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Review

Challenges and Barriers of Wireless Charging Technologies for Electric Vehicles

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Abstract: Electric vehicles could be a significant aid in lowering greenhouse gas emissions. Even though extensive study has been done on the features and traits of electric vehicles and the nature of their charging infrastructure, network modeling for electric vehicle manufacturing has been limited and unchanging. The necessity of wireless electric vehicle charging, based on magnetic resonance coupling, drove the primary aims for this review work. Herein, we examined the basic theoretical framework for wireless power transmission systems for EV charging and performed a software-in-the-loop analysis, in addition to carrying out a performance analysis of an EV charging system based on magnetic resonance. This study also covered power pad designs and created workable remedies for the following issues: (i) how power pad positioning affected the function of wireless charging systems and (ii) how to develop strategies to keep power efficiency at its highest level. Moreover, safety features of wireless charging systems, owing to interruption from foreign objects and/or living objects, were analyzed, and solutions were proposed to ensure such systems would operate as safely and optimally as possible.

Keywords: electric vehicle; wireless power transmission; battery system for energy storage; compensation networks; coil design; and wireless charging system

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1. Introduction

Electric vehicle (EV) technology has been gaining popularity due to its lower fuel emissions, and the numbers of EVs is anticipated to increase quickly. This has created a demand for ongoing improvements to charging infrastructures, especially wireless infrastructure. These must be designed for private, commercial, and public applications and be usable for both home and public charging stations. The technology of wireless power transmission can eliminate the use of wires, thus increasing the mobility, convenience, and safety of electronic devices for all users. Wireless power transfer is useful to power electrical devices where interconnecting wires are inconvenient, hazardous, or not possible. Thus, the accessibility of wireless charging stations resolves the problems with charging time, range anxiety, and charger connectivity, arguably the biggest obstacles to the widespread adoption of electric vehicles (EVs). The deployment of such effective and dependable high-power wireless charging infrastructures at close ranges would support a wider free range for EVs. However, many technical difficulties have arisen relating to the installation of EV wireless charging infrastructure. The main obstacles to wireless charging system adoption include low coupling coefficient between the transmitters and the receiver, misaligned power pads, and interruption from foreign objects like metal or live objects [1]. Electric vehicles (EVs) are a viable and feasible solution to the environmental problems the automotive industry is now experiencing. Figure 1 depicts wireless technology for charging electric vehicles.

Electrified transportation has created a paradigm shift in the transportation industry. It is regarded as being more intelligent, safe, and reliable, while also being more environmentally friendly. Less reliance on fossil fuels will result from the adoption of electrified transportation [2]. Conductive or plug-in chargers have provided trouble for EV owners struggling to meet the high voltage batteries' periodic charging needs. Electric vehicle wireless charging could be a remedy. The issues posed by conductive EV chargers would be avoided, and wireless charging would improve the EV user experience. Numerous researchers have been drawn to the idea of wireless power transmission via electromagnetic induction for use in the implementation of wireless charging of electronic devices and high-voltage batteries of electric cars. Despite the apparent advantages of EV wireless charging, substantial barriers to the economic feasibility and acceptance of wireless power transfer technology in the automotive sector have been defined. Compared to established conductive EV chargers, the main issues are high initial cost and limited power transfer efficiency.

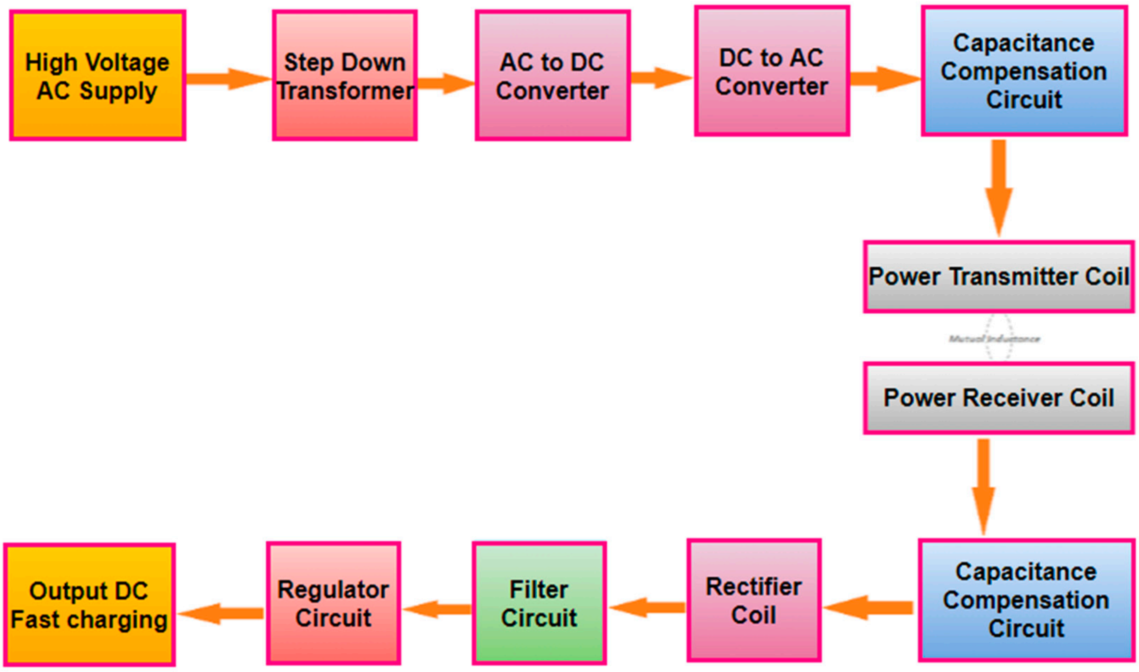

Figure 1. Wireless Electric Vehicle Charging Technology.

Additionally, significant standards and regulatory bodies have published guidance to avoid potential safety hazards. A new era of environmentally friendly and secure mobility has been made possible by burgeoning inventive research and ongoing improvements in the wireless charging technology of EVs [3].

Wireless power transmission (WPT) is a practical, cordless, trustworthy, appropriate, and all-weather power transmission or charging technology. A standard WPT system setup for charging an EV is made up of a transmitting coil buried in the ground at the charging station and a receiving coil built into the car. It consists of two separate electrical systems coupled to one another. The high-voltage EV battery can be charged wirelessly thanks to magnetic coupling. The inherent advantages of EV wireless charging performance include electrical separation, operation in harsh environments, and safety (owing to non-contact operation). However, high current is needed to charge high-voltage EV batteries, and any interruption to WPT will substantially impact the system's viability [4].

Therefore, power transfer efficiency must be close to 100% for wireless charging to be commercially feasible. Inductive charging can achieve such high efficiency provided the receiving and transmitting coils are correctly matched and there is no magnetic loss in the air. The practical constraints of transmitting and receiving coils to transfer power without loss and the necessity for precise alignment are two significant barriers to inductive coupling in wireless EV charging. MIT researchers suggested magnetic resonance coupling, with a 90% over-the-air power transmission efficiency within a few millimeters [5]. Currently, more power is lost through the process than is added to an EV's battery pack. The amount depends significantly on the electrical output and surrounding circumstances.

The standard inductive power transfer at a resonance frequency is magnetic resonance coupling. Compared to traditional inductive power transfer, where resonance aids in the maximum power transfer, the resonance coupling approach is slightly more complicated. Magnetic resonance coupling can effectively power/charge EVs wirelessly across a few millimeters [6]. Research and development must be done to maximize wireless power transfer efficiency under realistic and imperfect EV charging settings and to make wireless charging sustainable from a business standpoint. The following are the main obstacles to wireless EV charging as defined by this work.

Two crucial elements significantly impact the functionality and effectiveness of EV wireless charging systems: (i) the efficiency of the resonant frequency power electronics circuitry and (ii) the power pad in the coupling efficiency [7].

A WPT system must have at least two magnetic couplers to transmit power wirelessly; on the transmitter side, a central coupler and, on the receiver side, a secondary coupler similar to the other. For a more efficient WPT system, it is vital to have a high coupling coefficient (k) between the quality factor (Q) and the coupler. To understand the effective coupling of transmitter and receiver for wireless charging, it is crucial to investigate the effects of different coil shapes, coil structures, physical coil spacing, and coil materials, according to power transfer level, on the power transfer performance. The power electronics industry has been working hard to create efficient circuits, with significant advancements in semiconductor technology [8]. To date, there are very few standardized and optimized per-pad systems designed for commercially-feasible wireless EV charging, as the standards are still in the research stage [9]. This study examined and validated power pad design parameters for extremely effective wireless EV charging systems, keeping in mind that different vehicle segments may have different ground clearances, ranging from less than 10 cm for compact electric vehicles to roughly 30 cm for large SUVs [10]. Depending on the make and model of the car, the normalized distance between the transmission and receiver coils beneath the car (vehicle) will vary. Designing around limitations on the height and location of the coil on the vehicle body has proven difficult because it can limit other design elements, including aerodynamics, safety, and aesthetics. There is an an urgent need to design and create an EV wireless power transfer system to transfer power over the pads. The trick is to keep an appropriate power transfer rate while achieving a reasonable separation distance between the pads in the receiver and the transmitter coils. As the distance between the coils grows, the power transfer efficiency may drop quickly [11]. As the power input to the transmitting coil increases, magnetic flux leakage will simultaneously increase Therefore, a trade-off between distance, efficiency, and radiation leakage must be made for the best wireless charging system. These issues could be resolved in two ways: by creating a system with a low degree of transmitter-to-receiver mismatch, or by creating a resonant tank tailored for maximum power transfer. A transmitter to receiver pad auto-alignment strategy was established in this research work.

Regarding the ideal alignment of the coils, drivers cannot be expected to park their car precisely over the wireless charging pad. Thus, it is difficult to put into practice a purely mechanical technique for aligning the coils present in the transmitting and receiving coils. Still, alignment optimization is a creative approach with many benefits. First, complete alignment is feasible, as is maximum efficiency. Second, aligning the coils does not require a skilled driver. However, if coils are gravely misaligned, mechanical adjustment may be unavoidable [12]. Still, to facilitate a static solution, limiting such mechanical alignment methods may be desirable. An adaptive system must be developed and constructed to maintain wireless EV charging systems' best power transmission efficiency under various usage scenarios.

The impact of mounting metallic objects in EV wireless charging cannot be ignored. Therefore, substantial design attention must be paid to avoid interference from living objects and foreign object debris between the transmitting and receiving charging pads of

EVs. If these issues are not resolved, magnetic resonance coupling will be constrained and, therefore, unprofitable for wireless EV charging. This inspired the current work and this author's efforts to research and develop a method for maximizing power transfer efficiency in less-than-ideal, real-world EV charging circumstances [13].

