Comprehensive Analysis of Foreign Object Detection Techniques for Safe Electric Vehicle Charging

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Abstract: The adoption of electric vehicles (EVs) has grown exponentially in recent years, making EV charging infrastructure an essential aspect of modern transportation. The safety and reliability of EV charging stations are crucial factors for their widespread adoption. Foreign object detection (FOD) technology is critical in detecting and preventing foreign objects from entering charging interface. This can cause damage, safety hazards and downtime of charging station. This research paper presents a comprehensive survey of FOD for EV charging, highlighting various techniques and technologies used for FOD, their advantages, limitations, recent advancements and references from several research papers. The different types of FOD detection, such as mechanical, visual, electrical, thermodynamic and magnetic detection of foreign objects are reviewed in detail. This includes their working principles, performance and suitability for different objects and environments. In addition, impact of various factors on FOD performance, such as temperature, living objects, magnetic fields and electromagnetic interference, is discussed and methods to mitigate their effects are explored. The survey concludes by summarizing all information gathered from various papers for EV charging and highlighting the direction towards which this research is headed for future. The survey provides a valuable reference for researchers, practitioners and policymakers in the field of EV charging infrastructure. The insights obtained from this study can help stakeholders draft better products, policies and optimized solutions for EV charging domain.

Keywords: foreign object detection (FOD), wireless power transfer (WPT), electric vehicle, metal object, living object, mechanical.

1. Introduction

The security of wireless power transmission systems must be ensured using the foreign object detection (FOD) method. The International Electro Technical Commission (IEC) and Society of Automotive Engineers are two organizations that have investigated FOD technology (SAE) [1]. However, the aforementioned guidelines do not outline a particular method for foreign object detection. The only information provided is appropriate temperature level for foreign metal items. The resistance or changes in magnetic flux of the sensing coils are currently used by various research organizations and businesses. This includes KAIST, WiTricity and Qualcomm Halo, to realize FOD [2]. The existence and placement of coin-sized metal objects could be quickly and precisely determined using these electromagnetic detection techniques, although the detection area is only as large as transmitter surface in two dimensions [3]. The utilization of power has greatly raised standard of living for humans with a variety of electric devices. Normal power transfer occurs when two metals come into direct touch with each other [4]. There are several issues with this conventional power transfer. This includes issues with dependability, convenience and feasibility. To address these problems, Technology known as Wireless Power Transfer (WPT) has been established. Contrary to traditional power transfer. This can be dangerous, inconvenient, unreliable or even impossible, WPT can be used. Railway transportation [5], electric vehicles (EVs) [6], consumer electronics [7], implantable medical devices [8] and other unique circumstances like mining and underwater applications are examples of typical application situations [9]. Leung and Hu explained that there are two main energy carriers for WPT are electromagnetic wave and mechanical wave [10] (Leung & Hu, 2015), with the former being more prevalent. Long-distance power transfer is possible with electromagnetic radiation WPT. This is determined by the far field and separated into microwave [11] and laser [12], although it is expensive, inefficient and unsafe. Wireless power transfer exploiting capacitive induction WPT or capacitive power transfer (CPT) makes use of electric field created between two metal surfaces [13]. The human body is more negatively impacted by the electric field than magnetic field, hence much research must be done before CPT can be used commercially [14].

The human body is more negatively impacted by the electric field than magnetic field, hence much research must be done before CPT can be used commercially [14]. Due to its comparatively long transfer distance, high transfer efficiency and substantial transfer power magnetic induction WPT, also called inductive power transfer (IPT) is the most well-known WPT technology [15]. Commercially, it has been used for wireless cell phone and EV charging. The transmitting coil (TX) receives high-frequency AC current that creates magnetic flux some of which is connected to receiving coil (RX). Power is wirelessly delivered from the TX to RX when the load is linked to RX. The TX and RX. This are referred to as charging pads, are typically flat spiral coils. Despite the power transfer magnetic field between charging pads would remain strong. Any conducting substance, such a pin a clip, a coin a screw or a piece of tinfoil that falls in between pads while power is being transferred will produce an eddy current. This could cause overheating and other risks such as fire [16]. A magnetic coil with an alternating current generates a time-varying magnetic field, as seen in Figure 1. As a consequence, an electric current is transmitted to the test object.

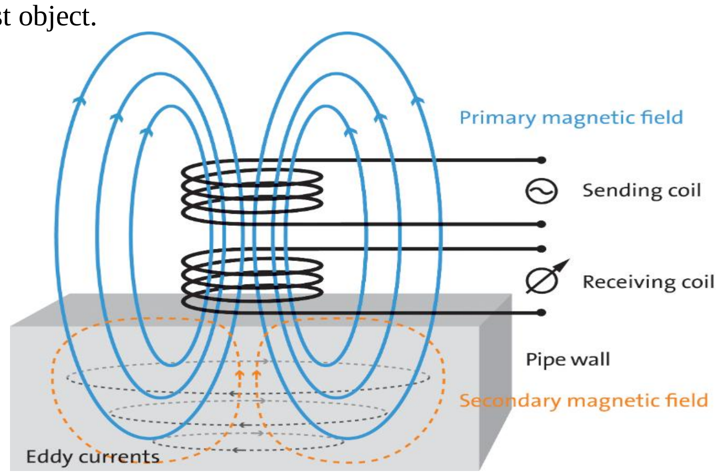

Figure 1: Eddy current phenomena.

