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TOPICAL REVIEW

Recent Results in Shielding Technologies for Wireless Electric Vehicle Charging Systems

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ABSTRACT Electromagnetic compatibility (EMC) is crucial when designing and operating wireless power transfer (WPT) systems for charging Electric Vehicles (EVs). WPT technology allows the transmission of electrical energy from a power source to a device without requiring physical contact. However, it can generate electromagnetic interference (EMI) that could disturb nearby electronic devices or harm people nearby. Shielding techniques are commonly employed to mitigate EMI in WPT systems. However, implementing effective shielding techniques can be complex, involving trade-offs between effectiveness, cost, and shielding weight. In this article, different types of existing shielding techniques for wireless charging systems of EVs are compared. The main concepts regarding the functioning of electromagnetic shields and the theory of the functioning of WPT systems have been also briefly introduced.

INDEX TERMS Electromagnetic compatibility, wireless power transfer, shielding.

I. INTRODUCTION

WPT technology has gained significant attention in recent years due to their convenience and ease of use. The wireless charging of Electric Vehicles (EVs) has revolutionized the automotive industries and the design of new EVs. WPT systems represent a convenient and efficient charging method since they eliminate the need for physical connections between the source and the load [1], [2]. It is widely used for several applications such as EVs [3], [4], [5], [6], [7], [8], [9], medical implants [10], [11], [12], [13], [14], [15], [16], and consumer electronics [17], [18], [19], [20], [21], [22], [23]. However, like any wireless technology, they are vulnerable to electromagnetic interference (EMI), which can impact their performance and safety, as well as disrupt the environment [24], [25], [26]. The electromagnetic fields generated during wireless charging can cause interference with other electronic devices and pose potential health risks to humans. Therefore, electromagnetic compatibility (EMC) plays a pivotal role in the design of WPT systems.

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The development of effective shielding technologies is crucial to ensure the safety and reliability of wireless EV charging systems. This paper aims to discuss the latest research results and innovations in electromagnetic shielding materials, designs, and techniques for wireless charging of EVs by presenting an extensive comparison of the shielding techniques currently employed for this application. Firstly, the fundamental principles of EMC, encompassing the origins and consequences of Electromagnetic Interference (EMI), are discussed. Various types of shielding techniques are analyzed. A comparison in terms of power, frequency, and type (simulation/ experimental case) between different shielding techniques has been carried out. The article is organized as follows. Section I discusses the main issues related to EMC due to EMI. In Section II, a description of electromagnetic compatibility is presented. In Section III, the WPT system technology is described. Section IV briefly describes the shielding theory and the kind of existing shield. Section V presents a description and a comparison of different shield techniques used in the WPT application. Finally, in section VI, conclusions are made highlighting the potential of these technologies to enhance the performance and safety of wireless EV charging systems and pave the way for a more sustainable transportation future. At the end of the article an Appendix with the summary of the scientific papers used to make the review is reported.

II. ELECTROMAGNETIC COMPATIBILITY

The exposure limits for WPT systems in EVs are defined by international safety guidelines, specifically the International Commission on Non-Ionizing Radiation Protection (ICNIRP) standards [27], [28], [29], [30]. The ICNIRP standards set the maximum allowable levels of electromagnetic field (EMF) exposure for various scenarios, including those involving WPT systems. Different field levels that must be respected have been identified based on the operating frequency. These have been reported in the Fig. 1. The external fields in the proximity of WPT systems for EVs, especially those requiring high power, may exceed the limits of international safety guidelines [31]. Dosimetric evaluations have been conducted to assess the EMF exposure for various scenarios, including a human body in front of the WPT system without shielding, with shielding, alignment, and misalignment between transmitter and receiver, and with a metal plate on the system for vehicle mimic floor pan [31], [32]. The dosimetric results and compliance with the ICNIRP standards are essential considerations in designing and evaluating WPT systems for EVs [33]. A review of the electromagnetic field exposure limits identified in international guidelines, including the ICNIRP standards, has been conducted for WPT applications, specifically for wireless charging of EVs [34]. Even in this article [34], a safety limit region (Fig. 2) has been identified around the vehicle where magnetic fields have a low impact on humans.

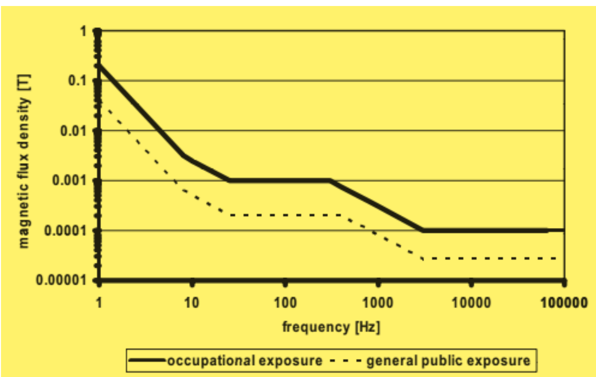

FIGURE 1. Reference level of magnetic field exposure in the operating frequency range of 1 Hz-100 kHz in ICNIRP-2010.

There are several techniques used to mitigate EMI in electronic devices and systems. These techniques include:

1) **Shielding:** Shielding involves enclosing electronic devices and systems in a conductive material, such as copper or aluminum, to block electromagnetic waves from entering or leaving the enclosure [35], [36], [37], [38], [39], [40].

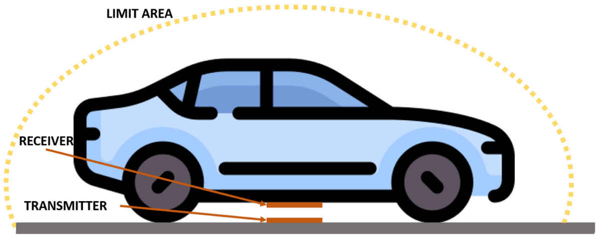

FIGURE 2. Boundary region around the wireless charging system.

