on the Qi standard [94] and (b) a 3.3-kW wireless EV charging coupler based on the SAE J2954 standard [99].

\[ Z'_{in} = R'_{in} + jX'_{in} = R_{Tx} + \frac{(\omega M_{TM})^2}{j\omega L_{MO} + R_{MO}} - \frac{(j\omega M_{TR} + \frac{\omega^2 M_{TM} M_{RM}}{j\omega L_{MO} + R_{MO}})^2}{R_{ab} + R_{Rx} + \frac{(j\omega M_{RM})^2}{j\omega L_{MO} + R_{MO}}} \]  

\[ Q'_{Tx} = \left( \frac{R_{MO}^2 + (\omega L_{MO})^2}{R_{Tx}^2} \right)^2 \left( \frac{L_{in} - \frac{\omega^2 L_{MO} M_{TM}^2}{R_{MO}^2 + (\omega L_{MO})^2}}{R_{MO}^2 + (\omega L_{MO})^2} \right) \]  

\[ Q'_{Rx} = \left( \frac{R_{MO}^2 + (\omega L_{MO})^2}{R_{Rx}^2} \right)^2 \left( \frac{L_{in} - \frac{\omega^2 L_{MO} M_{TM}^2}{R_{MO}^2 + (\omega L_{MO})^2}}{R_{MO}^2 + (\omega L_{MO})^2} \right) \]  

\[ P'_{out} = I_{Rx}' R_{ab} = \frac{(j\omega L_{MO} + R_{MO})^2 B^2}{(B^2 - AC)^2} V'_{AB} R_{ab} \]  

\[ \eta' = \frac{P'_{out}}{P'_{out} + P'_{loss}} = \frac{I_{Rx}^2 R_{ab}}{I_{Rx}^2 (R_{ab} + R_{Rx}) + I_{MO}^2 R_{MO} + I_{Tx}^2 R_{Tx}} \]

As can be seen from the above analysis, the MO placed in the power transfer area of a WPT system has an influence on all of its electrical parameters, i.e., the self-inductances and quality factors of the Tx and Rx coils, currents on the Tx and Rx coils, input impedance (magnitude and phase), output power, and system efficiency. Therefore, variations in one or more of these electrical characteristics can be used to detect the presence of metal objects. Table II summarizes some of the published literature in which the presence of metallic foreign objects was determined based on the variation of the WPT system’s electrical characteristics. Here, it should be pointed out that the Qi standard [21] for low-power WPT applications, the WPT system parameters variation, e.g., power loss and coupling factor, are applied to detect the metal objects.

Although this type of detection method is simple, has a low cost and requires no additional installation space, its application is limited by the WPT system power level. Furthermore, the detection accuracy of this type of method can be compromised by misalignment between the Tx and Rx coils, as well as by the equivalent resistance of the battery pack. Next, we will quantitatively analyze the effect of a US one-cent coin on the electrical characteristics of two WPT systems with different power levels to reveal the inherent limitations of this type of method in detail.

Fig. 5(a) shows a 15 W WPT coupler with an air gap of 5 mm. The geometry of the Tx and Rx coils are in compliance with the Qi standard [94]. When a US one-cent coin was placed on the center of the Tx coil, the variations (%) of the self-inductances of the Tx and Rx coils and coupling coefficient are measured, and these are shown in Fig. 6(a). It can be seen that the presence of the coin on the Tx coil dramatically affected \( L_{Tx} \), \( L_{Rx} \), and \( k \). For example, the variation of the self-inductance...
misalignment between the Tx and Rx coils. Furthermore, the output current and voltage, output power, and efficiency of the WPT system usually vary with the battery charging process [97], [98], [103], [104], and are affected by the condition of the battery, such as state of charge (SOC), temperature, and aging. Therefore, it is a challenge to distinguish the system parameter variation caused by the presence of metal objects, potential misalignment between the Tx and Rx coils or different battery state.