Three alternative charging modes—static, quasi-dynamic, and dynamic charging—could be used to automate the charging of automobiles using wireless charging [14]. Static charging has several advantages, including the possibility of being deployed in convenient places like parking lots or garages and eliminating the electric shock posed by cables [15]. The QWC system enables charging for EVs when they are temporarily stationary, such as at traffic lights, extending their range and reducing the requirement for energy storage [16]. The DWC system would continually charge the EV through authorized on-road charging lanes, increasing driving range and shrinking battery size [17,18]. Utilizing wireless charging systems with an efficiency range of around 88.5%, WPT was completed by level 2 (230-V ac) powering at a rate of 7.2 kW.

Today, the most efficient forms of wireless charging are resonant CPT [19–22], utilized in dedicated lanes for dynamic charging [23–25], and resonant IPT [26–30], used in both Static WC and Dynamic WC methods. In [19], a comparison of capacitive and inductive WPT was made. IPT has allowed for successfully marketed products at low power levels for many years [31,32]. Magnetic couplers—transformers with only a few millimeters between the propagation (transmitter (Tx)) and reception (receiver (Rx)) components—have been in various phases of development for some time [33]. Many researchers have used enhanced compensation strategies to increase efficiency [34–37], air gap, and power level [38–42]. WPT distances have been extended by MIT researchers, who published a study in 2007 detailing their success in lighting a 60-W bulb at a distance of 2 m, thereby building researchers' confidence in expanding WPT to the necessary distances [43].

There have been several emerging areas of interest in research, including system design and analysis [44], component stress optimization, and compensation networks. Ongoing research has led to an increase in WPT of about 96% at a distance of 200 mm and several kilowatts of output power. The conductive method of wireless charging is currently in its stabilization phase and has produced several commercial goods and standards.

Electric vehicle (EV) charging infrastructure development and implementation are necessary for the efficient use of EVs. EVs have fewer charging stations and range-specific connectors than ICE vehicles, requiring more recharge time. To solve this refueling issue, an EV charger with high power and efficiency is required. Using a fast charger, approximately 50% of the battery may be charged in 3 min, and up to 80% may be charged in 15 min [45,46]. Fast charging methods, however, have been shown to cause high-voltage batteries to degrade. Control algorithms are necessary, based on the cost and rating of the converter used in a charger, using different microcontrollers, digital signal processors, and specialized linear integrated circuits. Ideal voltage and current ratios contribute to longer battery. To address prolonged charging issues, however, fast chargers are necessary. The conductive charging method is nearly mature [47], and established standards have been made. Inductive charging, which is still developing, has the potential to supplement conductive charging.

The structure of this paper was as follows. The definition and the benefits of wireless charging devices were covered in the first section after the introduction. EV conductive charging methods were explained in the second part. The wireless power transmission methods were described in detail in the third section. Static and dynamic wireless charging methods were presented and discussed in the fourth section. Upcoming and present standards of EV in WPT were covered in the fifth section. EV-based V2G charging methods were described in the sixth section. The quadruple power pad coil analysis for wireless EV charging was explained in the seventh section, in detail. The compositions of wireless charging were presented in the eighth section. The last and final section was the conclusion, including the final decisions determined by this paper.

2. Benefits of Wireless Charging over Wired Charging

Plug-in and wireless power transmission methods have been used to charge electric vehicles. In the plug-in technique, the electric vehicle's battery is charged at the charging station via a cord or plug. In contrast, in the wireless charging method, the battery of an electric vehicle (car) is charged utilizing wireless power transmission. The wireless charging technique is superior to wired charging in several ways. First, there is no need to carry and store cords, which could be considered the primary advantage of using wireless charging. Using this method circumvents the possibility of having wires wear out over time [48]. A wireless charging system may also reduce the size of the typical electric vehicle battery using dynamic wireless charging. Large-sized batteries are currently used in electric vehicles. However, it has been projected that similar automobile batteries will grow lighter and smaller once wireless technologies are incorporated. As a result, these two requirements will lower the overall cost of electric vehicles. Due to these advantages, significant automakers like Hyundai, Nissan, and Tesla have been investing heavily in wireless technology, primarily for electric vehicles. However, very few companies currently have wireless technology incorporated into their models. Due to all of these factors, the market for wireless EV charging is expected to undergo revenue growth.

2.1. Restrictions: Maximize the Upgrading Costs for Wireless Charging Technologies

For power transmission with a power control device (PCU), wireless charging technology for electric cars requires transmitter and receiver coils. The transmitter coil is located in the base charging pad (BCP), whereas the receiver coil is located in the vehicle charging pad (VCP). The average entire cost of a fitted commercial wireless charging system for a home is between USD 2500 and USD 3000. The cost of an electric vehicle increases when wireless charging technology is used in the vehicle. Consequently, this raises the cost of wireless electric vehicle charging [49–52].

Wireless charging technology will become more affordable in response to rising demand and the widespread manufacturing of electric vehicles. The electric vehicle industry is still in the introductory stage, regarding wireless charging technology. However, it is anticipated that most vehicle OEMs will implement this technology into their car models in the future. Therefore, it can be concluded that, given the current state of the economy and scale-induced economies of scale, the very high cost of upgrading or enriching to wireless charging technology remains a significant constraint.

2.2. Chance: Increasing the Government Funding for Wireless Charging Technology

In many nations, the advancement of wireless charging is now supported by government incentives and support for electric vehicles. The main benefits of wireless charging include full autonomy, the lack of a charging station, the decreased risk of an electric shock to the driver, and smaller battery units. The general population would be able to work for extended periods without needing to wait for their cars to charge. This increase in productive hours would also contribute to the GDP growth of a nation. The absence, or reduced requirement for, charging stations for dynamic charging is another crucial factor supporting the implementation of wireless charging in urban areas with a lack of available space [53–55].

The UK government awarded over USD 48.5 million for 12 initiatives in July 2019 to improve the experience of electric car owners and drivers. A business called Charge received USD 3.01 million from the government to install technology for wireless charging in suburban buildings. The first wireless testing technology was completed in Buckinghamshire, Marlow, in December 2021.

Successful testing for a wireless charging road occurred in Sweden in 2021, in an effort to modernize transportation processes and hasten the transition to electric mobility. The Israeli company Electron erected a dynamic wireless charging system on a 1.65-kilometer public road in Sweden's Gotland. A fully electric transport truck was charged on this intelligent road. The US state of Michigan signed an agreement that would see the construction of the world's first wireless charging road infrastructure in Detroit. In Detroit, Electron will use its dynamic charging technology to offer on-the-go charging for battery-powered automobiles. The project is anticipated to be completely operational in 2023.

2.3. Challenge: Minimizing Efficiency Loss

An electric vehicle (EV) can be charged wirelessly by parking it at the top of the base panel, i.e., without any manual connections. Compared to conventional power transfer, power loss in wireless charging is approximately 7–12% higher. Additionally, the distance over which a wireless charger may transmit using electromagnetic induction and/or magnetic resonance is constrained [56–59]. This is a significant hurdle for manufacturers, particularly in the case of SUVs and LCVs possessing a high specific ground clearance as also for automatic design [60]. The ratio of energy power efficiency to transmitter-to-receiver separation is inversely proportional. Another difficulty facing the wireless EV charging industry is safety during vehicle charging because powerful electromagnetic fields could damage the biological environment. Thus, efficiency and safety concerns have become a barrier for manufacturers in this sector. An EV electric drive system is only responsible for a 15–20% energy loss, compared to 64–75% for a gasoline engine. EVs also use regenerative braking to recapture and reuse energy that would typically be lost in braking, and waste no energy idling.

The market category with the quickest growth rate is anticipated to be 3–11-kW. The segment (by power supply range) anticipated to increase at the quickest rate over the projection period is also 3–11 kW. For very small- and medium-sized battery-powered electric vehicles (EV), 3–11-kW wireless charging devices are typically employed. Wireless charging solutions could be portable and lightweight at this power level, making them appropriate for charging at both home and work. The Nissan Leaf and Chevrolet Volt now have access to a 3.3 kW wireless charger from Plugless Power. IncWiTricity and Prodrive Technologies unveiled a wireless charging system in 2016 that was able to charge an electric vehicle up to 11 kW more efficiently than cable charging solutions. Due to its applicability in the workplace and in home charging situations where rapid charging is not a requirement, the 3–11-KW category is anticipated to dominate the market [61–64].

The 3–11-kW infrastructure in the market for wireless EV charging was anticipated to develop at the highest rate in Europe over the research period. Growing demand for home charging systems, due to rising sales of battery-powered electric cars, has been credited with driving market growth in Europe. Major OEMs have taken steps to include wireless charging in their automobiles, including BMW, Audi, and Mercedes. This could encourage market expansion in Europe. During the forecast timeline, BEVs have been projected to experience the fastest growth. By propulsion, BEVs are anticipated to experience the quickest growth during the projection period. In BEVs, as opposed to Plug-in Hybrid Electric Vehicles (PHEVs), wireless charging system adoption has been higher. In BEVs, the battery is the only source of power, and it must be charged frequently. Wireless charging technology is installable in offices, malls, public spaces, and garages. Increasing expenditures in the deployment of wireless charging technologies for battery electric vehicles have been predicted to benefit the BEV segment in the wireless EV charging market in the coming years. These countries include Sweden, Germany, Italy, and the USA, among others. The Tesla Model S, Nissan Leaf, and Jaguar I-Pace are well-known BEVs that support wireless charging. As a result, it is anticipated that, over the projected period, the BEV segment will be greater than the PHEV segment.

During the forecast years, Europe is anticipated to be the largest market for BEVs in the wireless EV charging market. This market expansion can be attributed to the existence of top auto manufacturers seeking to employ wireless charging technology in Europe. Leading players using wireless charging will persuade other significant participants in the automotive sector to use the technology for BEVs. Revenues for the BEV market in the region are anticipated to increase due to rising BEV sales in Europe, as well as the European Union's legal targets, e.g., to cut CO_2 emissions from vehicles and vans by 55% and 50%, respectively, by 2030. The number of battery-electric vehicles in Europe increased from around 1 million in 2019 to 1.8 million in 2020.

The EV market in the Asia-Pacific region is predicted to undergo the most rapid increase during the forecast period. The Asia-Pacific region includes both developed and developing countries, like South Korea and Japan, and emerging economies, like India and China. The area has become a center for the manufacture of automobiles in recent years. The Asia-Pacific region has experienced increasing demand for electric vehicles due to rising environmental concerns and the rising purchasing power of the populace. Both municipal and federal governments have shown interest in lowering carbon emissions through electrifying transportation [65–69]. As a result, the use of electric vehicles has gained familiarity in the area. Governments have concentrated on constructing robust charging infrastructures to encourage the adoption of electric vehicles. Rapid technological development in South Korea and Japan's electronic equipment manufacturing hubs is anticipated to lower the price of the wireless charging technology used in electric vehicles. Cost savings are then anticipated to fuel the expansion of the wireless EV charging market in the area. It is also anticipated that the presence of some of the top companies in the wireless EV charging trending market will aid expansion in the Asia-Pacific region. Toshiba Corporation, ZTE Corporation, Mitsubishi Electric, and Toyota Motor Corporation are a few companies active in this area.