2) **Filtering:** Filtering involves using passive components, such as capacitors and inductors, to attenuate EMI on power and signal lines [41], [42], [43].
3) **Grounding:** Grounding involves connecting electronic devices and systems to a common ground to reduce the potential for EMI [44], [45], [46].
4) **Layout:** Layout involves designing the physical layout of electronic devices and systems to minimize the potential for EMI [47], [48], [49].

However, not all of these methods summarised in Fig. 3 can be used for wireless charging of EVs. In general, active and passive screens are used for this type of application using different approaches and materials. To identify the characteristics of the screen to apply, it is important to first describe the behavior of the wireless charging system for EVs.

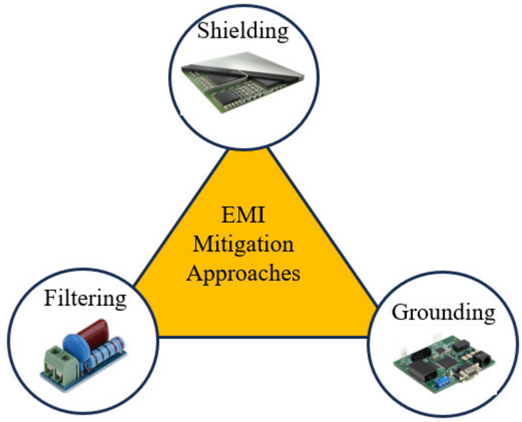

FIGURE 3. EMI mitigation approaches.

III. WIRELESS POWER TRANSFER SYSTEM

This technology uses magnetic fields to transfer electrical energy from a power source to an EV without physical contact between the two [50], [51], [52]. The mechanism of inductive WPT involves using two coils, one placed on the ground and the other in the vehicle, which are placed near each other. When an alternating current is passed through the charging pad coil, it generates a time-varying magnetic field that induces an electrical current in the vehicle's coil. This electrical current is then used to recharge the EV's batteries. Using inductive WPT for EV charging offers

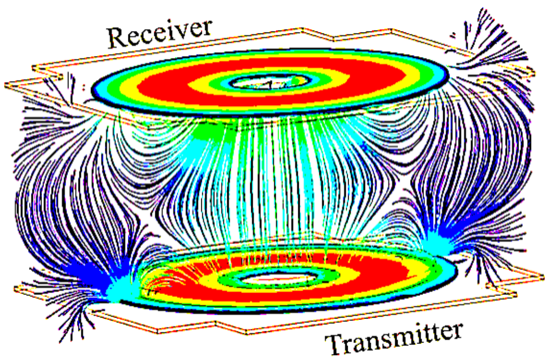

FIGURE 4. WPT system mechanism.

several advantages over traditional wired charging methods. Firstly, it eliminates the need for physical contact between the charging pad and the vehicle, which reduces wear and tear on both components and increases their lifespan. Secondly, it allows for more flexibility regarding where the charging pads can be located(see Fig.4). With traditional wired charging methods, the charging cable needs to be physically connected to both the vehicle and the charging station, which limits the location of the charging station. However, with inductive WPT, the charging pad can be embedded in the road surface or at any convenient location, providing greater convenience for EV owners. The basic principle behind inductive WPT is Faraday's law of electromagnetic induction. This law states that if the conductor is placed in the time-varying magnetic field then there will be a voltage difference across the conductor and consequently the current if the conductor is connected to a load. In the case of inductive WPT, this principle is applied to transfer electrical energy from a power source to an EV without any physical contact between them. The main components of a WPT system include a power source, a charging pad, and a receiver coil in the EV (Fig. 5).

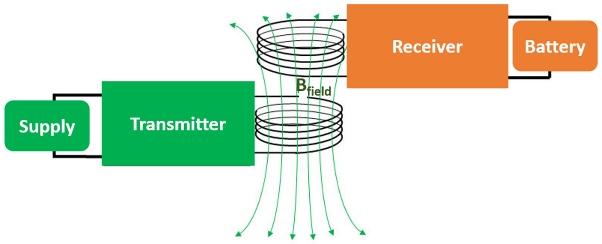

FIGURE 5. Wireless power transfer system components.

The power source can be any type of AC power supply, such as a grid-connected or a renewable energy source like solar panels linked to a DC/AC converter. The charging pad is typically made of copper or aluminum and contains a coil of wire connected to the power source. The receiver coil in the EV is typically placed underneath the vehicle and is connected to the batteries. The efficiency of WPT depends on several factors, including the distance between the charging pad and the receiver coil, the coils' size and shape, and the alternating current's frequency. The efficiency of WPT transfer decreases as the distance between the two coils increases. This is because the magnetic field generated by the charging pad decreases with distance, which reduces the amount of electrical energy transferred to the receiver coil. Several techniques can improve the efficiency of WPT. One technique is to use resonant coupling between the two coils. Resonant coupling occurs when the two coils' natural frequencies are matched, resulting in a stronger magnetic field and more efficient transfer of electrical energy. Another technique is to use multiple charging pads placed along the route of an EV, which allows for continuous charging as the vehicle travels.

IV. SHIELDING THEORY

Electromagnetic fields (EMF) are generated by the flow of electrical current through conductive materials. These fields can interfere with electronic devices, systems, and humans, leading to electromagnetic interference (EMI) and exposure to the human body. The types of fields generated are divided into three categories based on the operating frequency of the field source. Extemely Low frequencies (ELF), such as 50 Hz, low, and high frequencies. Each category is regulated by standards that define the limits of exposure to the related fields and how to mitigate them. Shielding is a technique used to reduce the effects of EMF on electronic devices and systems and human exposure. There are two main types of shielding: active and passive [53], [54], [55]. In the latter case, it is possible to distinguish two other categories based on the material used ferromagnetic or conductive [39], [56], [57]. A diagram of the most common type of shields is reported in Fig. 6.