When using wireless EV charging systems, powerful magnetic field can also harm animals that are located between the pads if the charging radius is adequate for a dog or a cat to reach charging area. Other instances could involve children snatching a ball rolling underneath the car or drivers reaching out to retrieve a car key that has fallen into charging area [17]. Foreign objects (FOs) between the charging pads ought to be detectable by WPT system such as living things and conducting materials like MOs (LOs). Metal object detection (MOD) and living object detection (LOD) technologies used in foreign object detection (FOD) offer a solution to these difficulties. One of the major challenges to advancement and use of IPT is FOD technology. MOD in this context also refers to the detection of nonmetal conducting materials like graphite. The global market for electric vehicles (EVs) is expected to reach 34.1 million units by 2026 growing at a compound annual growth rate (CAGR) of 32.5% from 2019 to 2026 (1). The growth in EV adoption is driven by various factors such as government regulations, environmental concerns and declining battery costs. As number of EVs on the road increases so does the need for a reliable and safe charging infrastructure. The charging infrastructure comprises charging stations, connectors and charging cables. A faulty charging infrastructure can lead to accidents damage to EV and even loss of life. Foreign Object Detection (FOD) is a critical technique used in the EV charging industry to detect presence of foreign objects in the charging connector and prevent accidents.

The main contributions of this study are:

- First, it offers a thorough review of FOD technology for EV charging. This is a relatively new field.
- Describes several FOD methods and technologies citing their benefits, drawbacks current developments and a number of scholarly articles as sources.
- Third, it examines in depth various FOD detection methods discussing their underlying mechanisms, levels of performance and applicability to a variety of items and settings.
- Discusses how environmental elements such as temperature living items, magnetic fields and electromagnetic interference can affect FOD performance and how these problems can be dealt with.
- The conclusion synthesizes the findings from many studies on EV charging and highlights the future directions for this field of study.

2. Types of Foreign Object Detection (FOD) Methods

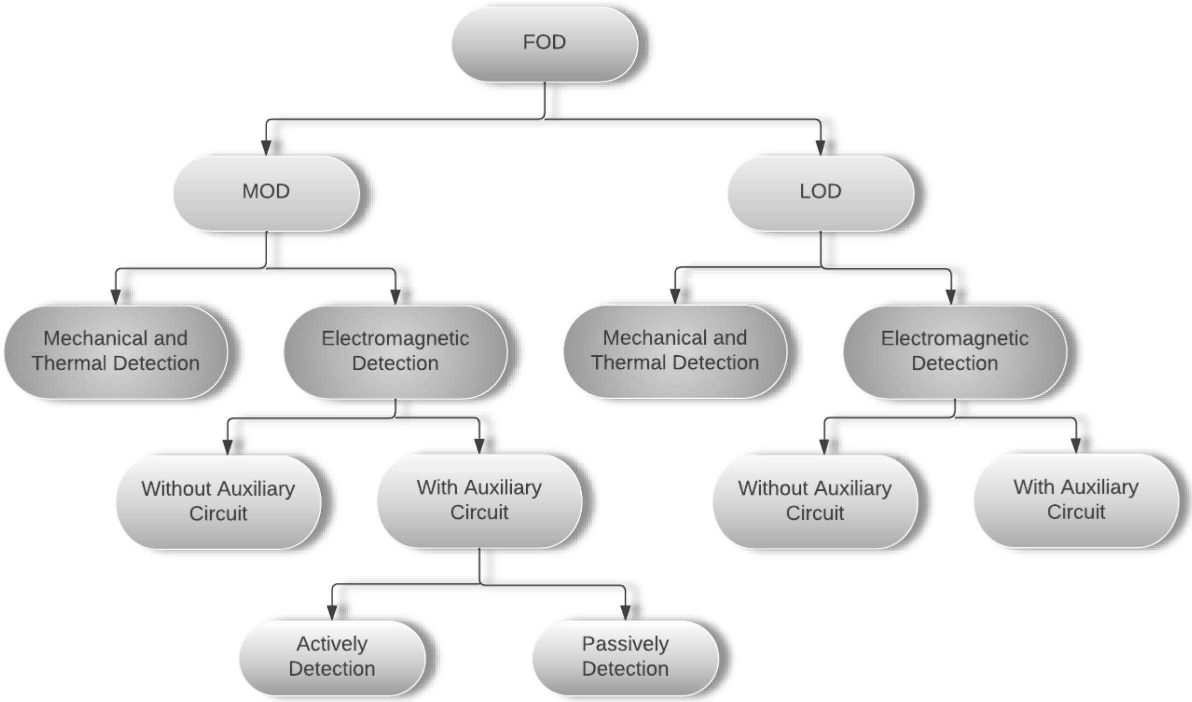

Figure 2: Types of FOD methods.