C. Sensing pattern-based detection method

The sensing pattern-based detection method has also proved to be a viable alternative for the detection of metallic foreign objects in WPT systems, especially in high power applications. In this method, one or more detection coils [69]–[73], as shown in Fig. 8, are mounted onto the WPT coupler. Fig. 9 shows an example of a WPT coupler with a number of detection coils. The variation of the electrical characteristic of the detection coil, such as its induced open-circuit voltage or impedance variation, is then sensed to indicate the presence of the metal objects.

1) Induced voltage detection:

Fig. 10(a) shows the equivalent circuit of a WPT system with a detection coil mounted on the Tx coil. \( L_D \) and \( R_D \) represent the self-inductance and parasitic resistance of the detection coil, respectively. \( M_{TD} \) and \( M_{RD} \) are the mutual inductances between the detection coil and the Tx coil and Rx coil. The open-circuit voltage (\( V_D \)) of the detection coil induced by the time-varying magnetic field generated by the WPT coupler can be expressed as

\[
V_D = j \omega M_{TD} I_{Tx} + j \omega M_{RD} I_{Rx} \tag{18}
\]

Fig. 10(b) shows the equivalent circuit of a WPT system when a metal object is placed on the detection coil. The metal object is mutually coupled with the Tx, Rx, and detection coils. The mutual inductances are represented by \( M_{TM}, M_{RM}, \) and \( M_{DM} \) respectively. In this case, the induced open-circuit voltage of the detection coil is given by

\[
V_D' = j \omega M_{TD} I_{Tx} + j \omega M_{RD} I_{Rx} + j \omega M_{DM} I_{MO} \tag{19}
\]

Compared with (18) and (19), the eddy current (\( I_{MO} \)) of the metal object placed in the proximity of the detection coil

<table>
<thead>
<tr>
<th>TABLE II</th>
<th>LITERATURE REVIEW OF METAL OBJECT DETECTION BASED ON VARIATION OF ELECTRICAL CHARACTERISTICS OF WPT SYSTEMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical characteristics</td>
<td>References</td>
</tr>
<tr>
<td>Inductances of the transmitter and/or receiver coils</td>
<td>[20], [41]–[48]</td>
</tr>
<tr>
<td>Currents on the transmitter and/or receiver coils</td>
<td>[49]–[54]</td>
</tr>
<tr>
<td>Quality factors of the transmitter and/or receiver coils</td>
<td>[21], [42]–[45], [51], [55]–[59]</td>
</tr>
<tr>
<td>Input impedance/phase angle</td>
<td>[40], [47], [51], [60]</td>
</tr>
<tr>
<td>Input power</td>
<td>[61]–[63]</td>
</tr>
<tr>
<td>Output power</td>
<td>[40], [51]</td>
</tr>
<tr>
<td>Power loss</td>
<td>[21], [52], [64], [65]</td>
</tr>
<tr>
<td>Efficiency</td>
<td>[44], [47], [51], [55], [59], [66]</td>
</tr>
</tbody>
</table>

Fig. 7. Self-inductances and coupling coefficient variations with respect to misalignment in the 15 W WPT system.

of the Tx coil (\( \Delta L_{Tx} \)) is up to 23.2% when the coin was placed on the center of the Tx coil. Then according to (12) and (14)-(17), the variation of \( L_{Tx}, L_{Rx}, \) or \( k \) leads to changes in the currents on the Tx and Rx coils, input impedance (magnitude and phase), quality factors of the Tx and Rx coils, output power, and efficiency of the system. This means that the coin significantly affects some of system’s electrical characteristics and that the parameter detection method may be an effective solution for detecting metal objects in low power WPT systems like mobile phones, tablets, etc.

Fig. 5(b) shows a 3.3-kW wireless EV charging system based on the SAE J2954 standard [99]. The effect of a coin on this system is shown in Fig. 6(b). According to the results, the coin caused only a negligible disturbance to the system parameters. This indicates that detection by monitoring the variation of electrical characteristics may be difficult for high power (high air-gap between the Tx and Rx coils) systems [23].