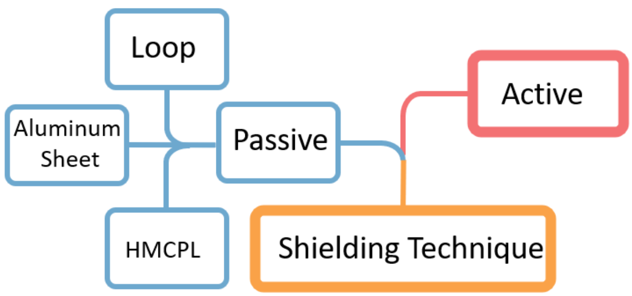

FIGURE 6. Type of shield.

Magnetic shielding involves using materials with high magnetic permeability to create a path of least resistance for magnetic flux lines. Unlike conductive shielding, the magnetic field is not stopped but redirected into the magnetic material. A closed topology shield surrounding the area is preferred to achieve optimal shielding, but this is not possible in a WPT system due to an air gap. The principle behind conductive shielding is rooted in Faraday's law. When magnetic fields fluctuate over time, they create electromagnetic forces that trigger eddy currents in conductive materials. These currents counteract the original magnetic field, effectively neutralizing it. However, not all of the magnetic field is eliminated - the eddy currents reflect some of it on the surface of the conductive shield. At the same time, the rest manages to penetrate through the shield's absorbent properties. The first one is typically achieved using materials that have high magnetic permeability. These materials are placed around the sensitive components to redirect the magnetic field away from them. Ferromagnetic shielding is effective at reducing low-frequency magnetic fields but less effective at reducing high-frequency magnetic fields. The last one is typically achieved using high electrical conductivity materials, such as copper or aluminum. These materials are placed around the sensitive components to absorb or reflect the electric field. Conductive shielding is effective at reducing high-frequency electric fields but less effective at reducing low-frequency electric fields. The shielding properties are measured by two possible parameters. The shielding factor (SF), which is the ratio of the magnetic field w/o the shield in a point in the space and the same with the shield applied. The shielding effectiveness (SE) that is similar to SF but it is expressed in decibels (dB) and they are calculated using the following formula [58]:

$$SF = \frac{B_0}{B_S} \tag{1}$$

$$SE = 20\, log(\frac{B_0}{B_S}) \tag{2}$$

where B_0 is the magnetic field without the shield and B_S is the magnetic field with the shield applied. These parameters depend on several factors, including the material used for the shield, the thickness of the shield, the shape (open or closed see Fig.7), and the frequency of the electromagnetic field. Generally, thicker shields from materials with high magnetic permeability or electrical conductivity provide better shielding.

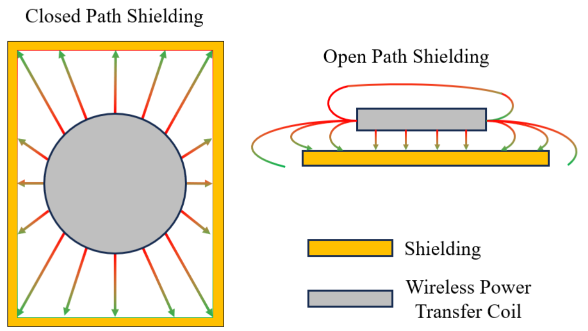

FIGURE 7. Type of shielding shape a) closed path, b) open path.

Several materials can be used for shielding, including metals, conductive polymers, and composites.

- **Metals**: are the most commonly used materials for shielding. Copper and aluminum are the most common metals used for electric shielding, while mu-metal and permalloy are commonly used for magnetic shielding. Metals can be formed into sheets or foil and applied to the surface of the shielded device or system [59], [60], [61].
- **Conductive polymers**: are a newer class of materials developed for shielding applications. These polymers, such as carbon or metal, contain conductive particles that provide electrical conductivity. Conductive polymers can be molded into complex shapes, making them ideal for shielding applications requiring a custom shape [62], [63], [64].
- **Composites**: are materials made by combining two or more different materials. Composites can be designed to have specific properties, such as high magnetic permeability or electrical conductivity, making them ideal for shielding applications. Composites can be formed into sheets or molded into complex shapes [65], [66], [67].

Following the description of the type of shielding and their operation, it is necessary to understand which phenomena are involved in the WPT system to design a correct shielding. For this reason, the operation of this system has been briefly described in the following chapter.

V. TYPES OF ELECTROMAGNETIC SHIELDS APPLIED ON WPT SYSTEM

A. ACTIVE

The principle of operation of an active electromagnetic shield is based on electromagnetic induction. Electromagnetic induction is when a changing magnetic field induces an electric current in a conductor. This process is used in many electrical devices, such as transformers and generators. An active electromagnetic shield generates the changing magnetic field by an array of coils around the sensitive electronic equipment. The coils are connected to a power source that generates an alternating current (AC) that flows through the coils (Fig. 8).

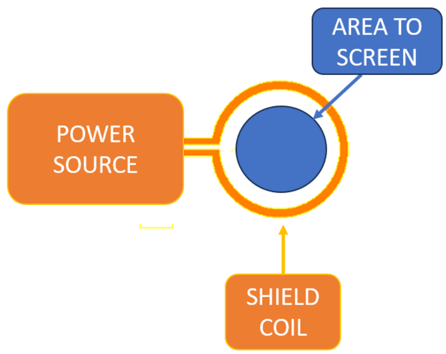

FIGURE 8. Active electromagnetic shield diagram.

The alternating current creates a changing magnetic field around the coils. An external electromagnetic wave entering the shielded area induces an electric current in the coils. This induced current creates a magnetic field that opposes the external field. The opposing magnetic field cancels out the external field, neutralizing the EMI. The effectiveness of the active electromagnetic shield depends on several factors, including the frequency and strength of the external electromagnetic wave, the distance between the shield and the sensitive equipment, and the number and placement of the coils. The shield must be designed to generate a magnetic field that is strong enough to cancel out the external field without interfering with the operation of the sensitive equipment. Active electromagnetic shields offer several advantages over other types of EMI shielding methods. One of the main advantages is their ability to adapt to changing EMI conditions. Unlike passive shielding methods, which rely on physical barriers to block electromagnetic waves, active shields can generate an opposing field that neutralizes the EMI. This makes them more effective in environments where the EMI is constantly changing. Another advantage of active electromagnetic shields is their ability to block specific frequencies of electromagnetic waves selectively. This is achieved by tuning the alternating current frequency that flows through the coils. By adjusting the frequency, the shield can block specific EMI frequencies while allowing other frequencies to pass through. This is particularly useful in applications where specific frequencies of EMI are more harmful than others. Active electromagnetic shields also offer a higher level of protection than passive shielding methods. Passive shielding methods like Faraday cages rely on physical barriers to block electromagnetic waves. However, these barriers can be breached by high-frequency electromagnetic waves or by gaps in the shielding material. On the other hand, active shields generate an opposing field that cancels out the EMI, providing a higher level of protection.