Based on suggested foreign object models this section explores the several types of FOD approaches for an EV wireless charging system. FOD methods can be categorised into numerous groups based on variations in foreign object kinds and detection principles, as illustrated in Fig 1. MOD and LOD methods are two categories of FOD approaches depending on the type of foreign object. Mechanical thermal and electromagnetic detection techniques are used whereas latter emphasizes electromagnetic properties and the former non-electromagnetic properties. Electromagnetic methods can be divided into two groups depends on whether a second detecting circuit is employed: both approaches and without a second circuit. The techniques using an auxiliary circuit can be classified as actively detection systems or passively detection systems depending if sensing circuit is powered by a power supply.

3. Survey on MOD

Metal object detection also known as MOD methods play a crucial role in various industries from wireless electric vehicle charging to industrial automation, where presence of metal objects can interfere with operations or safety. Recent research has focused on enhancing MOD systems using innovative coil designs, resonance tuning and sensor-less approaches to improve sensitivity, eliminate blind spots and simplify production processes.

Cheng, et al. [18] explained the market use of inductive power transfer technology requires metal object detection (MOD). The objective of this article is to enhance performance of inductance-based metal object detection systems. In order to reduce the impact of magnetic field utilized for power transmission, two unique multi-layer detection coil layouts are developed that can be separated from the transmitter and receiver and protect charging area without creating any blind spots. Parallel and series resonance are outperformed by the two proposed mixed resonant circuits.

In their study, Thai, Park, Jeong, Rim, and Kim (2020) introduced a novel design for a symmetric sensing coil, distinct from the traditional induced voltage sensing (IVS) approach used in metal object detection. Their high-sensitivity coil was developed through an analysis leveraging an equivalent circuit model and accounted for various influencing factors, including the metal object's surface characteristics, dimensions, and the mutual inductance between coils. Based on their findings, an optimized sensing coil design, supported by finite element simulation, was recommended to achieve maximum sensitivity with minimal use of sensing coils.

Thai et al. [20] proposed symmetric sensing coil set design is complete elimination of blind zones or areas where metal cannot be detected using traditional method. Additionally, the production of suggested sensing coil is simpler and more affordable because to reduction of layers to only one. Based on simulations using the finite element approach and a sensitivity equation proposed sensing coil's design is enhanced for very sensitive MOD.

In [21] A metal object detection (MOD) system, which falls under foreign object detection (FOD) specifically designed for wireless electric vehicle (EV) charging, has now been introduced. This system operates by using mistuned resonant circuits to alter the self-inductance within a sensor layout. The sensing layout, made up of multiple loop coil sets, is attached to the transmitting (Tx) pad of an EV charger. Each loop coil set consists of two coils arranged in series but with opposite polarity, effectively canceling the induced voltage generated by the Tx coil.

In [22] a system of field-oriented sensing coils is developed achieving super high sensitivity and removal of blind zones. To emphasize the impact of MOs, positioning of the detecting coils matches the pole-to pole field distribution of DD coils. A non-symmetric patch coil removes the blind zone brought on by coupling field's axial symmetry. The eddy current field flow in Fig. 3 can explain why this sensitivity is way it is.

In [23] bifurcation phenomena in inductive power transmission are foundation for a sensor less approach of metal object detection (MOD) (IPT). This approach is based on measuring heights of two major current peaks that appear during a bifurcation. By shorting load to cause bifurcation approach can be used in standby mode, for example before starting a power transfer. These current peaks have comparable magnitudes for a tuned system devoid of a metallic component (MO) close by. However, magnitudes are typically not comparable if a MO is attached to charging pads.

Table 1. Comparison of various methods

Author/Year	Method	Advantage	Disadvantage
S. Zhao et al., 2023	MOD with bipolar magnetic field	High sensitivity reached without a blind zone	High sensitivity reached only for 20% of Metal
Niu et al., 2022	Field-oriented sensing coils	High sensitivity	Extra power loss
Scher et al., 2022	Inductive power transfer	No additional space outside system	Influenced by moving nonconductive objects
Zhang et al., 2022	Quadrupole detection coils	Achieve sensitive and blind zone free detection of MOs	A high self-inductance variation rate
J. Tian et al., 2022	MOD based on fusion of spectral and texture features	Can detect both wrapped and unwrapped metal objects effectively	Advanced neural networks required
W. Zhong et al. 2022	MOD with detection power coils for wireless power transfer systems	Proposed method performs well with misalignment between Tx and Rx pads	System heavily relies on Eddy currents
S.Niu et al. 2022	Sensitive MOD method for DD coil-engaged wireless EV by passive EM sensing	Pole to-pole field distribution of DD coils to highlight influence of MOs	VDB methods typically struggle with low sensitivity
Y. Deguchi et al., 2022	Detection using	Clearly defines target and MOs	Works within a specific temperature