3. EV Conductive Charging Method

A logical interconnection exists between the electrical power system and the vehicle, through an EV conductive charger. It comprises a low-frequency AC to high-frequency AC converter, including the power factor adjustment, or DC–DC converters and AC/DC rectifiers (PFC). Off-board and on-board chargers are the two categories of conductive chargers. For onboard chargers, battery current regulators and rectifiers are inside the car; for off-board chargers, they are present outside of the vehicle [70]. Conductive chargers are categorized according to the level included in their power transmission. These device are capable of being charged with an AC level 1 charger. Conductive wireless charging has no practical application for enhancing system effectiveness. The efficiency of such systems is dependent on converters with a very high frequency.

SWC charges a vehicle when it is at a stop [71]. The vehicle is also charged while it is moving, thanks to dynamic en route charging (DWC) [72]. This was demonstrated by the proposed creation of a wireless on-the-go bus charging system in Malaga, Spain by the Endesa-led project Victoria (see also CIRCE and others) [73]. QWC, also referred to in [74] as the static en route charge method, is especially favorable for vehicles that stop at predetermined locations throughout the day, such as bus stops, traffic lights or taxi stands. Thus, wireless charging could be achieved via underground fit technology when a bus stops at a bus stop [75]. EM fields are the primary WPT system used to charge EVs. A discussion on the wireless charging modes DWC, QDC, and SWC is shown in Figure 2. Systems for wirelessly charging electric vehicles are a prospective replacement option for charging electric vehicles (EVs), potentially avoiding any plug-in issues (WEVCS). In this work, existing wireless power transfer technology that is currently available for EVs was outlined. Additionally, studied wireless transformer designs with different ferrite forms were included. Due to safety and health issues that have been brought up, WEVCS has been connected to the present expansion of international standards. The two primary application types, static WEVCS and dynamic WEVCS, were described, and the most current advancements, with components from academic and commercial research labs, were documented. Along with qualitative comparisons to other existing technologies, future concept-based WEVCS were also discussed and investigated, incorporating in-wheel wireless power systems as well as vehicle-to-grid (V2G) technologies (WCS).

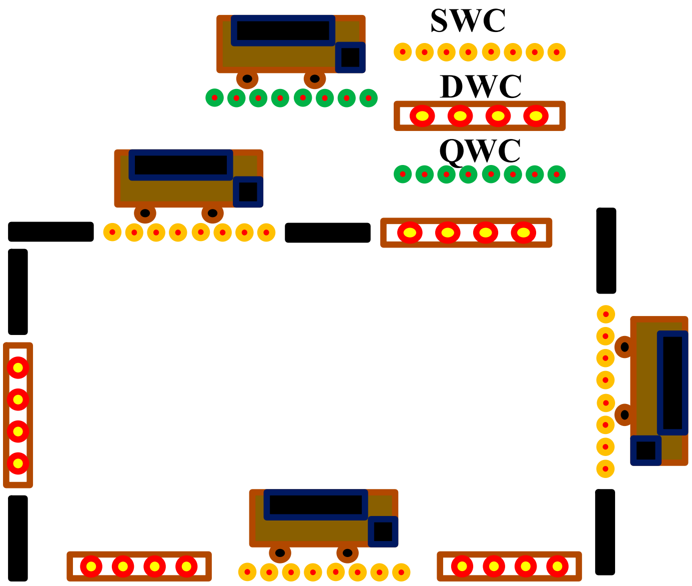

Figure 2. SWC, DWC, and QWC installation for statistical analysis.

The following various electric car (vehicle) wireless charging methods may be classified depending on their functioning principles:

1. Capacitive Wireless Charging System (CWCS);
2. Permanent Magnetic Gear Wireless Charging System (PMWC);
3. Inductive Wireless Charging System (IWC); and
4. Resonant Inductive Wireless Charging System (RIWC).

Four techniques have been utilized to develop WEVCS since wireless charging systems for EVs were first introduced: the capacitive method of wireless power transfer (CWPT), the traditional inductive method of power transfer (IPT), the resonant inductive method of wireless power transfer (RIPT), and the magnetic gear method of wireless power transfer (MGWPT) [76,77]. Currently available wireless power transfer technologies for rechargeable batteries in electric vehicles (BEVs) are listed in Table 1.

Table 1. Various methods of WPT and their parameters.

WPT Methods	The Distance between Transmitter and Receiver Circuits	Transmission of Power	Parameter Efficiency	Rate Cost	Safety and Protection
Inductive Coupling	Around a millimeter	A few watts or less	Minimum	It is economical to utilize secondhand equipment, since it is affordable and easily accessible.	It is secure from a biological perspective.
Capacitive Coupling	Multiple Kilowatts	A few Kilowatts or more	Minimum	It is less costly since the power transmission is done via aluminum plates.	Compared to the resonant approach, operation is safe.
Magnetic Resonance	A few meters	Kilowatts	Maximum	It is cost-effective, since old equipment is affordable and easily accessible.	It is secure from a biological perspective.
Microwaves	It can be produced up to 100 km.	Up to hundreds of Megawatts	Maximum	It is expensive compared to other treatments.	1 GHz to 1000 GHz high-frequency radiation is unhealthy for human health.
Optical	Using a high-intensity beam, it may be utilized across greater distances than a few meters.	Up to hundreds of Megawatts	Minimum	It has identical financial circumstances to inductive coupling.	It would be detrimental to human health.

3.1. Capacitive Wireless Power Transmission Method

For medium- and low-power implementations, like spinning machines [78], portable electronics [79], and phone chargers [80], the CWPT framework technology's cost-effectiveness and ease of use, utilizing improved mechanical configurations, as well as the geometric patterns of something like the coupling capacitors [76,77], are very advantageous. Inside the CWPT, coupling capacitors are employed to transmit power from the receiver to the source, rather than coils or magnets. Half-bridge converters receive their primary AC voltage via power quality control circuitry. The schematic of the capacitive wireless power transfer technique is presented in Figure 3.

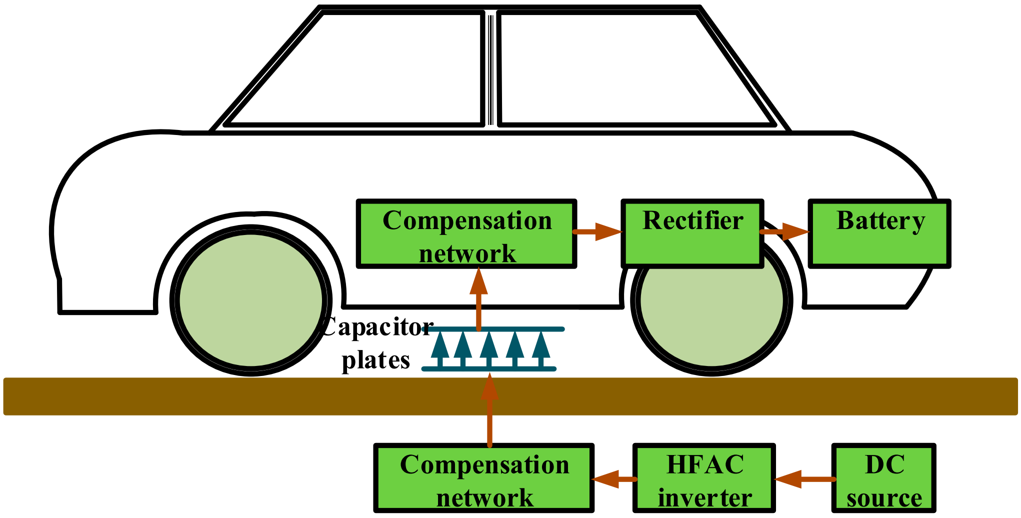

Figure 3. Schematic Representation of Capacitive Wireless Power Transmission method.

The coupling capacitors upon the receiver's side transmit the AC created by the H-bridge high-frequency. In contrast to the IPT, the CWPT runs on minimum and maximum current. Furthermore, in order to lower the range of impedance values of the transmitting and receiving sides, at the configuration of resonance, extra inductors should be coupled only with the combination present in the coupling capacitors. Given this arrangement, the circuitry could integrate soft switching. Rectifier and filter circuitry is used to change the incoming AC power to DC for either the load or the battery bank [81]. The two variables affecting power transfer levels are (1) the coupling capacitor's size and (2) the separation between its two plates. CWPT offers excellent performance and better field restrictions for small air gaps formed between the two capacitors' plates. Since its introduction, CWPT has only been partially applied to electric vehicles (EVs), owing to considerable high power level needs and air gaps. The authors of [82] offered suggestions for the rotary mechanism's high capacitance coupling designs and air-gap reduction. According to the authors of [83], a receiver might be attached to the vehicle's bumper bar to help close the air gap between the two connecting plates. A static research prototype with a power output of much more than 1 kW and approximately 83% efficiency (from the DC power supply to the battery bank) was demonstrated at the 540 kHz operating frequency.

It is possible to wirelessly transfer energy between both the transmitter and receiver sides by utilizing the displacement current that the varying electric magnetic field creates. In this case, coupling capacitors are used as the transmitter and receiver for wireless power transmission, in place of magnets or coils [84–90].

The AC voltage is sent into the power factor component adjustment circuit to improve the efficiency range, maintain voltage levels, and reduce transmission losses. The high-frequency supply of AC is then provided to the transmitting plate, producing an oscillating electric field that, via electrostatic induction, produces displacement current at the receiving plate. After that, it is provided to a half-bridge for the generation and improvement of maximum AC voltage. The receiver side AC voltage is transformed into DC and utilized to power or charge the battery throughout the BMS using filter circuits and a rectifier. The voltage, frequency, coupling capacitor dimension and size, and air gap produced between both the transmitting and receiving sides affect how much power is transmitted. It runs between 100 and 600 kHz in frequency.

3.2. Magnetic Gear Wireless Power Transmission Method

The magnetic gear WPT (MGWPT) is very different from the CWPT and IPT, as shown in Figure 4. This method uses two side-by-side synchronized permanent magnets (PM), as opposed to earlier WEVCS that relied on coaxial cable. The transmitter side winding gets the main power supply, as the current source causes the primary PM to suffer mechanical torque power. The primary PM spins and mechanically communicates with the secondary PM to apply torque, utilizing mechanical torque. The generator mode functioning is performed by the primary PM of such a combination of synchronous PMs. In contrast, the secondary PM gathers power and sends it to the battery through the power converter and BMS [91]. A 1.6-kW laboratory prototype called the MGWPT was created; it was able to provide and deliver over an air gap distance of 150 mm.