1) LOOP

Regarding this category of screens, several studies have been conducted [68], [69], [70], [71], [72], [73], [74]. Table 1 compares the most recent work on this screen type for the WPT system.

TABLE 1. Comparison of the latest active shielding methods using a loop.

ine Ref.	Power	Frequency	Sim./Exp.
ine [68]	12 kW	20 kHz	Both
[69]	20 kW	20 kHz	Both
[70]	100 W	85 kHz	Both
[71]	7.7 kW	85 kHz	Sim.
[72]	1kW	83.3 kHz	Both
[73]	-	85 kHz	Both
[74]	200W	85 kHz	Both
ine			

From the data reported in the table 1 it can be seen that the most used frequency of the WPT system is 85 kHz and alternatively in some particular cases 20 kHz. In the literature, tests have also been carried out for different values of transmitted power starting from a minimum value of 700 W up to a maximum value of 20 kW. For these ranges of values, in most cases both laboratory tests and simulations were conducted in order to validate the proposed shielding system. The design characteristics of each application are reported in the summary of the relative table in the appendix.

B. PASSIVE

A passive electromagnetic shield is a device that protects sensitive electronic equipment from the harmful effects of electromagnetic interference (EMI) by creating a physical barrier that blocks electromagnetic waves. The principle of operation of a passive electromagnetic shield is based on the concept of Faraday's cage. A Faraday cage is an enclosure made of conductive material that blocks electromagnetic waves from entering or leaving the enclosure. The cage creates a conductive shield around the sensitive electronic equipment, which reflects the electromagnetic waves away from the equipment. The effectiveness of a passive electromagnetic shield depends on several factors, including the conductivity and thickness of the shielding material, the size and shape of the enclosure, and the frequency and strength of the electromagnetic waves. The shield must be designed to block all frequencies of EMI that could interfere with the operation of the sensitive equipment. Passive electromagnetic shields offer several advantages over other types of EMI shielding methods. One of the main advantages is their simplicity and reliability. Passive shields do not require any external power source or complex electronics, making them easy to install and maintain. They also do not generate any additional heat or noise, which can be crucial in applications where temperature or noise levels are critical. Another advantage of passive electromagnetic shields is their complete isolation from external electromagnetic fields. Unlike active shields, which generate an opposing field that cancels out the EMI, passive shields create a physical barrier that completely blocks the electromagnetic waves. This provides a higher level of protection against EMI that could harm sensitive electronic equipment. Passive electromagnetic shields also offer high durability and resistance to environmental factors. The shielding material used in passive shields is typically made of metal, resistant to corrosion and physical damage. This makes passive shields ideal for use in harsh environments.

1) ALUMINUM SHEET

Aluminum sheet shields are one of the most commonly used shielding materials in WPT system design [75], [76], [77], due to their high conductivity, flexibility, and ease of (Fig. 9).

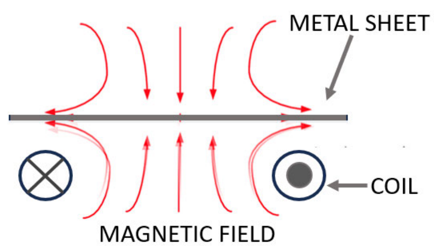

FIGURE 9. Metal sheet electromagnetic shield diagram.

Aluminum sheet shields offer several key characteristics that make them an attractive choice for WPT system design. These include:

- **High Conductivity:** Aluminum is a highly conductive material, with a conductivity of approximately 37.7 MS/m. This high conductivity allows for efficient transfer of electromagnetic energy through the shield, reducing losses and improving system efficiency.
- **Flexibility:** Aluminum sheet shields are highly flexible, allowing them to be easily shaped and molded to fit complex geometries. This flexibility makes them an ideal choice for applications where space is limited or where the shield must conform to irregular shapes.
- **Easy to Use:** Aluminum sheet shields are easy to work with, requiring only basic cutting and shaping tools. They can be easily attached to other components using screws, adhesives, or other fasteners.
- **Lightweight:** Aluminum is a lightweight material, making it an ideal choice for applications where weight is a concern. This can be particularly important in aerospace or automotive applications, where weight reduction is a key design consideration.

When designing an aluminium sheet shield for a WPT system, several key considerations must be taken into account. These include:

1) **Shield Thickness:** The thickness of the aluminum sheet shield depend on the frequency range of the electromagnetic energy being shielded. Thicker shields are typically required for higher frequency ranges, as these frequencies are more difficult to block.
2) **Shield Size:** The size of the aluminum sheet shield depends on the size of the components being shielded. The shield must be large enough to completely enclose the component while allowing for proper ventilation and heat dissipation.
3) **Shield Shape:** The shape of the aluminum sheet shield depends on the shape of the shielded component. The shield must be designed to completely enclose the component while allowing for proper access and maintenance.
4) **Shield Attachment:** The aluminum sheet shield must securely attach to the shielded component using screws, adhesives, or other fasteners. The attachment method must be strong enough to hold the shield in place while allowing easy removal and reinstallation.

2) LOOP

Passive loop shields are electromagnetic shielding used in the design of WPT systems [78], [79], [80]. They consist of a loop of conductive material, such as copper or aluminum, placed around the system (Fig. 10).