	flux density of metal	in D WPT system	range
Li et al., 2021	Long Short-Term Memory (LSTM)	Appropriate for all climates	To increase dependability, detection techniques should be thoroughly thought out
Tian et al., 2021	Multi thread sensing coils	Independence of coil mismatch and average power	Influenced by environment
Long et al. 2021	Dual-frequency IPT system	Simple to incorporate in Tx pad	A challenge to find little metal things
Cheng et al., 2020	Two brand new multi-layer coil layouts	No additional sensor	Affected by coil and power fluctuation
Thai et al., 2020	The conventional MOD approach based on induced voltage sensing (IVS)	High flexibility to coil misaligned and power level	Temperature increase
Thai et al., 2019	Symmetric sensing coil	High detection speed	Huge installation area
Jeong et al. 2018	Mistuned resonant circuits	Simple and low cost	Influenced by bad weather

Tian Lin, Tian, and Xiang [25] propose an innovative approach to MOD (Metal Object Detection) using multi-threaded sensing coils. They first perform simulations to confirm the basic operational principles of conventional even-sensing coils and to identify their limitations regarding sensitivity based on position. In the newly designed multi-thread coil, coil turns for each thread and spacing between neighboring threads are optimized to achieve a uniform voltage distribution, ensuring detection regardless of a metal object’s position within the detection area. A MOD prototype with this multi-threaded coil design is then developed and tested, demonstrating improved performance over traditional sensing coils.

Long et al. introduce a monitoring technique for 5th-order harmonic current in IPT systems, driven by a voltage-fed inverter generating square waves, as an MOD method [26]. To facilitate metal object detection, the 5th-order frequency is integrated into the Tx circuit, which enhances the detectability of harmonic currents while allowing fundamental power transfer to continue. The Rx circuit is likewise tuned to the 5th-order frequency, effectively blocking the harmonic current. In the presence of a metal object, the harmonic current significantly drops at the Tx side, while the Rx circuit remains open, unaffected by the metal object's impact on power flow.

In [27], Yiming, Hui, and Z. (2023) present a novel two-layer coil layout for MOD within wireless EV charging systems. The first layer is designed to detect metal objects in most areas between the receiver and transmitter, while the second layer addresses blind spots, ensuring complete detection coverage. The coil layout reaches a maximum self-inductance change rate of 28.11%, providing high sensitivity both at the center and along the edges, resulting in a quadrupole design that offers effective, blindspot-free detection.

Zhou et al. [28] identify that current MODs struggle with blind spots and difficulty detecting encased metal objects. This research introduces a method combining hyperspectral and texture features to improve detection accuracy. Hyperspectral reflectance density captures material spectral properties, while Tchebyshev moments reflect texture characteristics of foreign objects. Together these features form a feature vector, which is processed through a YOLO v5 neural network to enhance detection. Tests revealed this approach achieved a 100% detection accuracy at the target level.

Zhong et al. [29] propose a MOD technique with detection coils positioned perpendicular to power coils. When no metal object is present, the induced voltage in the detection coils remains zero. However, the placement of a metal object on the Tx pad generates an eddy current, inducing voltage in the detection coils. This method is effective even if there is misalignment between the Tx and Rx pads, operating seamlessly without adjustments across different winding positions. Experimental validation confirms its reliability.

In their study, Zhao et al. [30] address blind zone issues caused by excitation magnetic fields in current MOD technologies. First, they analyze the causes and locations of these blind spots in EV wireless charging systems, focusing on the Tx coil excitation field. They then describe the structure and working principles of a bipolar checkerboard MOD system, providing a clear definition of MOD sensitivity. An

experimental setup demonstrates that the system can achieve a maximum sensitivity of 20%.
In related research, Niu et al. [31] tackle low sensitivity in VBD methods with a new approach using field-oriented sensing coils to eliminate blind zones effectively. The team further developed a MOD mechanism with refined criteria for metal object detection. This helps in achieving heightened sensitivity. Tested with a 3-kW prototype across ten potential intrusion points, the optimized coils successfully removed blind zones along the y-axis.