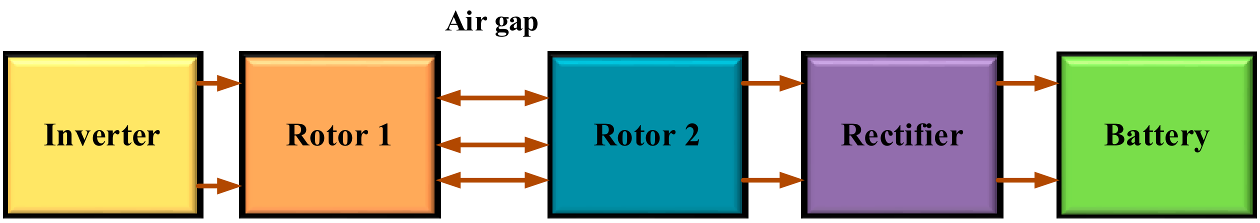

Figure 4. Magnetic gear wireless power transmission method.

Nevertheless, this approach in dynamic and static systems is fraught with several challenges. According to [92], rotators stopped synchronizing at 150 Hz, which significantly affected the transmitted power. A sophisticated feedback mechanism must be used to continuously shift the speed from the primary side to the battery side to avoid going over the upper limitation of power. As the coupling between the two synchronized windings dramatically weakens, the capacity to transmit power is inversely associated with separating the primary and secondary PMs from axis to axis. This makes it potentially beneficial for fixed WEVCS, but rather tricky for dynamic applications [93].

The armature winding and the synchronized permanent magnets make up the transmitter and receiver, respectively. Functioning at the transmitter side is comparable to motor operation [94–100]. The spinning of the transmitter magnet is caused by the mechanical tension induced on the transmitter winding when AC is applied to it. The receiver's PM is torqued by the transmitter's magnetic interaction shift, which makes the receiver magnet rotate synchronously with the transmitter magnet. The receiver now acts as a generator because the permanent magnetic field of the receiver has changed, converting mechanical power input into electrical output at the receiver winding. Permanent magnets connected by rotating gear are referred to as magnetic gear. Power converters rectify and filter the produced AC power at the receiver side before feeding it to the side of the battery.

3.3. Inductive Power Transmission Method

In 1914, Nikola Tesla developed the traditional IPT for wireless power transmission. Figure 5 shows the fundamental block diagram of the conventional IPT. Several EV charging systems have had an impact on it. IPT has been evaluated and carried out in some packages, ranging from mW to kW for the transmission of contactless strength from the supply to the receiver. In 1996, a well-known automobile manufacturer (GM) unveiled the Chevrolet S10 EV. The magnet-charge IPT (J1773) system was used to feed it, which provided stage 2 (6.6 kW) slow and degree three (50 kW) rapid charges [101]. The magnetic-number-one rate coil, a charging paddle (inductive coupler), was inserted into the auto's charging port, where the secondary coil received energy and could charge the vehicle. The University of Georgia displayed a 6.6 kW stage 2 EV charger with a seventy-seven kHz running frequency and a two hundred–four hundred V charging variety. This IPT made use of a 10-KVA coaxial winding transformer. The core premise of IWC is induction by Faraday's law. Electricity is transmitted wirelessly using magnetic field mutual induction between the transmitter and receiving coils [102–108]. When the principle AC delivery is supplied to the transmitter coil, an AC magnetic area that passes through it and transports the electrons creates AC power. The electric car's storage device is charged with this rectified and filtered AC output. The frequency, mutual inductance, and separation between the transmitter and receiver coils all affect how much electricity is sent and received. IWC makes use of a frequency variety of 19 to 50 kHz.

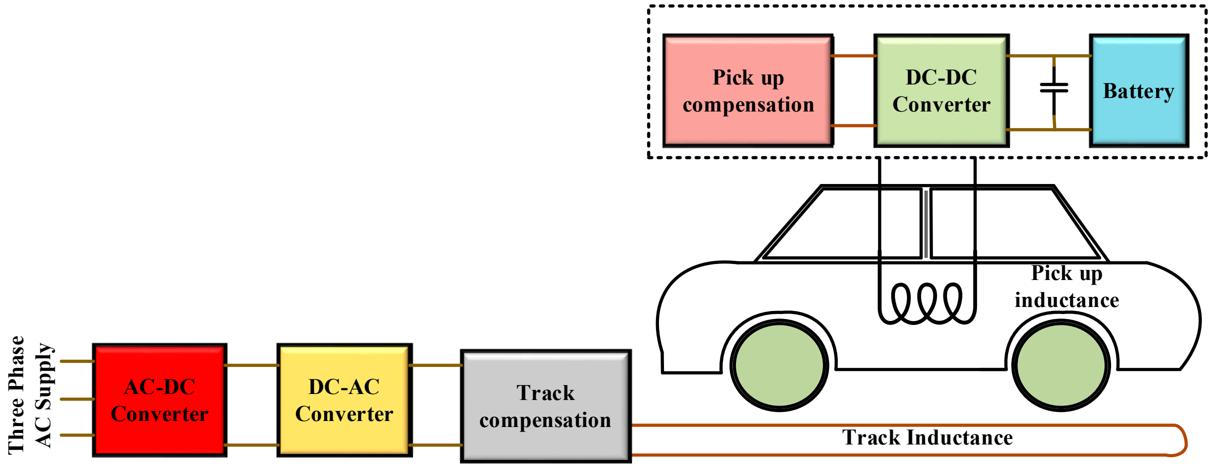

Figure 5. Inductive power transmission method.

3.4. *Resonant Inductive Wireless Charging System (RIWC)*

Regardless of weaker magnetic fields, resonance operation makes it possible to switch an equal amount of electricity as in IWC because resonators with excessive pleasant elements transmit electricity at a much higher charge. Power can be transmitted across long distances without the use of cables—the resonant inductive wireless charging system is shown in Figure 6.

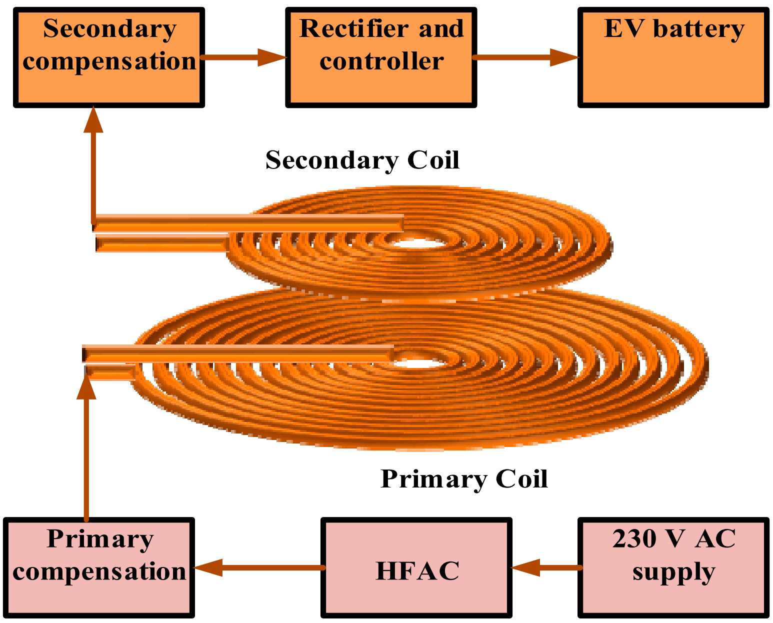

Figure 6. Resonant Inductive Wireless Charging System (RIWC).

The most significant power that may be sent over the air occurs when the resonant frequencies (bandwidth) of the sides of the propagation (transmitter) and reception (receiver) coils are matched, or when the transmitter and receiver coils are adjusted [109–112]. Additional reimbursement networks are consequently delivered in series and parallel to the transmitter and receiver coils to achieve appropriate resonance frequencies. Together with an increase in resonance frequency, these extra compensation networks also help to cut down on additional losses. The RIWC's operating frequency ranges from 10 to 150 kHz.

4. Static and Dynamic Wireless Charging

Wireless EV charging systems fall into two categories, depending on the application:

1. Static Wireless Charging;
2. Dynamic Wireless Charging.

4.1. Static Wireless Charging Method

As the name suggests, the vehicle charges every time it is in static mode. The block representation of the static wireless charging technique is shown in Figure 7. Thus, it would be easy to park the EV within a particular spot or in storage that permitted interface with the WCS. The transmitter would be located underground, while the receiver would be set up in the automobile's underside. Before getting out of the car to complete charging, the driver would align the transmitter and receiver [113–120]. The space between the edges of the transmitter and receiver, the scale of their pads, and the AC supply strength would all affect charging speed.

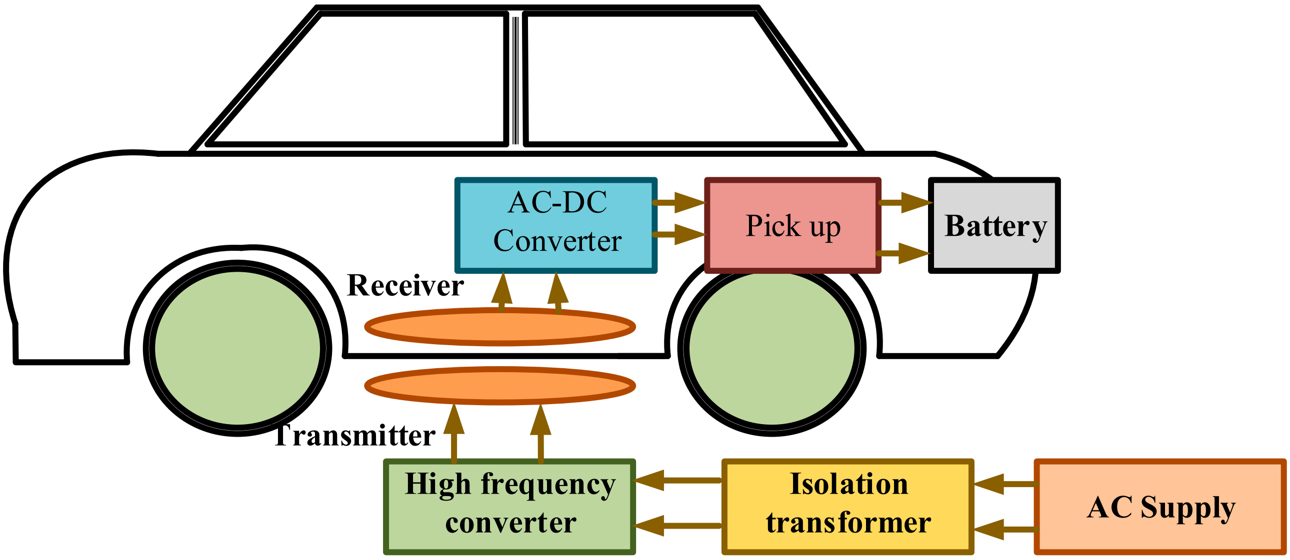

Figure 7. Static Wireless Charging Method.