The loop is a barrier, preventing electromagnetic energy from passing through and interfering with the component's performance. Passive loop shields offer several key characteristics that make them attractive for WPT system design. These include:

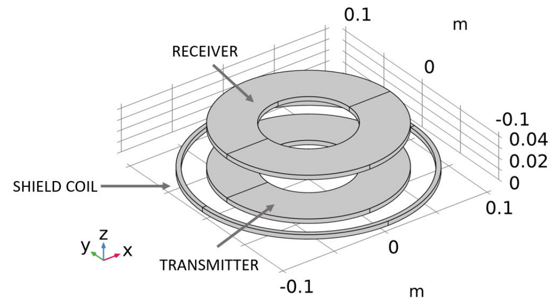

FIGURE 10. Passive loop electromagnetic shield diagram.

- **High Shielding Effectiveness:** Passive loop shields are highly effective at blocking electromagnetic energy, providing excellent shielding performance for sensitive electronic components.
- **Low Cost:** Passive loop shields are relatively inexpensive to manufacture, making them an economical choice for many applications.
- **Easy to Install:** Passive loop shields are easy to install, requiring only basic tools and materials. They can be attached to the component being shielded using screws or other fasteners, or simply placed around the component.
- **Compact Size:** Passive loop shields are typically small and compact, making them an ideal choice for applications where space is limited.

Several key considerations must be made when designing a passive loop shield for a WPT system. These include:

1) **Loop Size:** The loop size depends on the frequency range of the electromagnetic energy being shielded. Larger loops are typically required for lower frequency ranges, while smaller loops may be sufficient for higher frequency ranges.
2) **Loop Shape:** The shape of the loop depends on the shape of the shielded component. The loop must enclose the component while allowing complete access and maintenance.
3) **Loop Material:** The material used for the loop depends on the conductivity and magnetic permeability required for the application. Copper and aluminum are commonly used for passive loop shields, offering high conductivity and low magnetic permeability.
4) **Loop Placement:** The loop placement depends on the location of the shielded component and the direction of the electromagnetic energy. The loop should be placed close to the component and oriented to block the incoming electromagnetic energy.

Regarding this category of shields, several studies have been conducted [81], [82], [83], [84], [85]. Table 2 compares the most recent work on this screen type for the WPT system. From the data reported in the table 2 it can be seen that the

TABLE 2. Comparison of the latest passive shielding methods.

Ref.	Power	Frequency	Sim./Exp.
[81]	3 kW	85 kHz	Sim.
[82]	6.6 kW	3.125 MHz	Both
[83]	7 kW	85 kHz	Both
[84]	100 W	30 kHz	Both
[85]	800 W	30 kHz	Both

most used frequency of the WPT system are 30 or 85 kHz. In the literature, tests have also been carried out for different values of transmitted power starting from a minimum value of 100 W up to a maximum value of 6.6 kW. For these ranges of values, in most cases both laboratory tests and simulations were conducted to validate the proposed shielding system. Compared to articles in which active screens are used, the transmitted power values are considerably lower. This is certainly a factor related to the type of electromagnetic screen to be used, depending on the power output of the system. The design characteristics of each application are reported in the summary of the relative table in the appendix.

3) HIGH MAGNETIC COUPLING PASSIVE LOOP

The article [86] discusses a new shielding technique for WPT systems, called High Magnetic Coupling Passive Loop (HMCPL). The technique combines magnetic and conductive materials to create a shield that can block unwanted magnetic fields and reduce energy loss during power transfer. This innovative approach has shown promising results in reducing energy loss and improving transmission efficiency. The article also highlights the potential applications of this technique in various industries, such as electricity. Overall, this new shielding technique has the potential to improve significantly the performance and reliability. The system was simulated in conditions of both alignment between the transmitting and receiving coil and in misalignment conditions. In both cases, a good shielding factor was achieved with this innovative technique, represented in the Fig.11.

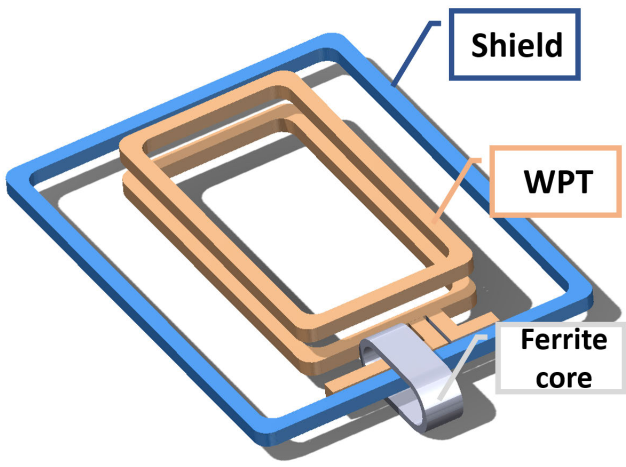

FIGURE 11. High magnetic coupling passive loop shielding system.

VI. DISCUSSION

WPT systems have become increasingly popular due to their convenience and ease of use. However, these systems require a shielding method to prevent interference with other electronic devices and to ensure safe operation. In this discussion section, the advantages and disadvantages of the different shielding methods used in WPT systems are compared.

1) Magnetic Shielding: Magnetic shielding is the most common method used in WPT systems. It involves the use of a magnetic shield to contain the magnetic field generated by the system. The advantages of magnetic shielding include:
   - Effective in containing the magnetic field and preventing interference with other electronic devices.
   - Simple to design and implement.
   - Low cost.

   However, there are also some disadvantages to magnetic shielding:
   - Magnetic shielding can be bulky and heavy, which can limit its use in certain applications.
   - Magnetic shielding can reduce the efficiency of the WPT system by absorbing some of the energy.
2) Electric Shielding: Electric shielding involves the use of an electric shield to contain the electric field generated by the WPT system. The advantages of electric shielding include:
   - Effective in containing the electric field and preventing interference with other electronic devices.
   - Can be designed to be lightweight and compact, making it suitable for a wide range of applications.