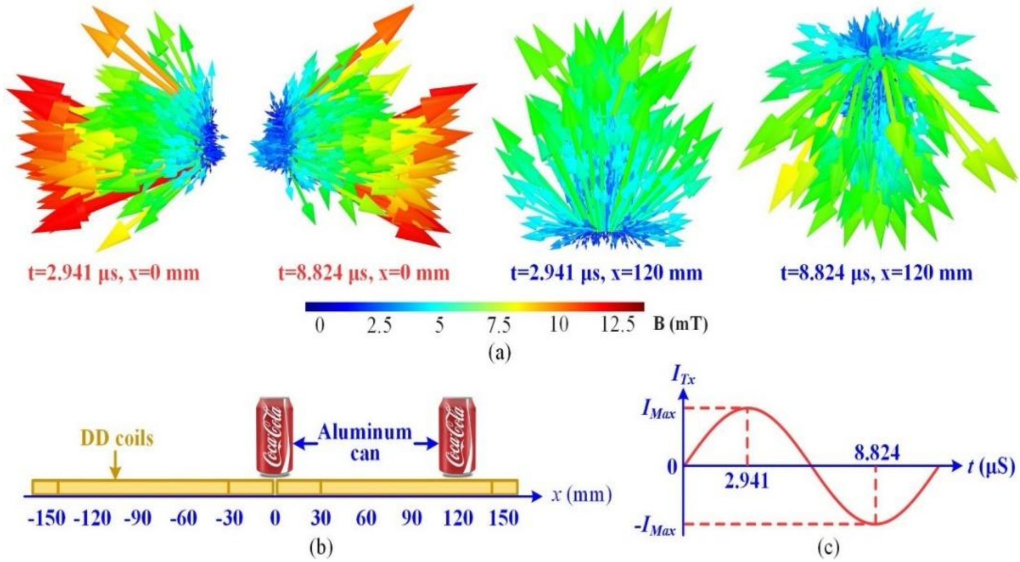

Figure 3: Field flux of Al can in DD coil MOs detection.
(a) Flux distribution (b) Test positions. (c) Test time points.

Deguchi et al. [33] provided a strategy for identifying detecting targets and regions for the D-WPT system. First, an electromagnetic field simulator is utilized to calculate the average magnetic flux density of a single charge in D WPT. Following that, the S-WPT test seat is used to calculate the average magnetic flux density and temperature of many metal plates. The application duration and the D WPT driving condition are same. Finally, the magnetic flux density at the point when each metal's saturation temperature hits 80°C is used as the threshold value, and by comparing it to the average magnetic flux density distribution, the required detection zone is found. The proposed WPT system has a rated power of 20 kW.

4. Survey on Electromagnetic Detection Methods

Electromagnetic detection methods play a pivotal role across various domains from foreign object detection in wireless power transfer systems to ensuring the security of communication networks against potential attacks. Recent research has delved into innovative approaches, such as utilizing perovskite-based detectors active shielding technologies and finite element analysis, to enhance detection accuracy mitigate electromagnetic interference and optimize the performance of electromagnetic systems in diverse applications.
Song et al. [33] The study introduces a novel approach to foreign object detection (FOD) that relies on tracking changes in electromagnetic energy transfer between resonance-based detection coils. Unlike conventional FOD methods that focus on impedance measurement, this approach leverages shifts in electromagnetic resonance to identify foreign objects. A unique coil array structure is proposed, arranged vertically in a domino-like configuration. This structural design allows the detection coil array to be decoupled from the transmitting coil without impacting the power transfer in the wireless power transfer (WPT) system. By aligning the detection magnetic field horizontally, the method effectively eliminates any blind zones across the detection coil surface.
Both simulations and experimental tests confirm the effectiveness of this FOD system. Results demonstrate that the system maintains high sensitivity across various object positions and angles within the detection area, successfully identifying objects as small as a one-yuan coin and a U-shaped needle. This capability ensures that the FOD system performs consistently across the entire detection field,

regardless of the positioning or orientation of the objects..

In [34] waves with high frequencies are highly permeative. This thesis explores the use of perovskites to design two new detector device structures. This includes a unique photodetector that can detect different regions of the visible spectrum and be used for encrypted communications and a novel X-ray detecting device that overcomes limitations of direct X ray detectors. The potential of perovskites as scintillators for indirect X-ray detection is also investigated and suggestions for overcoming remaining challenges are proposed. The thesis emphasizes importance of characterizing perovskite based detectors accurately and discusses challenges of characterizing direct X-ray detectors. Overall, work brings perovskite detectors one step closer to commercialization.

In Thiagarajan & Thangavelusamy research [35] provide a method facilitates EMI reduction without using sophisticated filters. The system is examined for SAEJ2954 violations. The article also illustrates networks of compensation utilized in IPT applications and their efficiency in lowering leakage current induced by converters and coils. This supports precognitive modelling. The research examines how coil's air gap varies with efficiency of power transfer and how this affects electromagnetic interferences. The Fast Fourier Transform (FFT) assessment used in PSIM demonstrates leakage current and harmonic reduction with both compensation platform and Pulse Width Modulation (PWM) approach.

The issue in Zhang & Rasmussen research examines potential for wires connecting an actuator to its control electronics to function as antennas capturing electromagnetic signals from surrounding area [36]. This enables a remote attacker to wirelessly inject signals (energy) into these cables in order to go around controller and command actuator directly. We suggest a cutting-edge detection technique to help microcontroller spot such attacks as a departure from desired value in control signal. We were able to accomplish this without microcontroller having to sample signal frequently or perform any signal processing. Because of this, our protection mechanism is workable and simple to incorporate into current systems.

In [37] double coil dynamic shielding approach is applicable to wireless power transfer (WPT) platforms with varying transmission strands is suggested in this article as an enhanced active shielding technology. For WPT system using double-coil dynamic shielding method, modelling, simulation and testing are carried out and compared to other scenarios. The findings demonstrate that for WPT systems at various transmission strands, suggested double coil dynamic shielding method can block about 70% of electromagnetic field leakage.