The best places to build SWCs are those where EVs are routinely parked for long periods.

Wireless Charging Types and Charging Methods

These days, the world is moving toward electrified mobility, both to offer an alternative to expensive fuel for transportation and to minimize the pollution emissions created by nonrenewable fossil fuel cars. However, for electric vehicles, the two main problems preventing their adoption over conventional vehicles are their driving ranges and charging procedures.

Wired charging technology made it possible to charge your electric vehicle while parked. There is no longer a need for drawn-out charging station lines. Why can't power be delivered over the air? We are already accustomed to wireless data, audio, and video transmission [121].

The principles of transformer operation and wireless charging are identical. Wireless charging uses a transmitter and a receiver. The transmitter coil receives high-frequency alternating current from a 220 V 50 Hz AC source. The high-frequency AC creates an alternating magnetic field, which interrupts the receiver coil and enables the receiver coil to generate AC power. However, the transmitter and receiver's resonance frequency should remain constant for wireless charging to function. Compensation networks are implemented on both aspects to preserve this resonance frequency. Furthermore, the battery management system delivers this rectified DC power, generated from the receiver side which is connected to the battery side (BMS). Figures 8 and 9 show the wireless charging methods.

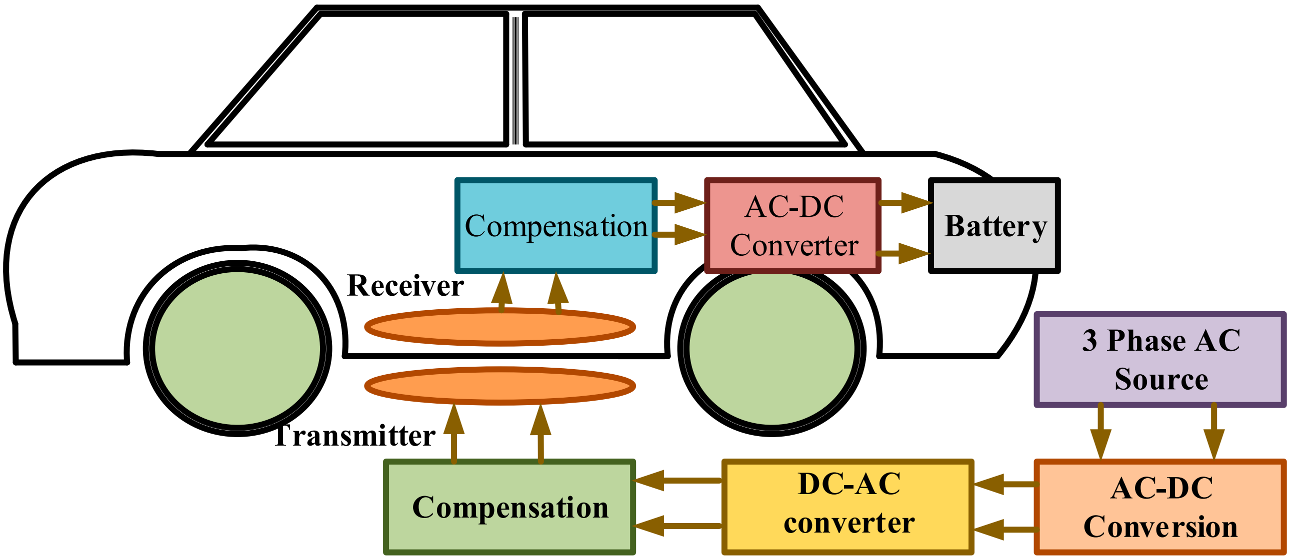

Figure 8. Wireless charging system.

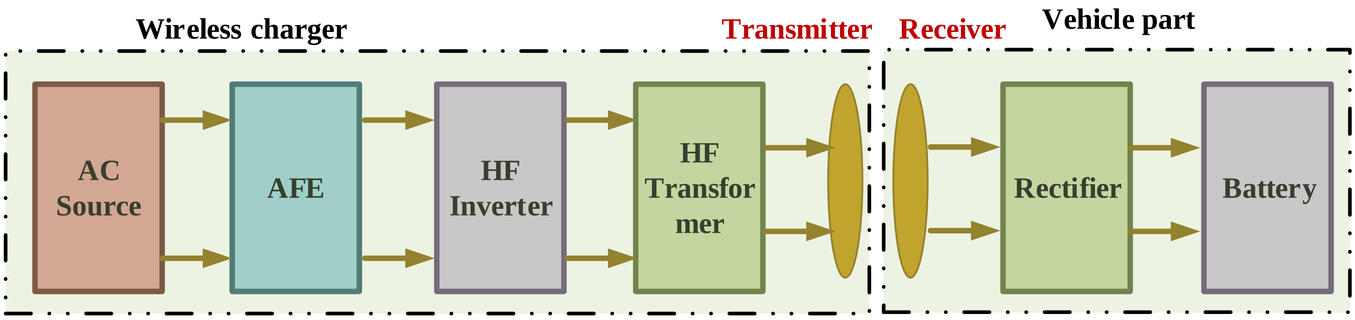

Figure 9. Block Representation of a Wireless Charging System.

The wireless charging block diagram displays the conversion processes and their overall effectiveness. Each conversion step is designed such that you the end user is able acquire the most effective efficiency [122]. The efficiency depicted in the diagram is general. More than 95% efficiency has been attained, according to Qualcomm, Oak Ridge National Laboratory (ORNL), and others [123–127]. There are several phases in a wireless charging system, and each stage varies in complexity and efficiency. When converting PS from AC to DC, Active Front End (AFE) with Power Factor Correction is used. Power transmission from IPT calls for excessive-frequency AC to be successful. As a result, the DC–AC converter transforms low-frequency DC into high-frequency AC. A remote high-frequency transformer is placed between the converter and the primary coil in order to prevent primary winding isolation breakdown. The alternating magnetic discipline produced by this excessive-frequency AC follows Ampere's equation. Due to the interplay of this magnetic discipline with the secondary coil, high-frequency AC is produced, in keeping with Faraday's law. The secondary repayment community is utilized to evolve to resonant surroundings, improving performance. A compelling rectifier is then used to feed the battery to rectify the AC energy. The three crucial components of an EV wireless charging system are the compensation network, the power electronics converters, and the remote, loosely coupled primary and secondary coils, which are covered via ferrite.

4.2. Dynamic Wireless Charging Method

Dynamic wireless charging is used to recharge EVs while they are being driven, making it unnecessary to wait while the battery charges. This theory, put forth in 1978 by J. G. Bolger et al., states that energy is transferred to the vehicle as it moves [128]. A study at KAIST has been working to develop dynamic wireless charging since 2009.

This study addressed continuous power transmission, high-frequency contemporary controlled inverters, and various electromagnetic interference parameters [129]. Choi et al. provided a beneficial analysis of OLEV. Dynamic wireless charging solves most of the problems with electric vehicles, such as battery capacity range, range anxiety, cost, etc. Inductive wireless power transfer is used by current dynamic wireless charging gadgets [130–133]. This technique is based on a pickup coil mounted in the electric vehicle (EV) that obtains an electromagnetic field, generating high-frequency current, and coils hidden beneath the road pavement. The on-road coils constantly deliver power to the pickup coil throughout a track. After being adequately prepared, the EV battery can be charged by the current captured by this coil. To transfer energy to the integrated system with a transmitter coil and several resonators, low-power wireless systems have been created. However, because they follow a path, these systems are worthless for electric vehicles (EVs) [134]. The two track types developed for DWC systems have different shapes, referred to as stretched tracks and lumped tracks. A stretched track includes a transmitter coil that is notably larger than the pickup coil of a lumped track, which contains many coils with radii that could reach near the pickup coil. Even as KAIST evolved the OLEV (electric automobile) prototype as a consequence of researching stretched tracks, a study group from Auckland University researched aggregated tracks [135,136]. Only a portion of the lumped track with the linked transmitter coil can drive the related receiver coil. This supply strategy, often referred to as segmentation, aids in increasing DWC effectiveness and reducing electromagnetic field radiation from the non-coupled rail segments. Prior research on coil sizing for static wireless charging systems has centered chiefly on sizing the coils [137] and researching axes misalignment's effects [138]. In terms of DWC systems, some researchers have looked into coil-based lumped tracks placed side by side [139], while others have assessed the appropriate coil length in a stretched track [140,141]. Galvanic isolation and user ease are two benefits of EV wireless charging over touch charging. To avoid using wires and cords and to circumvent the need for careful charging and discharging, it is possible to top off a vehicle's battery frequently. At the same time, a vehicle may be parked at different charging places, including at work, at home, at a traffic light, and while shopping. By incorporating a charging lane into motorways that would allow charging while driving, DWC could do away with fast charging infrastructures. Compared to cable charging, wireless charging has lower cost, size, manufacturing complexity, efficiency, and power density.

Table 2 shows the study's review of the works based on WPT.

EV wireless charging presents difficulties that must be considered for effective power transfer. Wireless power transfer necessitates energy conversion, which reduces the efficiency of conversion and transfer; as a result, it must to be optimized, and transfer efficiency improved. These issues have made it difficult for certain businesses to switch from conductive charging to wireless charging. Each component is a crucial research subject in the application of wireless chargers. Each factor—e.g., distance, geometry, frequency, compensation topology, coil design, and alignment—has an indirect or direct impact on the practical system's performance. DWC effectiveness is also influenced by EV speed and many underlying issues, as demonstrated in Figure 10.

Table 2. Overview of earlier works on WPT.

Problems Addressed	Performance Assessment	Key Contribution	Resolution
In an EV, using a cable circuit will harm the charger. Daily maintenance will be performed. The AC outlet requires plug-in.	Yokogawa digital power meter	Simple, cheap WPC prototype	The receiver coil attached to the battery picked up the magnetic induction created by the transmitter under the road.
Inductance coupling (efficiency improved).	Network reflection coefficient and scattering parameters	Employment of repeater concept	The power was doubled and reproduced in the air by the repeater coil, which was positioned between the transmitter and receiver.
Inhibited transmission efficiency and power loss transmission.	Unnamed optimization strategy	Phase shift amplitude control	While the active portion of the blockage was left alone on the receiving end, the sensitive portion of the obstruction had its impedance modified.