Additionally, misalignment in the lateral and/or longitudinal directions and air gap variation between the Tx and Rx coils are inevitable and these will also affect the electrical characteristics of the WPT systems [68], [100]–[102]. Fig. 7 shows the variations of the self-inductances and coupling coefficient with respect to the misalignment in the 15 W WPT system. It can be observed that the coupling coefficient decreased by about 80% when there was a 20 mm horizontal
changes its induced voltage. The induced voltage variation can then be used to indicate the presence of the metal objects [73], [75]–[78].

As mentioned above, however, the currents on the Tx and Rx coils may vary with power level, which means that the detection accuracy of the method based on induced voltage variation is influenced by the working state of the WPT system. To address this issue, the induced voltage difference of two symmetrical detection coils can be configured to detect the presence of the metal objects [23], [69], [74]. Fig. 11 shows an equivalent circuit of a WPT system coupled with two symmetrical detection coils. The voltage induced by the magnetic field crossing the surface area of one of the coils is approximately equal and opposite to that by the magnetic field crossing the area of one of the other coils. Therefore, the induced voltage difference ($V_{Da} - V_{Db}$) of these two detection coils is substantially zero and independent of the system output power in the absence of the metal objects. If the voltage difference exceeds the predetermined threshold value, it will indicate that an MO is present on the detection coils. Additionally, the induced voltages of detection coils decoupled from the Tx coil (for example, a bipolar pad is adopted for
the detection coil, while, the Tx coil is an unipolar pad) can also be configured to detect metal objects [70], [79]–[81]. The working principles of these types of detection coils are similar to those of the two symmetrical coils. The induced voltage is no longer zero when metal objects present on these detection coils.

2) Impedance variation detection:

Fig. 12 shows the equivalent circuit model of a detection coil under the influence of a metallic foreign object. The detection coil is excited by a sinusoidal signal source with a voltage $V_s$ and a frequency $\omega_0$. Usually, $\omega_0$ is designed to be different from the operating frequency of the WPT system to minimize its interaction with the WPT system and improve its sensitivity to foreign objects.

Without and with the presence of a metal object on the charging area, the input impedances of Fig. 12 can be expressed as, respectively,

$$Z_{in-w} = R_D + j\omega_D L_D$$

$$Z_{in-w} = R_D + j\omega_D L_D + \frac{(\omega_D M_{DM})^2}{R_{MO} + j\omega_D L_{MO}}$$

$$= \left( R_D + \frac{(\omega_D M_{DM})^2}{R_{MO}^2 + (\omega_D L_{MO})^2} \right)$$

$$+ j\omega_D \left( L_D - \frac{(\omega_D M_{DM})^2}{R_{MO}^2 + (\omega_D L_{MO})^2} \right)$$

From (20) and (21), it can be seen that both the equivalent resistance and inductance of the detection coil change with the presence of a metal object. This means that the impedance variation of the detection coil can also be used as an indicator for the presence of metallic foreign objects [32], [33], [68], [71], [82]–[90].

However, the effect of a relatively small metallic foreign object on the impedance variation of the detection coil is too small to be detected directly. For example, the self-inductance and resistance of a detection coil having a square size of 60 mm and 21 turns, decreased and increased by only 3.03% and 1.83%, respectively, when a US one-cent coin was present on the center of the detection coil. To amplify and convert the impedance variation to an easily detectable voltage or frequency signal, a capacitive network is usually added to resonate with the detection coil [68], [71], [85]–[88]. In addition, the resonant network can also suppress and filter the voltage induced by the alternating electromagnetic field used for transferring power as well as the noise of harmonics. Fundamentally, there are two types of resonance topologies, series and parallel, as shown in Figs. 13(a) and 13(b), respectively. These were analyzed and compared in [68] and it was determined that the parallel resonance is the better option because of its high sensitivity to the presence of foreign objects and its high signal-to-noise ratio. In addition to the series and parallel resonances, any other type of resonant networks, such as series-parallel mixed-resonance [85], [88], can also be used to amplify the impedance variation.