Hwang et al. [38] suggested a quick and precise linked analysis technique. Electromagnetic finite element analysis (FEA) is used to calculate motor circuit parameters. The time-consuming FEA is not included in repeating process of proposed technique. This comprises of two steps. The circuit parameters are saved as look up tables (LUTs) in pre-processing stage while taking motor temperature into account. Additionally a method that permits considering a large operating temperature range while taking up less time has been created. Equations for torque and voltage are computed using circuit parameter LUTs in primary process stage. In order to determine thermal properties, deficits are added to lumped parameter thermal network (LPTN) as heat sources.

Alzuabidi & Hussein [39] demonstrated use of finite element methods for early flaws detection of motors for electric vehicles relying on flux performance evaluation in defective electrical machines (FEM). The proposed method has been developed and tested to offer an effective method with excellent precision and timing to identify problems in Electric Vehicle motors. Earlier identification of these errors will allow ample time to avert numerous issues throughout motion, reducing possibility and timing of electric motor failures. The spreading in suggested approach is provided by various scheduling waveforms for motor torque in each circumstance coupled with stator current waveforms.

In [40] electromagnetic risks caused by WPT systems are addressed using three workable solutions. (1) During system's regular charging, a safe distance for pedestrians is established. (2) Based on findings on distribution traits of the WPT system's nearby magnetic field, a thorough power control method is offered. (3) A new method for determining a WPT system's offset distance is suggested and a simple prototype WPT system coupler is created to test the technique.

Zhao et al. [41] explains the technology for multi physics assessment and electromagnetic structure of the axial flux permanent magnet synchronous motor (AFPMSM) for electric vehicles in detail. First, an analytical algorithm-based electromagnetic assessment approach for effective evaluation of AFPMSM was investigated. To confirm accuracy of analytical algorithm the outcomes of the simulation were evaluated to those of a 3D electromagnetic field simulation. Second, torque ripple of AFPMSM was optimized by Auxiliary slot opening with the stator core. This resulted less torque ripple. Table 2 illustrations comparison of various electromagnetic methods.

Table 2. Comparison of various electromagnetic methods

Author/Year	Method	Computational Cost	Current Flow	Voltage Flow
H.Song et al. 2023	Arrayed vertical decoupled coils	High	Moderate	Low
Moseley et al., 2022	Foreign object detection using X-rays	Low	High	Low
Thiagarajan et al., 2022	Fast Fourier Transform (FFT) analysis	High	Moderate	High
Zhang et al., 2022	Defense mechanism	Moderate	Low	Low
Li er al. 2021	Double coil dynamic shielding technology	Low	High	Moderate
Alzuabidi et al. 2021	Electrical machine using finite element methods (FEM)	High	Low	Moderate
Zhao et al. 2019	Axial flux permanent magnet synchronous motor	Low	High	Moderate
Zhao et al., 2019	Electromagnetic Radiation (EMR)	Low	High	Low
Wu et al., 2019	Electromagnetic topology (EMT) based model	High	Moderate	Low
Mohammad et al., 2019	Shielding technique	Moderate	High	High
Wang et al. 2018	Power control strategy	Moderate	Low	High
M. Zhou	Electromagnetic finite element analysis (FEA)	Low	Low	High

Zhao, et al. [42] suggested solution prevents unnecessary visits by using arc's electromagnetic radiation (EMR) as a test platform. To determine how similar the steady-burning arc spectra are, formulas like structural similarity index (SSIM) and 6 dB bandwidth bins (6-dB BWBs) are derived. The experimental validation reveals that suggested steady pattern approach can effectively prevent the occurrence of malfunctions, distinguish arc faults from normal operations and be used as a supplement to conventional methods. In several dc power systems it can also effectively detect arc faults.

Wu et al. [43] proposed a framework and analytical technique for predicting vehicle-level EMI based on electromagnetic topology (EMT). This divides an electric vehicle into many subsystems and converts electromagnetic coupling routes into design parameters. As a result it was possible to model each component independently using various methods and anticipate vehicle level EMI using algebraic calculations. By comparing anticipated low-frequency vehicle emissions with experimental findings and using it to troubleshoot emission issues, efficiency of the suggested strategy was confirmed.

Mohammad, et al. [44] suggested to use a shielding approach to keep magnetic field emissions under the International Commission on Non Ionizing Radiation Protection's guidelines (ICNIRP). Since leakage pattern produced by DD coil is different from that of monopolar (circular, rectangular etc.) pads conventional eddy current-based aluminum shields are ineffectual at controlling this leakage field. Consequently a magnetic shield that has been carefully thought out might be more efficient. In order to reduce the magnetic field emissions this paper suggests a shielding method for DD coils that combines aluminum shielding with a low reluctance magnetic shield.

5. Survey on LOD Based Methods

Living Object Detection (LOD) methods are vital for ensuring the safety and efficiency of wireless electric vehicle (EV) chargers where presence of living organisms near charging coils can pose risks. Recent research has explored diverse approaches. This includes capacitor based systems deep learning with infrared imaging and millimeter radar sensors aimed at enhancing sensitivity and accuracy in detecting living objects to mitigate potential health hazards and operational disturbances in EV charging environments.