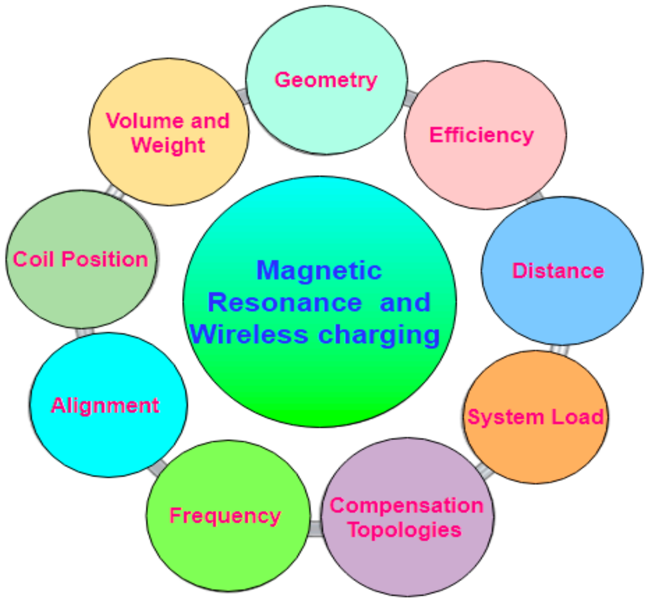

Figure 10. Demonstration of wireless charging.

5. Standards for Wireless Electric Vehicle Charging

Electric vehicles may now be wirelessly charged without the need for a plug. However, it would be unproductive or harmful if every manufacturer developed their own proprietary standard for wireless charging that could not be used in conjunction with other technologies. The user experience for wireless EV charging could be improved. The Society of Automotive Engineers (SAE), International Electro-Technical Commission (IEC), Underwriters Laboratories (UL), and Institute of Electrical and Electronics Engineers (IEEE) are a few of the international organizations working to develop standards [142–144].

SAE J2954 established the Alignment Technique for Light-Duty Plug-In EVs WPT. According to this standard, the maximum input power at level 1 is 3.7 kW, level 2 is 7.7 kW, level 3 is 11 kW, and level 4 is 22 kW. The minimal target reliability must also be higher than 85% when aligned. The side-to-side accuracy should be less than 4 inches, and the maximum permitted ground clearance should be 10 inches. The best alignment technique was determined to be magnetic triangulation, helping both human-controlled and autonomous vehicles find parking spaces.

- SAE. J1772 standard described the EV/PHEV conductive system of charge couplers.
- SAE. J2847/6 standard described the communication transmission between wireless EV Chargers and wirelessly-charged vehicles.
- SAE. J1773 standard described the EV inductive method of coupled charging.

- SAE. J2836/6 standard described the usage of a wireless charging system of communication for PEVs.
- UL subject 2750 described the investigation's general plan for WEVCS.
- IEC. 61980-1 Cor.1 Ed.1.0 described the general configuration of the EV WPT system.
- IEC. 62827-2 Ed.1.0 described the WPT-Management: Multiple Varieties of Management of Device Control.
- IEC. 63028 Ed.1.0 described the WPT-Air fuel alliance resonant baseline system requirements.

Table 3 shows the safety and technical standards for WPT.

Table 3. WPT U.S. Technical specifications and safety requirements.

Standard Developer	Standard Name	Published Year	Description
SAE	J2836/6_201305	2013	Applications for PEV wireless charging communication
SAE	J2953/1_201310	2013	Equipment for PEV compatibility with electric vehicles (EVSE)
SAE	J2953/2_201401	2014	Procedures for testing PEV compatibility with EVSE
SAE	J2953/3	2016	EVSE and PEV interoperability test scenarios
SAE	J2953/4	2020	reporting on PEV charge rates
SAE	J2847/6	2020	Wireless EV charging stations and light-duty PEVs can communicate for WPT.
SAE	J2954	2020	WPT for plug-in light-duty vehicles, as well as alignment techniques

5.1. EV Wireless Charging: Implementations and Standards

For the reliable implementation of high voltage and high power WPT, standards are necessary, since wireless charging is quickly overtaking other EV charging methods on the market. In addition to checking setup configurations for wireless charging, standardization also encompasses safety requirements, efficiency, electromagnetic restrictions, and interoperability goals as for a reliable computational design [145]. A crucial prerequisite for EVs to be practical after standardization is ubiquity. Customers should not need to worry about charging station compatibility [146–150]. The entire wireless power transfer system is contained in the IEC-61980-1 standard, from the network supply to electric vehicles (EVs) for charging the vehicle's battery, or the use of standardized equipment (or equipment parameters) at the standard power supply range of 1000 V AC or 1500 V DC. All of these were addressed using the SAE standard in SAE TIR J2954. This was the first actual wireless power transmission specification created by SAE considering EV charging. The static wireless charging industry largely followed its own trends. The owner of an EV might want to wirelessly charge their vehicle from a domestic wireless charger, workplace charger, or commercial charger, among many others, while enjoying similar charging functionality due to the frequency spectrum, interoperability, protection, coil specifications, and EMC/EMF constraints in SAE TIR J2954. The suggested frequency band per SAE 2954 is 85 kHz for any light-duty electric cars (81.39 kHz–90 kHz). Table 4 [151–158] shows the major wireless charging standards ready to be checked in the next years to be cyber-resilient [159].

Table 4. Standardization of charging power levels for light-duty EVs.

Classification	Power Level	Standard Status
WPT1	3.7 kW	SAE J2954
WPT2	7.7 kW	SAE J2954
WPT3	11 kW	SAE J2954 (WIP)
WPT4	22 kW	SAE J2954 (WIP)

A schematic diagram of a static wireless charging improvement for a stationary placement is shown in the Figure 7. A high-frequency converter is connected to the grid-side supply [160–169]. The principal pad receives this high-frequency feed (transmitter). Magnetic resonance is connected with the coils of the primary and secondary regions. An AC–DC converter is also employed on the load side to deliver power straight to the battery type. A battery management system (BMS) regulates the battery's state of charge (SOC) and overall health. The BMS is linked to the car's controller area network (CAN), which manages the vehicle's sensing component. The vehicle is connected to the management pole for wireless charging through radio indicators [17–177].

Alternately, a different DC–DC converter must be used if the vehicle's battery management system does not permit powering the battery directly. The deployment of static wireless charging is completely operator-free. With an intelligent controlling system coupled with CAN and BMS, all charging types would be feasible without human intervention. Wireless charging will only overtake the market if it provides more convenience at a lower cost [178–182] together with optimization algorithm adopted in other fields [183]. Table 5 shows the international technical standards of the EV.

Table 5. Worldwide technical standardization.

Standards Inventor	Name of the Standard	Invention Year	Description
IEC	61980-1-Ed.2.0	2020	General Requirement, Part-I, EV-WPT system
IEC	61980-3	2019	WPT System-part-3 for electric vehicles: particular specifications for entire magnetic field WPT systems
IEC	61980-2	2019	Specific criteria for wireless communication systems among electric road vehicles (EVs) and infrastructure, outlined in part two of the electric vehicle WPT systems.
IEC	61980-1:2015/COR1:2017	2017	General Requirement, Part 1 of the EV-WPT system
IEC	61980-1:2015/COR1	2017	General Requirement, Part 1 of the EV-WPT system
IEC	61980-Ed.1.0.New Addition	2015	General Requirement, Part 1 of the EV-WPT system
IEC	61980/1 AMD 1 Ed.1.0	2015	General Requirement, Part 1 of the EV-WPT system
IEC/TS	61980-2 Ed.1.0	2017	Widespread requirements for communication between electric-powered road cars and infrastructure concerning WPT devices and element 2 of EV-WPT systems
IEC/TS	61980-3 Ed.1.0	2015	Part 2 of the general necessities for the magnetic field power transmission gadget for EV-WPT systems
ISO	19363:2020	2020	Magnetic field WPT for electrically-driven road vehicles: protection and interoperability necessities
ISO	9363:2017	2017	Safety and interoperability criteria for electrically-driven road vehicles' magnetic fields

5.2. Companies Working to Develop and Improving WCS

- The Evatran Group developed plug-less charging for first-generation wireless electric vehicles such the Nissan Leaf, Chevrolet Volt, Tesla Model S, and Audi i3.
- Recently, WiTricity Corporation worked with Honda Motor Co. Ltd., Nissan, GM, Hyundai, and Furukawa Electric to create WCS for sedans and SUVs.
- Qualcomm Halo produced WCS for passenger, sport, and race cars, and Witricity Corporation obtained Qualcomm Halo.
- Hevo Power has been manufacturing WCS for a passenger automobile.
- Bombardier Primove manufactured WCS for vehicles ranging from rider automobiles to SUVs.
- Siemens and BMW have been manufacturing WCS for rider automobiles.

- Momentum Dynamic manufactured WCS for corporate and commercial fleet buses.
- Conductix-Wampfler manufactured WCS for buses and industrial fleets.

5.3. Challenges Faced by WEVCS

- The current infrastructure is insufficient for the necessary installations. Hence, developing dynamic and static wireless charging stations on highways will necessitate building new infrastructure [184–189].
- Maintaining EMC, EMI, and frequencies according to standards is necessary for human health and safety. Table 6 shows the various challenges faced by WEVCS.

Table 6. Challenges and issues faced by WEVCS.

WPT Types	Resonant Coupling	Induction Coupling	Microwave
Difficulties	Moderate	Low	High
Distance capability	Maximum of 1 km	5 mm	-
Efficiency performance	High	Low	High
Transmission of Loss	Moderate	High	Low
Number of receivers entering	Multiple receivers are applicable	Utilizing a single receiver is appropriate	Single receiver
Power wave	Fluctuating power signal	Continuous	Continuous
Radiation energy	Non-radiant power	Non-radiant power	Radiant power
Frequency range	Power transmitted at 6.7 MHz Control signals at 2.4 GHz	110–205 KHz	300 MHZ–300 GHz
Receiver	Coil of copper with few turns	Coil of copper with few turns	Rectenna with SCR
Safety considerations	Risk of sparks produced at several million volts	Considered harmless	Detrimental to living matter, like telecommunications
Transmission of energy	Electromagnetic resonance	EMI	Radiowave, microwave, and laser
Transmitter	Primary coil with a short gap and few turns. The secondary coil contained 10 times as many turns as the primary coil without a gap.	Several-turn copper coil	Antenna for transmission that uses a wave guide

6. EV-Based Vehicle-to-Grid (V2G)

Wireless charging—the need for EV charging, specifically—is one of the most significant difficulties facing the current electrical infrastructure. Vehicle-to-grid (V2G) topologies could be used to solve this problem. Vehicle-to-grid (V2G) is a well-known application for EVs, representing power delivery to the electrical grid. H. Nguyen et al. performed an in-depth analysis of V2G technology's integration and coordination with conductive charging methods [190–196]. Flexibility, automated charging, and bidirectional discharging are necessary components for a V2G integration. Most of the aforementioned criteria can be met via wireless charging. Through the electrification of transportation, fossil fuels may eventually be replaced by renewable energy. Local microgrids could gain power from V2G, and these could be combined with renewable energy systems [197–204]. Although they cannot be used to generate electricity directly, batteries are used for storage. Numerous initiatives have been made in the last ten years to increase energy conversion and lessen reliance on fossil fuels for electricity production and transportation electrification. As a result, we have seen expanding usage of electric vehicles (EVs) for mobility. In the future, it is anticipated that renewable energy sources will be used to generate power [205–214]. Because of the unpredictability of climatic conditions, renewable electricity sources (RES), especially wind and solar systems, present issues relating to the main grid's sustainability and power supply quality.

