Shielding Technologies for Solar Wireless ElectricVehicle 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 makes it possible to transmit electrical energy without having to physically touch a device from a power source. 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. In addition, a brief overview of the main ideas behind electromagnetic shield theory and WPT system operation has been provided.

***Keywords*—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 . It is widely used for several applications such as Evs, medical implants, and consumer electronics. 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. The electromagnetic fields generated during wireless charging can cause interference with other electronic devices and pose potential heal thrisks to humans. Therefore, electromagnetic compatibility(EMC) plays a pivotal role in the design of WPT systems.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 analysed. 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.

II. ELECTROMAGNETIC COMPATIBILITY

In EVs, the exposure limits for WPT systems are established. by international safety guidelines, specifically the International Commission on Non-Ionizing Radiation Protection (ICNIRP) standards. The ICNIRP standards set the maximum allowable levels of electromagnetic field (EMF) exposure for various scenarios, including those involving WPT systems. Based on operating frequency, various field levels that must be adhered to have been identified. The external fields in the proximity of WPT systems for EVs, especially those requiring high power, may exceed the limits of international safety guidelines. 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. The dosimetric results and compliance with the ICNIRP standards are essential considerations in designing and evaluating WPT systems for EVs. For WPT applications, specifically for wireless charging of EVs, a review of the electromagnetic field exposure limits identified in international guidelines, including the ICNIRP standards, has been carried out. Even in this article, a safety limit region (Fig. 1) has been identified around the vehicle where magnetic fields have a low impact on humans.

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

A. Shielding:

Shielding involves enclosing electronic devices and systems in a conductive material, such as copper or aluminium, to block electromagnetic waves from entering or leaving the enclosure

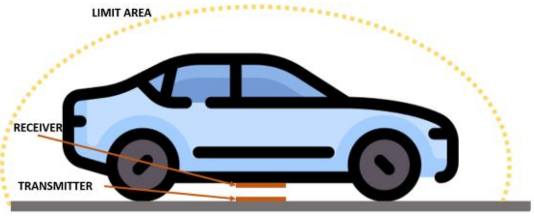

Fig. 1. Boundary region around the wireless charging system.

B. *Filtering*

Filtering involves using passive components, such as capacitors and inductors, to attenuate EMI on power and signal lines.

C. *Grounding*

Grounding involves connecting electronic devices and systems to a common ground to reduce thepotential for EMI

D. *Layout*

Layout involves designing the physical layout of electronic devices and systems to minimize thepotential for EMI

However, not all of these methods summarised in Fig. 2 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 behaviour of the wireless charging system for EVs.

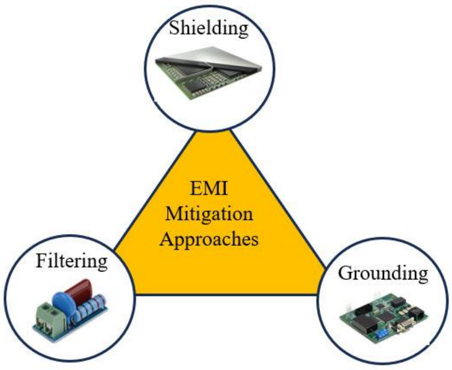

Fig. 2. EMI mitigation approaches.

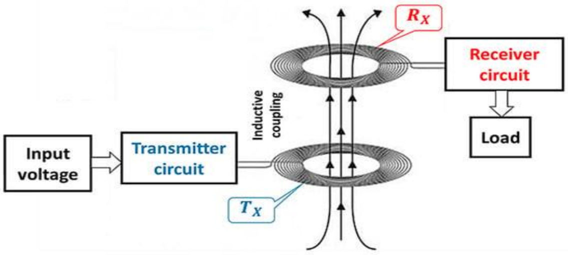

Fig 3. WPT system mechanism.

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. 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 magneticfield that induces an electrical current in the vehicle’s coil. This electrical current is then used to recharge the EV’sbatteries. Using inductive WPT for EV charging offers 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.3). 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.

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. Extremely 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. In the latter case, it is possible to distinguish two other categories based on the material used ferromagnetic or conductive. A diagram of the most common type of shields is reported in Fig. 4

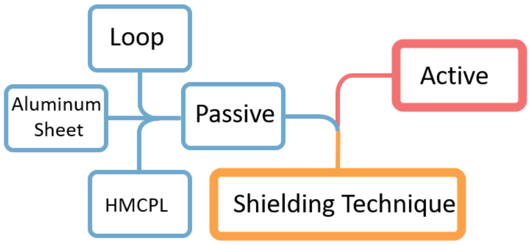

Fig. 4. Type of shield.