In [45] in order to increase sensing sensitivity a multiple comb-pattern capacitor topology based living object detection (LOD) system for wireless electric vehicle (EV) chargers is suggested in this study. A specifically designed parallel-resonant circuit senses fluctuating capacitance of the sensor affected by a neighboring organism. This confirms the presence of living object. Living things that come into contact with potent AC electromagnetic field (EMF) produced by an EV WPT system's power transfer coils may experience symptoms like body warmth blood pressure changes spinning nausea and exhaustion.

In [46], the sufficient spacing between human bodies and the EV-WPT technique is examined using a Wireless Power Transfer technique and a model of human anatomy functioning at multiple frequencies and output powers. The distribution of human organs' generated electric field intensities at various levels

of power at 85 kHz operating frequency is computed using models. This are mostly simulations of electromagnetic fields and thermal impacts. It is evident that when energy level increases, the produced electric field's intensity increases on body parts of human.
Wang et al. [47] suggested to use a FOD system that combines deep learning with infrared imaging. The system develops a model using a denoising convolutional auto encoder technique using random noise as source basic images of foreign objects were recorded by the infrared cameras. In order to determine whether there are outside objects in image, the final output is a noise free source image. This technique also works with LOD to find metal items.
In [48] mentioned to use a millimeter radar sensor-based LOD approach. On cover whole detection area, a radar is mounted to EV edge. The system can detect items that are just slightly moving and differentiating between moving and stationary objects when combined into a developed two dimensional signal processing method.
In [49] an EV-WPT system uses Tx side-mounted 77 GHz millimeter wave radars to look for moving foreign objects. To implement multiple moving object identification and tracking, a detection method incorporating Kalman filtering target gathering and data correlation is also created. Fig. 4 shows living object detection.

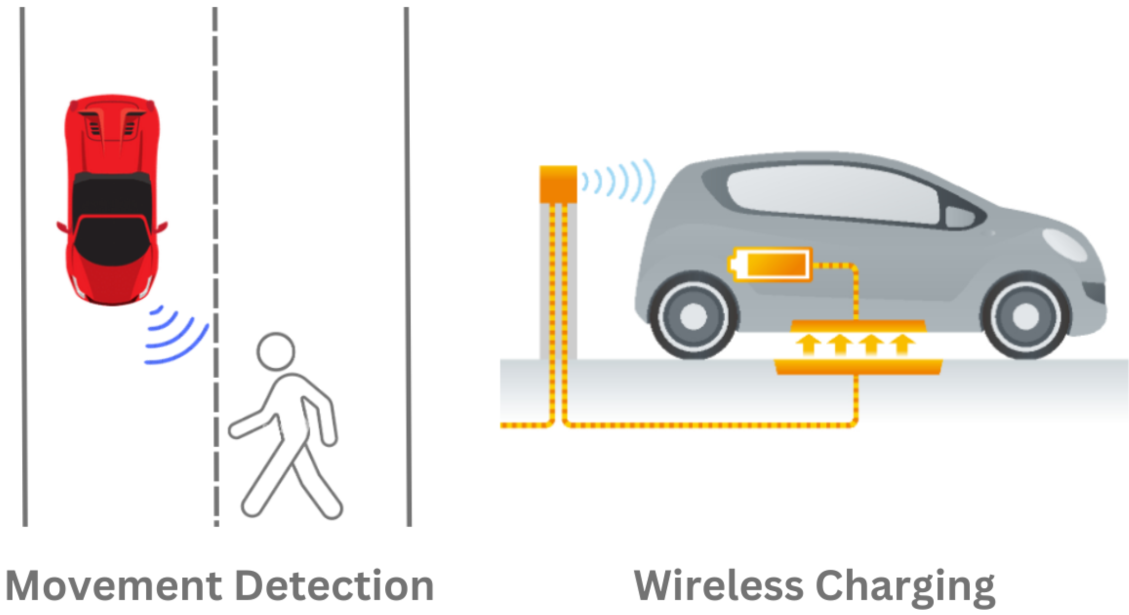

Figure 4: LO detection: (a) Movement detection. (b) Wireless charging
In [50], the paper proposes C4, a real-time, highly accurate human detection method. This approach achieves real-time precision through two main innovations. Firstly, it demonstrates that capturing contour is essential, with pixel comparison signs between neighbors providing crucial contour information. Secondly, the CENTRIST visual descriptor is shown to be particularly effective for human detection, as it encodes sign information and can represent global contours indirectly. This approach achieves a detection speed of 20 frames per second on a robot with a 1.2 GHz CPU, maintaining both accuracy and speed.
Gajjar et al. [51] introduced an advanced human detection method that combines Histograms of Oriented Gradients (HOG), Visual Saliency theory, and the Deep Multi-Level Network saliency prediction model to detect humans in video footage. Additionally, the k-Means algorithm was applied to cluster HOG feature vectors from detected windows, enabling the identification of a person path within the video. This approach achieved a precision rate of 83.11% and a recall of 41.27%, processing at a speed 76.866 times faster than traditional image classification.
In [52], a new living object detection (LOD) system for wireless EV chargers is presented, utilizing a comb pattern capacitive sensor characterized by simplicity and cost-effectiveness. Mounted on a transmitter (Tx) pad, the LOD system employs an optimized comb shape for uniform capacitance, unlike typical capacitive sensor applications. This sensor is specifically adapted for wireless EV chargers,