Adopting EVs on a broad scale, whether hybrid or entirely battery-based, also poses significant issues for the electrical grid [215]. The best option would be to use RES to offset the necessary demand for EVs [216]. Additionally, the power grid's stability and power quality could be improved by integrating RES with EVs, which has already been acknowledged by V2G systems. For this level of RES, EV, and grid integration, EV charging and discharging systems must be flexible, autonomous, easy, safe, and reliable. Research has placed great emphasis on design elements such as maximum efficiency, very low rate (cost), adaptability, and autonomous charging and discharging techniques. Due to automation, wireless charging of EVs could offer and produce bidirectional power flow between EVs and the grid. The comparison of interactivity between wired and wireless connections was briefed in [217,218]. According to the studies mentioned above, wireless connectivity or charging could achieve up to 65% connectivity, whereas conventional connectivity only achieved rates of 10% [219]. Several wireless communication devices have proven able to detect automatically and comply with V2G standards, helping to automate wireless charging. With the advent of wireless charging, a vehicle's interface with the grid could improve, enabling extra vehicle power whenever required.

6.1. Applications for EV Wireless Charging: LOD and FOD

Foreign Object Detection (FOD) detects foreign objects that are close to the charging pads and might or might not interfere with the transmission fields. Snow, dirt, twigs, water, oil, grease, leaves, and other items that might or might not interact with the magnetic field are considered benign objects. FOD may include magnetic materials, metal objects interacting with high-frequency fields, and animals sleeping on charging pads. Any object with metal available between the transmission and the reception sides prevents the charging process from continuing because of the power flow of eddy current through it [220]. The EV and the charging system could thus be impacted by the heating of the object that has the metal particle or any other conducting object.

Due to a strong electromagnetic field, living matter and objects are also affected. Any living thing could suffer harm during charging. Under FOD Detection Methods, numerous real-world examples of a charging apparatus coming into contact with living things for both short- and long-term exposure, such as children near the car to pick up a ball/toy, a driver reaching out to hold something felt, a pet lying still for a while, etc, were detailed.

- System variables
- Efficiency of power loss
- Actual temperature
- Image from wave-based detection
- Thermal ultrasonic radar
- Field-based laser light detection
- Resistance inductance capacitance

Most things exposed to intense magnetic fields experience both long- and short-term effects. Therefore, the International Committee on Electromagnetic Safety (ICES), Institute of Electrical and Electronics Engineers (IEEE), and International Commission on Non-Ionizing Radiation Protection (ICNIRP) recommendations [221] have determined rules governing magnetic field limits. The FOD detection methods are shown in Figure 11.

Different scientists have introduced various LOD and FOD techniques. WiTricity created an FOD technique using an overlapping coil structure that measured current, voltage, and resonators that had the phase and frequency. Another type of FOD technique is power detection, which measures a power loss brought on via the availability of a foreign object [222]. This technique is typically helpful for the minimum power transmission of wireless charging. An FOD method mainly depends on the fluctuation of quality factor (Q), as introduced by S. Fukuda et al. in [223]. Due to the position of the coils, this approach's Q could not be used for EV charging applications. Other FOD techniques, e.g., RFID, video cameras, and radar-based systems, were also considered in SAE standards [224,225]. The category-by-category classification of FOD techniques is shown in Figure 12. The benefits and drawbacks of each of the strategies mentioned above are listed in Table 7.

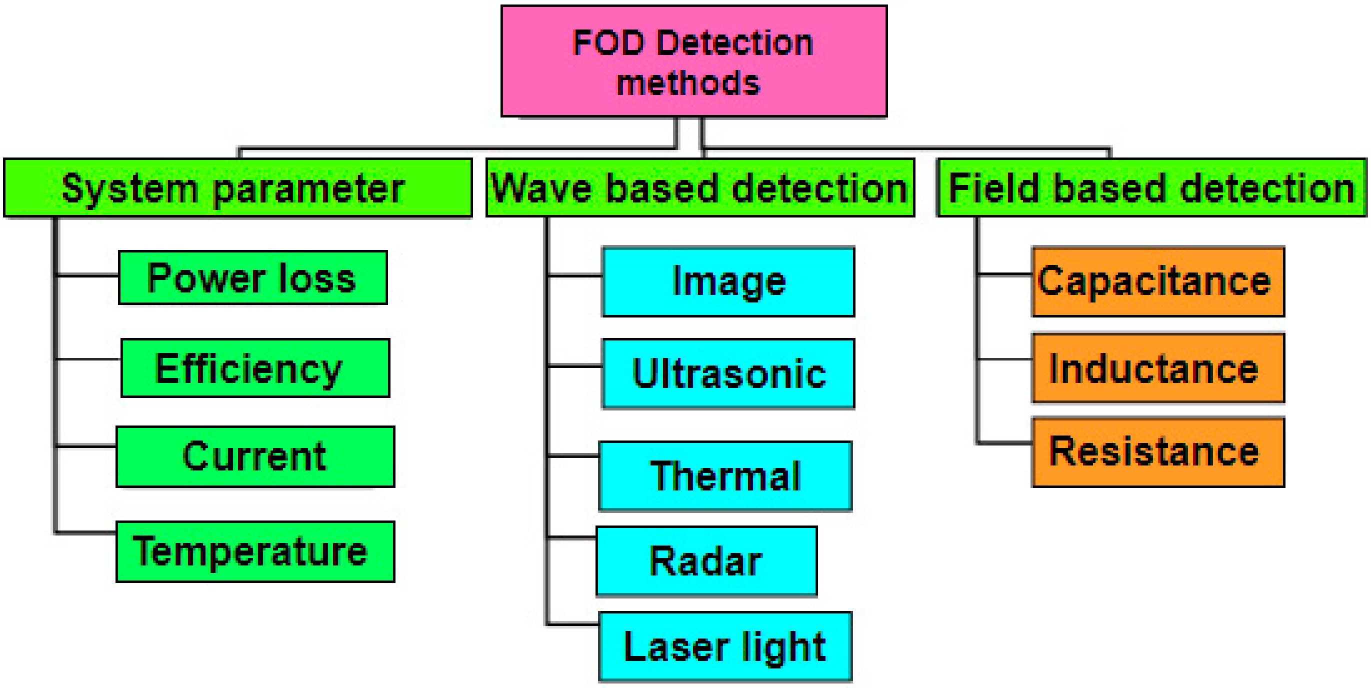

Figure 11. Categories of foreign object detection and metal object detection.

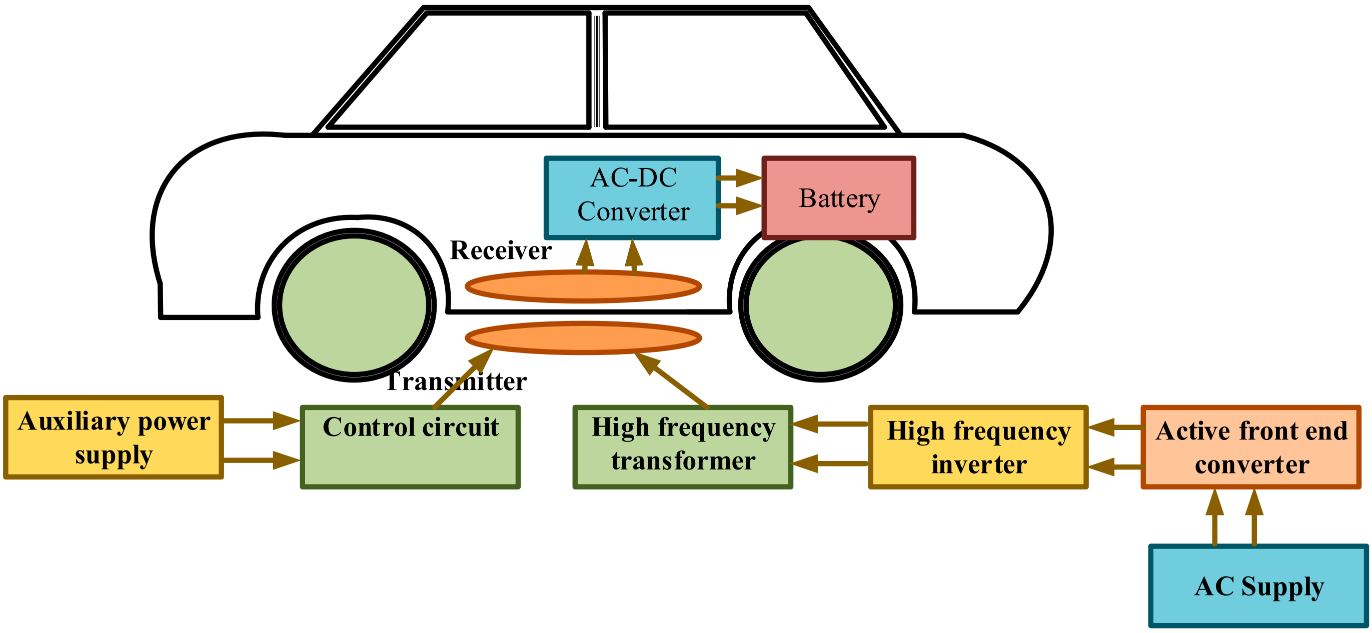

Figure 12. A wireless charging system and an FOD system.

For EV wireless charging for light-duty plug-in and alignment techniques, SAE. J2954 was created. [226–228]. This standard had to be revised to include FOD technologies. Metal objects represent a serious problem, and must be found and removed because of intense heat, and living things are a problem because magnetic radiation can distort living cells. Numerous researchers have put forth solutions to FOD (foreign object detection) and LOD (living object detection) problems.

Table 7. Advantages and disadvantages of FOD.