   However, there are also some disadvantages to electric shielding:
   - Electric shielding can be more complex to design and implement than magnetic shielding.
   - Electric shielding can be more expensive than magnetic shielding.
3) Hybrid Shielding: Hybrid shielding involves the use of both magnetic and electric shielding to contain both the magnetic and electric fields generated by the WPT system. The advantages of hybrid shielding include:
   - More effective in containing both the magnetic and electric fields compared to using either magnetic or electric shielding alone.
   - Can be designed to be lightweight and compact, making it suitable for a wide range of applications.

   However, there are also some disadvantages to hybrid shielding:
   - More complex to design and implement than either magnetic or electric shielding alone.
   - More expensive than either magnetic or electric shielding alone.

The trend of the magnetic field lines generated by the WPT system is influenced by the type of vehicle structure. The structure of the vehicle can affect the shielding

TABLE 3. Summary of the latest active shielding methods.

Reference	Method's summary
Su Y. Choi et al. [68]	The authors proposed three generalized design methods for canceling the electromagnetic field (EMF) in inductive power transfer systems (IPTSs) of wireless electric vehicles (WEVs). The cancellation of EMF is crucial for the safety of pedestrians and should be achieved for every space, time, and load condition of interest. The first design method involves adding active EMF cancel coils to each primary and secondary main coil, independently canceling the EMF generated from each primary coil. The second method suggests canceling a dominant EMF source with a 3-dB margin, which can be applied to any resonant-type WPT system. The third method focuses on placing cancel coils aside from the magnetic coupling path to minimize power drop. The proposed design methods are demonstrated through design examples for U-type and W-type IPTSs and a wireless stationary EV charger. Experimental verifications are shown for an I-type IPTS with a narrow rail width structure and alternating magnetic polarity along a roadway. The optimum spacing for canceling coils from primary coils and the optimum number of turns is determined through experiments. The article highlights the importance of EMF mitigation techniques, such as the magnetic mirror method and passive shielding on the receiving side, in achieving effective EMF cancellation. The proposed methods offer a comprehensive approach to reducing EMF in IPTSs for WEVs, ensuring the safety of pedestrians while maintaining efficient power transfer.
W.Songcen et al. [69]	The paper focused on developing an electromagnetic shielding design for the magnetic coupler of an N-type dynamic EV WPT (WPT) system. The N-type dynamic WPT system is a wireless charging system used to charge the batteries of EVs while they are in motion. The main objective of the research is to reduce the electromagnetic field (EMF) leakage and improve the electromagnetic compatibility (EMC) of the N-type dynamic WPT system. The article proposes an improved active shielding technology called the double-coil dynamic shielding scheme, designed to shield the electromagnetic field generated by the currents flowing into the coils of the WPT system. The research includes modeling, simulation, and experiments to evaluate the performance of the double-coil dynamic shielding scheme. The study results show that the proposed shielding scheme is able to shield approximately 70% of the electromagnetic field leakage for WPT systems at different transmission distances while causing only a 3.1% degradation in transmission efficiency. This demonstrates the effectiveness and feasibility of the proposed scheme. The article contributes to developing electromagnetic shielding designs for N-type dynamic WPT systems, which can help improve the efficiency and safety of wireless charging for EVs.
J. Ahn et al. [70]	A control method for an active shield system using an independent power source under misalignment conditions was proposed. The method controls the current strength and phase of the shielding system according to magnetic field leakage characteristics, resulting in high shielding performance (SP) under misalignment conditions. The proposed method considers x and y misalignment conditions and analyzes SP and power transfer efficiency (PTE). Simulations and experiments were conducted to verify the proposed method regarding SP and PTE. The experiments confirmed that, due to the shielding system control, SP increased from 49.22% to 61.74% under misalignment conditions. However, there was no additional PTE reduction due to shielding coil control under these conditions.
S.Cruciani et al. [71]	Discusses optimizing a shielding structure composed of multiple active coils for mitigating the magnetic field in an automotive WPT system at 85 kHz. The proposed procedure is described and applied to shield the magnetic field beside an EV with SAE standard coils during wireless charging. The results show that the magnetic field in the most critical area is significantly reduced (i.e., approximately halved) with a minimal influence on the electrical performances (i.e., WPT efficiency decreases by less than one percentage point compared to the case without active shielding)
K. Furukawa et al. [72]	This work proposes and analyzes low-radiation noise WPT systems with active shielding. The method involves compensating the current flowing on additional windings around the WPT coils with additional power supplies to cancel the magnetic field generated by the coils. The current of the additional windings is controlled with the additional power supplies to achieve a zero magnetic field at rated power. The proposed active shielding technique achieves a transmission power of 1 kW and a reduction in radiation noise by 39.5 dB. It is also revealed that reducing the magnetic field increases the transmission power. The article presents a detailed analysis of the system and its performance, demonstrating the effectiveness of the proposed active shielding method in reducing electromagnetic radiation while maintaining high transmission power.
Y.Li et al. [73]	The article proposes an improved active shielding technology for WPT systems with different transmission distances in EVs. The transmission distance during wireless charging can vary, leading to different electromagnetic field (EMF) leakage levels. The proposed double-coil dynamic shielding scheme aims to address this issue. The study includes modeling, simulation, and experiments to evaluate the performance of the WPT system with the double-coil dynamic shielding scheme. The results are compared with other cases to assess the effectiveness and feasibility of the proposed technology. The findings demonstrate that the double-coil dynamic shielding scheme can shield approximately 70% of the EMF leakage for WPT systems at different transmission distances. Additionally, it causes only minimal degradation in transmission efficiency, with a reduction of 3.1% compared to the cases without shielding. This indicates that the proposed technology effectively reduces EMF leakage without significantly impacting the transmission efficiency of the WPT system in EVs.
J.Kim et al. [74]	The authors proposed a dual loop reactive shield application to reduce leakage electromagnetic field (EMF) while enhancing power transfer efficiency (PTE) in WPT systems. The proposed dual-loop reactive shield generates in-phase and out-of-phase magnetic fields simultaneously. The out-of-phase magnetic field suppresses leakage EMF, while the in-phase magnetic field increases PTE, balancing shielding effectiveness (SE) and PTE. The method is tested on symmetric and asymmetric WPT systems, including misalignment conditions. Experimental results for the symmetric WPT system showed a 2.1% PTE increase with 55.5% SE in an alignment condition and a 3.9% PTE increase with 53% SE in a misalignment condition. The results of the asymmetric WPT system demonstrated a 1.6% PTE increase with 61.3% SE in an alignment condition and a 2.7% PTE increase with 54.1% SE in a misalignment condition. The proposed dual-loop reactive shield application offers a promising solution for reducing leakage EMF without significant PTE degradation in WPT systems, potentially addressing the adverse effects of exposure to leakage EMF on human health.