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

$$SF = \frac{B_0}{Bs} \quad (1)$$

$$SE = 20 \log(\frac{B_0}{Bs}) \quad (2)$$

where $B0$ is the magnetic field without the shield and BS 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.5), and the frequency of the electromagnetic field. Generally, thicker shields from materials with high magnetic permeability or electrical conductivity provide better

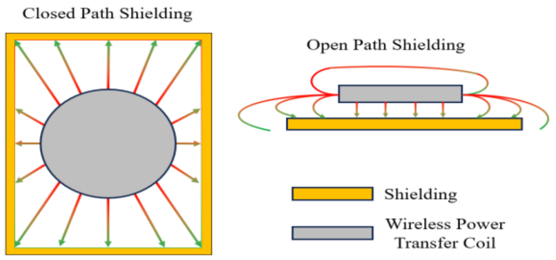

Fig. 5. Type of shielding shape

shielding. Several materials can be used for shielding, including metals, conductive polymers, and composites.a) closed path, b) open path.

- 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 perm alloy 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
- 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.
- 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 beformed into sheets or molded into complex shapes

V. TYPES OF ELECTROMAGNETIC SHIELDS APPLIED ON WPT SYSTEM

A. *Active*

The principle of operation of an active electromagnetic shieldis based on electromagnetic induction. Electromagnetic induction is when a changing magnetic field induces anelectric 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. 6).

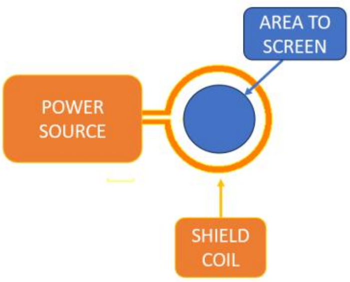

Fig. 6. Active electromagnetic shield diagram.

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. Table 1compares the most recent work on this screen type for the WPT system.

Power	Frequency	Sim/Exp.
12kW	10kHz	Both
20kW	20kHz	Both
100W	85kHz	Both
7.7kW	85kHz	Sim
1kW	85kHz	Both

200W	85kHz	Both

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 700Wup 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. There are a number of advantages that passive electromagnetic shields have over other methods of EMI shielding. 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. In applications where temperature or noise levels are crucial, they also do not produce any additional heat or noise. 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. Additionally, passive electromagnetic shields have excellent durability and environmental resistance. 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

aluminium sheet shields are one of the most commonly used shielding materials in WPT system design due to their high conductivity, flexibility, and ease of (Fig. 7).

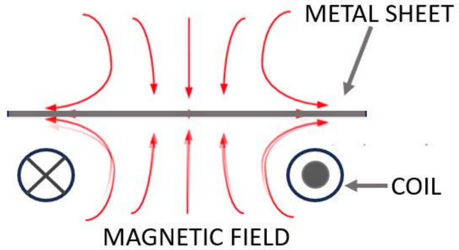

Fig. 7. Metal sheet electromagnetic shield diagram.

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

- High Conductivity: Aluminium is a highly conductive material, with a conductivity of approximately37.7 MS/m. This high conductivity allows for efficient transfer of electromagnetic energy through the shield, reducing losses and improving system efficiency.
- Flexibility: aluminium 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: aluminium 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: aluminium 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 aluminium 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 aluminium 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 aluminium 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 aluminium 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. They consist of a loopof conductive material, such as copper or aluminium, placed around the system (Fig. 8).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

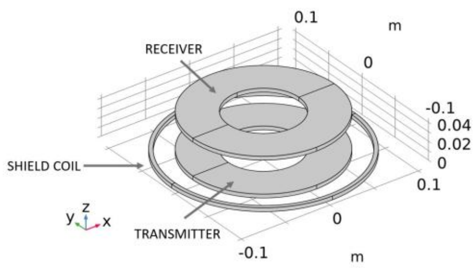

Fig. 8. Passive loop electromagnetic shield diagram.

- 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.

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 aluminium are commonly used for passive loop shields, offering high conductivity and low magnetic.

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.

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.9.

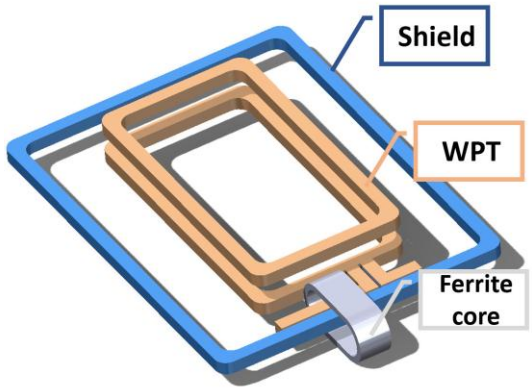

Fig. 9. High magnetic coupling passive loop shielding system.

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 these 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 tempt 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 orelectric 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

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.

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