taking into account significant capacitive coupling between living objects and the ground. A static circuit model incorporating an RC integrator was developed to detect even minor voltage variations, and experimental results showed that the proposed sensor increased capacitance readings by up to 27.5% when a living object was present.
Study [53] explored the magnetic impact on human blood. This could inform improved detectors for tracking living objects with oxyhemoglobin in their blood. This research examines how magnetism affects blood's apparent viscosity, noting that blood flow under gravity decreased by 30% when subjected to a high magnetic field of 10 T. This reduction is attributed to the increase in apparent viscosity caused by the magnetic field, with a correlation based on the Langevin function and other parameters providing a model for these effects.
In [54], research on capacitive pressure sensors could refined detectors within EV charging stations. This study introduces a capacitive pressure sensor for monitoring human activity, fabricated using Au-Au diffusion bonding under ambient pressure. Optimized conditions for Au-Au bonding were explored, achieving a bonding strength of 26.7 MPa at 400ºC and 5.5 MPa. Pressure-capacitance measurements revealed a sensitivity of 7 fF/kPa, showing good linearity over pressure range of 60-100 kPa.
Yonemoto's study presents advancements for EV charging infrastructure optimization. A real-time motion capture system for 3D multi-part objects was developed, reconstructing motion parameters through a vision-based system. This system allows simultaneous acquisition of additional scene details, such as shape and surface characteristics. Implementing a color marker-based system. It is a multi-view fusion was achieved, with real-time processing on PC clusters demonstrating system feasibility.
Lastly, [56] highlights low-energy infrared sensing for wireless EV charging infrastructure, featuring PIR systems for detecting living objects. This paper describes three applications of PIR sensing: a rotating sensor with a self-controlled servo motor for detecting nearby thermal subjects, a sensor with a mask for low-complexity posture recognition and a wearable wrist sensor for identifying nearby objects (particularly beneficial for visually impaired users). According to Compressive Sensing (CS) theory, random down-sampling enhances original signal accuracy more effectively than even sampling.

6. Challenges and Future Directions

Addressing challenges and exploring future directions in metal object detection (MOD) and foreign object detection (FOD) methodologies is crucial for advancing safety and efficiency in wireless charging systems, particularly for electric vehicles. These challenges include enhancing sensitivity and reliability in detecting small metal objects establishing universal metrics for assessing FOD effectiveness integrating multiple detection techniques for improved adaptability and addressing issues related to system parameter variations and detecting constancy. Addressing these challenges will not only refine existing detection methods but also pave way for innovative solutions capable of ensuring robust and reliable operation in diverse environmental conditions.

- Concurrently increasing the assessment of picture quality of image quality, sensitivity and reliability. Small metal objects like a paper clip or perhaps a pin, are still exceedingly challenging for detecting coil based approach of high-power EV wireless charging to detect reliably. Typically sensitivity and dependability are at odds with one another.
- Due to the diverse qualities of foreign objects. This includes their size, shape and placement it is currently challenging to assess the effectiveness of various FOD studies equitably. The establishment of this technology would be substantially accelerated by a universal metric to assess efficacy of FOD approaches and standardized test scenarios might be very beneficial.
- Most of suggested detection techniques for MOD and their implementation during charging center on the change in system characteristics caused by foreign items and don't require an additional circuit. These techniques are always affordable and simple to use. When compared to a high power WPT system, state variation is always relatively moderate and the approaches are not always sensitive to minor objects. Additionally load state and receiver coil misalignment always have an impact on the detection findings and can vary system parameters.
- Combining several detection techniques would help them become more adaptable to various objects, power levels and weather situations while also improving their resolution sensitivity and dependability.
- The detecting constancy needs to be improved. Because the scattered magnetic field is not homogeneous, existing MOD techniques frequently produce varied results for same foreign object depending on the power and position. This makes designing a signal processing circuit more

challenging.

7. Conclusion

The most recent advancements in FOD technology used in IPT systems are reviewed and summarized in this study. The two main detecting items in the FOD technology are MO and the LO. Thus MOD and LOD are two categories for FOD. The deviation from a readily trained model to a pessimistic model, conventional electric field model led to detection metric for foreign object recognition that was provided utilizing the subsequent mistake in restoration of the transmitter current. We have outlined main issues for each component and grouped numerous exemplary approaches and techniques. Further we have outlined several routes specially in the living object detection and Metal object detection that could speed up development of more Scalable, safer and reliable wireless EV charging infra in near future.

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