method of the WPT system. Research has shown that the WPT system's structure, including the coupling structure, coil alignment, and shielding method, can significantly impact the system's efficiency, misalignment tolerance, and electromagnetic interference (EMI) reduction. For example, a study proposed a method to optimize the WPT structure to improve efficiency, and another paper discussed an active shielding control method to enhance shielding performance

TABLE 4. Summary of the latest passive shielding methods.

Reference	Method's summary
A. Dolara et al. [81]	The paper focuses on the design and magnetic shielding of a resonant WPT system for EV battery charging. The main objective of the research is to evaluate the impact of design parameters on people's exposure to electromagnetic fields and to analyze the effectiveness of magnetic field shielding methods. The article discusses the following key points: Evaluation of design parameters: The research evaluates the impact of the design parameters of a power pad for an EV wireless charging device on people's exposure to electromagnetic fields. The International Commission tests the overall system's behavior on Non-Ionizing Radiation Protection directives regarding people's exposure to the risks arising from electromagnetic fields. Effectiveness of magnetic field shielding: The effectiveness of magnetic field shielding methods, specifically through conductive panels, is analyzed. The shielded coreless transformer is modeled and examined using Finite Element software. Optimization of shielding structure: The research proposes optimizing a shielding structure composed of multiple active coils for mitigating the magnetic field in an automotive WPT system. Each active coil is independently powered, and the most suitable excitation is obtained through an optimization procedure based on the Gradient Descent algorithm. The results show that the magnetic field in the most critical area is significantly reduced with a minimal influence on the electrical performances. Shielding design for high-frequency WPT system: The article provides a complete coil and shielding design solution for a 6.6 kW EV WPT system based on compact self-resonant (SR) coils. The high-frequency parasitic capacitance introduced by the magnetic and conductive shielding materials is analyzed, and a shielding geometry optimization method is proposed. Prototype aluminum-backed SR coils are fabricated to validate the modeling, achieving 92.3% dc-dc efficiency and 7.1 kW/dm3 volumetric power density. Shielding sensor coil for misalignment and leakage magnetic field issues: A shielding sensor (SS) coil is proposed to solve the misalignment and leakage magnetic field issues of the WPT system for EVs. The proposed SS coils are located over the Tx coil, and the newly created mutual inductance between the Tx coil and the SS coil is used to detect the misalignment of the receiver. The current phase of the SS coil is adjusted through impedance control to reduce the leakage magnetic field.
R.Qin et al. [82]	The article provides a complete design solution for a 6.6 kW WPT system for EV charging. The system is based on compact self-resonant (SR) coils with shielding considered. The paper analyzes high-frequency parasitic capacitance introduced by the shielding material and proposes a shielding geometry optimization method. A conductive vehicle body above the receiver coil requires the shielding of vertical fringing flux in any EV wireless charger. Standard shielding design approaches can introduce parasitic capacitance that degrades the quality factor of high-frequency SR coils. The article proposes a shielding geometry optimization method that uses ferrite for shielding and an additional dielectric spacer to minimize the total thickness of the coils. Prototype aluminum-backed SR coils are fabricated to validate the modeling. The total thicknesses of the transmitter and receiver coils are only 11.4 mm and 7.4 mm, respectively. The system achieves 92.3% DC-DC efficiency and 7.1 kW/dm3 volumetric power density, demonstrating the first 6.6-kW WPT system for EV charging using compact self-resonant coils at MHz with practical shielding implementation.
M.Mohammad et al. [83]	The article proposes a novel hybrid shield structure to limit electromagnetic field (EMF) emission and minimize shield loss in a wireless charging system (WCS) designed for EV applications. The article's primary focus is to develop a detailed lumped model of the shield and an optimization method to minimize the shield loss while suppressing the emission within the standard limit set by the International Commission on Non-Ionizing Radiation Protection (ICNIRP). The electromagnetic emission in a WCS is a severe concern for health and safety, especially for medium- and high-power applications, where a strong magnetic field propagates through a large air gap. Usually, a flat aluminum plate is used as a shield to suppress the emission outside the charging area. However, this field emission increases proportionally with the coil ampere turn, requiring a much higher shield current to suppress the additional emission under the ICNIRP limit. The proposed hybrid shield structure is evaluated on a laboratory prototype of a 7-kW WCS designed for EV applications. The experimental results show that, while suppressing the EMF under the limit, the shield loss has been reduced by 21% compared to the commonly used aluminum shield. This improvement in shield loss can lead to more efficient and safer wireless charging systems for EVs.
H.Kim et al. [84]	The article presents a method to reduce the leakage of a magnetic field from a WPT system. The method involves using a ferrimagnetic material and metallic shielding in the coil structure of the WPT system. The advantages of this coil structure are demonstrated through a 3D electromagnetic field solver and SPICE simulations, as well as experimental verification with a 100 W-class WPT system for an LED TV. The proposed method considerably reduces the leakage magnetic field near the WPT system without significant loss of electrical performance. This is important as exposure to leakage electromagnetic fields (EMF) can have adverse effects on human health. The article also mentions other studies focusing on reducing leakage EMF through shielding methods. However, these methods often resulted in decreased power transfer efficiency (PTE) of the WPT system. Therefore, a shielding method providing high shielding effectiveness (SE) without PTE degradation is necessary.
Y.Yashima et al. [85]	The article presents a new conceptual magnetic shielding method that reduces the leakage of magnetic field exposure from the wireless Inductive Power Transfer (IPT) assembly. The method is based on the combined magnetic shielding implementation, which uses the magnetic flux path concept by magnetic material and the magnetic field cancellation principle eddy current induced into the conductive plates. Analytical considerations and experimentally observed data prove the effectiveness of the leakage magnetic shielding technique in WPT. The authors have developed a cost-effective WPT-OBC embedding the voltage-fed quasi-resonant ZVS high-frequency inverter with a single IGBT switch, which operates under the condition of a PWM-dependent PFM control scheme.