3) FOD system design:

A metallic foreign object may fall anywhere in the charging area of a WPT system. To protect the whole charging area and improve the sensitivity to small metal objects, a plurality of detection coils configured as grid spaces in a column and row format [69], [70], [72], [73], [82], [83], [86], [89], [91], [92], such as that shown in Figs. 14(a), 14(b), and 14(c), can be applied to detect the metal objects. For these detection coil sets, however, the blind spots/zones, where the foreign object cannot be detected because of the effect of the metal object on the induced voltage or impedance variation of the detection coil may be substantially negligible, and this is a problem that
need to be addressed. Multilayer detection coil sets deposited on each other, for example, as shown in Fig. 15(a), 15(b), or 15(c), are an effective way of reducing or eliminating the blind spots [74], [82]. In addition, in [23], a single-layer non-overlapping sensing coil set that will completely eliminate the problem of the blind zone, is proposed, as shown in Fig. 16.

For the detection coil set shown in Fig. 16, an overall FOD system is proposed in [23], as shown in Fig. 17. In this system, the induced voltage difference of two symmetrical detection coils is used to indicate the presence of metal objects. Specifically, two multiplexers (MUX) are required to make sure that only two symmetrical detection coils (for example, coil 1-a and coil 1-b) are activated at a time and to eliminate interference from other detection coils. A digital potentiometer is then used to ensure that the induced voltage difference is always zero in the absence of a metal objects, regardless of the manufacturing error and the misalignment of the Tx and Rx coils. Finally, a signal conditioning circuit is configured to improve the signal-to-noise ratio and modulate the output signal to be controlled by a microcontroller unit (MCU). The MCU stores the measured data and compares it with the reference value to indicate the presence of a metal object by sounding an audible alarm or actuating a visual alarm.

As mentioned above, in addition to sensing the induced voltage variation of the detection coil, its self-inductance variation can also be measured to detect the presence of metal objects. Figs. 18(a) and 18(b) show two examples of such an FOD system [68], [88]. Similar to Fig. 17, an MUX is also adopted to control the detection coils time-divisionally in both of these systems. The capacitors are designed to resonate with the detection coil to amplify the impedance variation of the
detection coil and convert it to a voltage (Fig. 18(a)) or phase signal (Fig. 18(b)) that can be easily and accurately measured. Finally, the measured voltage or phase signal is isolated, filtered, amplified, and converted so it can be controlled by an MCU.

Although this type of method has been proven to accurately detect some metal objects [23], [68], it is necessary to conduct a comprehensive evaluation of all common metallic foreign object. Then, according to Fig. 18(a), a 3.3-kW WPT prototype with FOD function included was implemented. Some metal objects were applied to evaluate the performance of the FOD system. Fig. 19 shows the experimental results when a US one cent coin, a key and an aluminum block were placed on the detection coil set. It can be seen that the output voltage of the FOD system changes up to 23.67%, 28.61%, and 25.30%, respectively. The experimental results of other metal objects are shown in Table III. The results reveal that this method can detect most of the metal objects, however, a couple of the relatively small metal objects, the paper clip and staple, were not detected. Although decreasing the detection coil size would be an effective way to improve sensitivity to these small metal objects, it inevitably increases system cost and complexity. Additionally, this method fails to detect certain small ferromagnetic objects, such as nails, screws, spring washers, and so forth.