under misalignment conditions [70], [87]. Additionally, a novel coupling structure was designed to improve the tolerance of the EV WPT system, considering coupling structure misalignment and the deflection caused by relative location changes, demonstrating good anti-misalignment and anti-deflection performance [88]. These findings indicate that the vehicle's structure can influence the choice and effectiveness of the shielding method in WPT systems. For the design of each type of screening system, different geometric and performance optimization methodologies are used. In this

TABLE 5. Summary of the latest passive shielding methods 'Loop'.

Reference	Method's summary
M.Lu et al. [94]	The article discusses the effectiveness of different passive shielding methods for reducing the magnetic field in inductive power transfer (IPT) systems. The study evaluates the shielding performance (SP) and power transfer efficiency (PTE) of various passive shields under different conditions. The authors compare the performance of three passive shields: a shielded coreless transformer, a shielded pad, and a shielded coil. They use Finite Element software to model and examine the behavior of these shields in a resonant WPT system for EV battery charging. The results show that the shielded coreless transformer and the shielded pad are more effective in reducing the magnetic field than the shielded coil. However, the shielded coil has a higher PTE than the other two shields, indicating that it is a more efficient option for power transfer. The study also considers the effects of misalignment on the SP and PTE of the passive shields. The results show that the shielded coreless transformer and pad maintain high SP even under misalignment conditions. In contrast, the shielded coil experiences a decrease in SP due to the misalignment. In conclusion, the article comprehensively compares different passive shields for coils in IPT systems. The results can guide the design and optimization of shielding structures for various applications, such as automotive WPT systems.
M.Lu et al.[95]	The article investigates a resonant reactive shielding coil for WPT systems. The focus is on designing and optimizing a Litz shield, which attenuates the magnetic field above and to the side of air-core WPT coils. The article provides a parameterized coil model that allows for arbitrary circular winding geometry and current direction, detailed modeling, mathematical calculations, and an optimized design algorithm. Experimental results show that the peak flux density on the top-center area of the coil is suppressed from 105 μT to 50 μT, and the magnetic field to the side of the vehicle is maintained well below the safety standard. The effect of the shielding coil in WPT systems with metal and ferrite plates is also investigated.
M.Mohammed et al. [96]	The article "A Litz-Wire Based Passive Shield Design to Limit EMF Emission from Wireless Charging System" proposes a passive shield design using a litz wire to suppress electromagnetic field (EMF) emission from wireless charging systems. The traditional methods of using a passive aluminum plate or active anti-turn design show limited controllability of the shield current, and the high-frequency eddy current loss in the passive aluminum plate can be significant, especially under misalignment. The proposed shield design consists of a thin aluminum plate and a passive litz-wire-loop around the outer radius of the pad. The litz wire helps mitigate the high-frequency skin effect and significantly reduces the shield resistance, resulting in excellent controllability of the shield current and EMF suppression. This method is also effective for minimizing shield loss. Experimental results demonstrate that approximately 80% of the shield current is induced in the litz-wire-loop, leading to effective EMF suppression and minimized shield loss.

discussion section the different existing typologies will not be listed but a general discussion will be made. The optimization methods for the design of a shielding system for WPT systems of electric vehicles include the following:

A. SYSTEMATIC APPROACH FOR OPTIMIZATION OF DESIGN PARAMETERS

The design of the magnetic field is crucial for determining the electrical performance of the power transfer system. A systematic approach for the optimization of design parameters is required to maximize transfer power efficiency while satisfying power transfer efficiency and electromagnetic field (EMF) regulation [89].

B. METAMODELING WITH A MULTIOBJECTIVE OPTIMIZATION ALGORITHM

The combination of metamodeling with a multiobjective optimization algorithm, such as Polynomial Chaos Expansions (PCE) and Multigene Genetic Programming Algorithm (MGPA), provides an efficient approach for shielding optimization. This method is used to determine the optimal design variables for a practical shielding design, considering the magnetic coupling and the cost of the shielding as objective functions [90].

C. RAIN OPTIMIZATION ALGORITHM (ROA)

The rain optimization algorithm is used to optimize the coupling coefficient in the design of the charging coils for inductive type WPT systems in electric vehicles [91].

D. DESIGN OPTIMIZATION METHOD FOR COIL WINDING

A design optimization method for rectangular pad winding is proposed to improve the coupling coefficient of the coupling coil. This method involves optimizing the turn-to-turn distance, the number of coil turns, coil start position, and coil size [92].

E. SHIELDING GEOMETRY OPTIMIZATION METHOD

For high-frequency WPT systems, a shielding geometry optimization method is proposed to address the degradation of the quality factor of the coils due to the parasitic capacitance introduced by standard shielding design approaches. This method involves the analysis of high-frequency parasitic capacitance and the use of ferrite and an additional dielectric spacer in the shielding design [93].

VII. CONCLUSION

In conclusion, various methodologies have been developed to shield the electromagnetic field of WPT systems. Each of these methods has its advantages and limitations, and the choice of shielding technique depend on the specific application and requirements. Further research and development are needed to optimize their effectiveness and practicality for different applications. By continuously improving and refining these techniques, it is possible to pave the way for more efficient and reliable WPT systems, enabling the widespread adoption of EVs and other wireless charging applications. For greater completeness of the work, tables are added in the appendix, which includes a summary of the works in the bibliography.

APPENDIX

See Tables 3–5.

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