### D. Comparison and discussion

Table IV summarises the performance comparison of all available MOD methods according to the analysis above. Relatively speaking, the method of detecting changes in electrical characteristics of the WPT system is the simplest and most economical solution. In addition, it has the fastest detection and reaction time. Its application, however, is limited to low power WPT systems. Furthermore, the misalignment between the Tx

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**Table III**

<table>
<thead>
<tr>
<th>Metal objects</th>
<th>( \frac{V_{\text{w/o metal object}} - V_{\text{w/ metal object}}}{V_{\text{w/o metal object}}} \times 100% )</th>
</tr>
</thead>
<tbody>
<tr>
<td>US quarter dollar coin</td>
<td>27.30</td>
</tr>
<tr>
<td>Steel wool</td>
<td>26.58</td>
</tr>
<tr>
<td>Aluminum foil (20 × 20 mm²)</td>
<td>34.52</td>
</tr>
<tr>
<td>Hex cap screw</td>
<td>5.29</td>
</tr>
<tr>
<td>Nail</td>
<td>4.12</td>
</tr>
<tr>
<td>Paper clip</td>
<td>0.61</td>
</tr>
<tr>
<td>Staple</td>
<td>0.43</td>
</tr>
</tbody>
</table>

---

**Fig. 19.** Experimental results of the FOD system with the effect of different metal objects. (a) A US one cent coin, (b) a key and (c) a 32 × 30 mm² aluminum block. It should be pointed out that the metal objects were removed from the charging area, which can ensure that different metal objects were placed in the same position for the sake of a fair comparison.
TABLE IV
SUMMARY AND COMPARISON OF ALL MOD METHODS.

<table>
<thead>
<tr>
<th>MOD methods</th>
<th>Features</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor-based</td>
<td>* Temperature sensor, thermal camera (e.g., infrared sensors), and thermistor</td>
<td>* High sensitivity</td>
<td>* High cost</td>
</tr>
<tr>
<td></td>
<td>* Pressure sensor</td>
<td>* Independent of WPT system power level, operating frequency and misalignment</td>
<td>* Difficult to distinguish the metal objects and non-conductive materials (stones, plastics, and glasses)</td>
</tr>
<tr>
<td></td>
<td>* Radar sensor</td>
<td>* Can detect any metal objects</td>
<td>* Be susceptible to the environment (temperature, dust, and rain)</td>
</tr>
<tr>
<td></td>
<td>* Image camera</td>
<td>* Detection coil set should be designed carefully to make no contribution to any power losses, eliminate the blind spots and improve the sensitivity</td>
<td>* Take up a large installation space</td>
</tr>
<tr>
<td>Parameter variation</td>
<td>* Self-inductances of the Tx and Rx coils</td>
<td>* Low cost</td>
<td>Limited to low power applications</td>
</tr>
<tr>
<td></td>
<td>* Quality factors of the Tx and Rx coils</td>
<td>* Require no additional space</td>
<td>Even in low WPT system, its detection accuracy is susceptible to the misalignment and different SOC of the battery load.</td>
</tr>
<tr>
<td></td>
<td>* Currents on the Tx and Rx coils</td>
<td>* Simple</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Input impedance/phase angle</td>
<td>* High detection speed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>* Input power, output power, power loss, and efficiency</td>
<td>* Appropriate for IPT and CPT systems</td>
<td></td>
</tr>
<tr>
<td>Sensing pattern-based</td>
<td>* Induced voltage of the detection coil (or induced voltage difference)</td>
<td>* High sensitivity</td>
<td>* Detection coil set should be designed carefully to make no contribution to any power losses, eliminate the blind spots and improve the sensitivity</td>
</tr>
<tr>
<td></td>
<td>* Impedance of the detection coil</td>
<td>* Not affected by non-conductive materials</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>* Independent of the environment, and misalignment</td>
<td></td>
</tr>
</tbody>
</table>

and Rx coils and the variation of the battery condition (such as state of charge, temperature, and aging) inevitably affect its detection accuracy. The sensor-based and sensing pattern-based methods work independent of the above mentioned misalignment and WPT power level in theory. However, high cost and difficulty in installation limit the practical application of the sensor-based method, which additionally is susceptible to some non-conductive materials and the environment. The sensor temperature may takes tens of seconds or even minutes to detect the presence of metal objects. During the reaction time, the WPT system will be operating in a low efficiency condition. For the sensing pattern-based method, designing a detection coil set to 1) make no contribution to any power loss of the WPT system, 2) cover the whole charging area and eliminate the blind spot and 3) improve sensitivity to small metal objects and ferromagnetic objects is an additional challenge.

III. LIVING OBJECT DETECTION

There is no doubt that living objects that appear on the Tx coil will cause variations of some non-electrical characteristics of WPT systems, including the surface deformation of the Tx coil. Therefore, sensor-based detection methods, such as those using pressure sensors, infrared sensors [26], [35], radar sensors [32], [35]–[39], ultrasonic sensors [35], or image cameras can be used to detect the presence of living objects.

The capacitive detection method [70] is another available solution for detecting the presence of living objects. In this method, the equivalent capacitance variation of the detection system is used to indicate the presence of living objects. In patent [35], multiple metal plates are mounted around the Tx coil. When living matter is not within a distance sufficient to be coupled with any of the metal plates, the capacitive detection system is modeled in Fig. 20(a). When a living object, for example, a dog or a cat, comes in the proximity of the charging area, an extra capacitance is added between the object and the plate, as shown in Fig. 20(b). The added capacitor will cause a change in the amplitude and/or phase of the voltage on the capacitor between the metal plate and ground \(C_{\text{plate-GND}}\), thus indicating the presence of living objects. In addition, a comb pattern capacitive sensor [24] and a multiple comb pattern capacitor sensor [93], as shown in Figs. 21(a) and

![Fig. 20. Equivalent circuits of the LOD system (a) without and (b) with a living object present in the charging area [35].](image1)

![Fig. 21. (a) A comb pattern capacitor sensor [24] and (b) a multiple comb pattern capacitor sensor [93] for detecting of living objects.](image2)

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21(b), respectively, have been proposed to detect living objects. The presence of living objects on the charging area will cause the capacitance variation of the comb pattern capacitor sensor. Then, an inductive network is added to amplify and convert the capacitance variation to an easily detectable voltage signal. The overall detection system is shown in Fig. 22.

There is less literature on LOD than on MOD for WPT systems. Further, both the sensor-based method and the capacitive detection method may be difficult to use in practical applications. The sensor-based method is limited by its vulnerability to non-conductive materials and its high cost. One major issue with the capacitive detection method is that eddy current is generated in the capacitor plates, which will lead to their temperature rise and affect performances of the WPT system. In addition, the capacitive detection method typically has a low signal-to-noise ratio.

IV. CONCLUSION

This paper presents the overview of MOD and LOD in WPT systems. The working principles, challenges, available applications, and comparisons of all detection methods were presented. Based on the literature review, the following conclusions and suggested research topics will be critical for the commercialization of WPT technology.

Conclusions-(a) The sensor-based method can be used to detect the presence of both metal and living objects of any size and is independent of the WPT power level and misalignment between the Tx and Rx coils. However, its cost and installation space should be taken carefully into consideration in practical applications. In addition, some non-conductive materials will affect its detection accuracy. (b) Although detecting the parameter variation of the WPT system is the simplest and most economical method to sense the presence of metal objects, the application of this method is limited by the WPT system power level, misalignment between the Tx and Rx coils, and battery condition. (c) The sensing pattern-based detection method has recently been the most popular solution for detecting the presence of metal objects because it has a high accuracy, inexpensive, and easy to install. However, the detection coil set used in this method should be designed carefully to eliminate blind spots and improve sensitivity to small metal objects.

Suggested research topics-(a) The integration of different detection methods would contribute to the sensitivity, accuracy, signal-to-noise ratio, and object localization. (b) A method that can detect metal and living objects simultaneously and is not influenced by non-conductive materials and the environment is desirable. (c) MOD and LOD are necessary for capacitive power transfer (CPT) systems. (d) The EMI/EMC issues. (e) Rather than halting the provision of power to the load, an effective approach for removing metal and living objects without user intervention should be of paramount importance.

REFERENCES


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