Methods for Detecting Foreign Objects	Benefits	Drawbacks	Comments
Method for power; oss analysis	Detects while it is powered.	High-powered wireless charging is not recommended. Only metal detection is involved, not the transmitter or receiver.	Power consumption is low.
System parameter change detection method	No extra equipment and implementation is easy.	A small metal item is hard to find. Depending on the primary power source, only metal detection occurs.	Power consumption is low.
Image, thermal and radar sensing	Can identify living things and metal.	High price, failure-pronse, and has environmental factors.	Detects both metal and living things.
Magnetic field change detection method	High-power wireless charging is acceptable, regardless of the weather.	Low-power wireless charging is challenging; detection occurs while charging.	Relates to high-power wireless charging.
Laser sensor	Able to find any object, suitable for all wireless charging levels. Reliable and simple to implement.	Costly, but very simple and robust.	Proposed laser sensor-based system.

6.2. LOD Detection Prototype Implementation

A novel method of FOD and LOD detection was put forth in this research work. First, a beam array of light was produced over the transmitter using two different multiple laser-sensor combinations. Second, a similar type of technology was also introduced; a reflecting mesh covered the transmitter, with two high-quality reflecting mirrors and two identical combinations of laser-detectors, which were used and utilized [229–231]. The configuration was presented in the suggested method of the laser-sensor-based detection system. The suggested system could be added as an accessory to any wireless charging system already in use. The laser sensor arrangement, control circuit, and auxiliary power supply made up the auxiliary system. Enclosed ferromagnetic shielding was used to protect the auxiliary control and power systems from the strong magnetic field. To make the charger installation simple and compatible with all static types of charging, the laser-sensor arrangement was placed in a physical, non-magnetic, sturdy frame that could be made according to the transmitter form and size.

Moreover, each electric vehicle's underbody system is unique, and their chassis are elevated from the ground by at least 10 cm. As a result, the auxiliary system was created to elevate 5 to 10 cm.

7. Quadruple Power Pad Coil Analysis for Wireless EV Charging

The power pad coil configuration is among the most important design considerations for EV wireless charging applications. The most crucial stage of creating an effective and trustworthy wireless power transmission system is choosing the best power pad design. Each available coil design offers benefits that are appropriate for particular applications. In this chapter, the two-objective optimization challenges, involving optimum size and design, dimension and shape, and current directions in sub-square structures of Quadruple Power Pad (QPP), were examined. Finite Element Analysis (FEA), utilizing ANSYS Maxwell®, was used to verify the dimensional design's optimization for minimum area interaction with the current directions, as well as the maximum amount of coupling coefficient with minimal interference among the corresponding coils. The outcomes of each case study were thoroughly examined and analyzed in comparison. The comparability evaluation of the structure of the QPP structure design with the Double (DD), Rectangular (D), and Double D Quadrature (DDQ) coil architectures represented another significant contribution to this chapter. Results were observed and compared, and other coil structures were used to confirm the QPP structure's computability. Figure 13 shows the quadruple power pad coil.

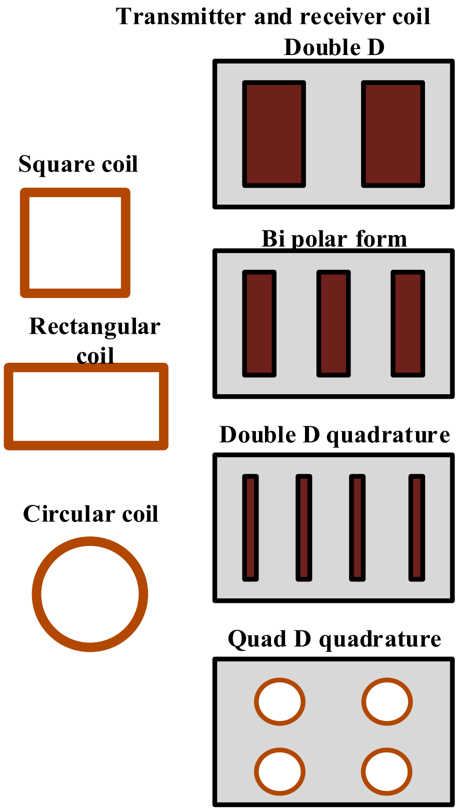

Figure 13. Quadruple Power Pad Coil.

7.1. Background

A new technique for charging electrical items was made possible by wireless power transfer. However, problems in wireless charging of EVs exist, including high-frequency power conversion converters, power pad design [232–234], electromagnetic field protection [235,236], metal object detection, and foreign object detection [237]. All of these are crucial to research and the creation of standards as in optimization [238] and structural field [239]. The main topics of this chapter were the structural study and compatibility of the QPP structure with other coil winding structures, including the D, DD, and DDQ power pads. Maximizing the value of the quality factors and the geometrical layout were the main design difficulties for the power pad.

However, the quality factor and the coupling coefficient of the transmitted and received coils directly impacts the efficiency of wireless power transmission. Unipolar, bipolar, and solenoid coil architectures are the three primary coil types used in the static method of wireless charging systems. The unipolar coil's configurations create the vertical magnetic flux and exhibit a maximum coupling coefficient due to the coil excitation, which only creates one set of polarities. Due to the primary coil excitation producing two sets of magnetic polarities, bipolar coil configurations produce the vertical magnetic flux and exhibit a low coupling coefficient [240]. Due to the double-sided magnetic flux that the solenoid coil produces, and the fact that only half of it is interconnected with the receiver coil, the solenoid construction is ineffective for EV wireless charging. DD, DDQ, BP, and solenoid pads are examples of non-polarization of power pads. Polarization coil structures, such as rectangular, circular, and square-shaped power pads, are another way to classify power pads. Non-polarized pads have one single pole and magnetic flux dispersed in all directions, with one pole located in the coil's core and the other outside of it. Two poles, north and south, are produced in the polarized power pad.

The magnetic field is localized in the central region and is parallel to the corresponding nonpolarized power pads. While at the center of the polarized power pad, the magnetic field is parallel. The interoperability between polarized power pads will, therefore, be higher when they are not in alignment, even if no evident power (VA) links appear when they are correctly aligned. Multi-coil topologies like DD and bipolar pads have many sets of mutually-disconnected coils (BP) [241,242]. The circular coils' lack of sharp edges results in a limited amount of eddy current and a dramatic peak in magnetic flux in the center of the primary coil, which is advantageous for high power transfer. The coil design structure is round and reduced, but nevertheless prone to misalignment, because of the restricted dispersion of the flux diameter [243]. D-shaped coils [244] are the ideal coil configuration, i.e., an array-type arrangement, such as in dynamic wireless charging. Unfortunately, corners with sharp edges in the coil structure are inappropriate, owing to the development of hotspots and eddy currents. Although hexagon configurations have very high maximum power transmission at the coil's core, they are inappropriate because they lose power at the periphery [245]. Better misalignment tolerance is demonstrated by the oval-shaped coil structure, although it performs less well in high-power applications. Because non-polar power pads perform poorly under horizontal misalignment, multi-coil rectangle configurations have been used to create polar pad constructions. Both single-phase and three-phase applications can benefit from multi-coil designs. Bipolar, DD, solenoid, QPP, DDQ, and Quad D Quadrature architectures are a few examples.

7.2. Analysis of the QPP Configuration

An in-depth analysis and discussion of QPP structures was provided in Figure 14. A structural investigation of the QPP structure was carried out with mathematical study, modeling, and simulation to determine its coupling coefficient. Later, interoperability testing was done to see how well the QPP structure worked with other rectangular coil topologies like D, DD, and DDQ. Geometrical diagrams of the quadruple power pad structure are illustrated in Figure 14.

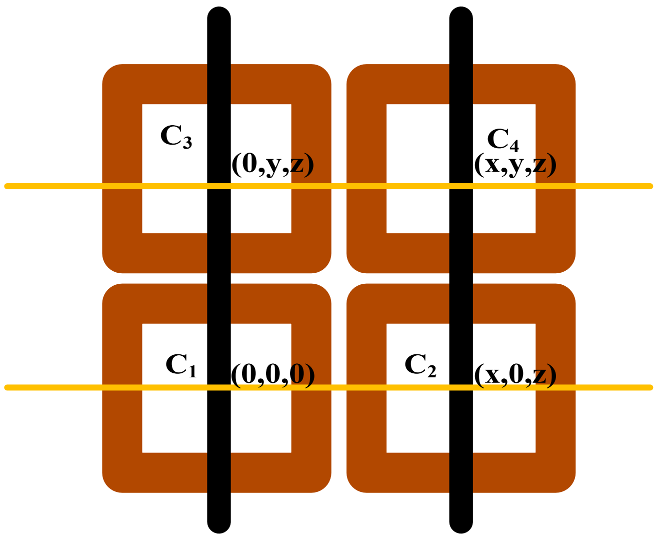

Figure 14. Geometrical diagram of quadruple power pad structure.

7.3. Misalignment Prevention for Wireless Charging Technology of Electric Vehicles: Design, Development, and Implementation

One of the primary barriers to wireless charging for electric vehicles (EVs) is the mismatch between power pads [246]. In this chapter, the intelligent alignment of the receiving coil to minimize electromagnetic leakage was discussed. The recommended remedy comprises the employment of sensors to gauge the flux intensity, both in the center and at the corners of the receiver coil. A controller circuit and a stepper motor driver are coupled to orient the receiver coil in two dimensions. To detect flux, the receiver is outfitted with a variety of Hall effect sensors, with the sensor that receives the minor flux producing the least voltage. Additionally, the controller instructs the reception coil to be moved in the direction of the sensor that registers the most excellent flux level. This chapter evaluated and confirmed the magnetic flux distribution at the optimum alignment site between the transmitter and receiver with finite element analysis (FEA) utilizing Ansys Maxwell®. The recommended modification enhanced the efficiency of wireless power transmission while reducing flux leakage. The conceptual model built the suggested system, and each system component was briefly examined and discussed. The simulation and modeling results confirmed the value of the recommended intelligent alignment.

With the improvement of EV technology's range, complex research on the wireless charging infrastructure will be required [247]. The main elements that significantly influence wireless charging include the charging coil design [248], compensation topologies [249–251], coil misalignment [252], and the frequency of wireless power transmission [253]. Coupling efficiency, however, increased at a precisely aligned location when a ferrite core was used [254,255]. Even a minimal change in the charging coils' alignment caused the efficiency to decline [256]. The charging efficiency was significantly impacted by lateral and horizontal misalignment [257]. Numerous academics have suggested compensation topologies to increase misalignment tolerance [257,258]. The effectiveness of WPT is impacted by misalignment in all directions [259]. Misalignment is inevitable if vehicles are manually parked, however, even if the suggested solutions were put into practice. Additionally, a method to self-align the transmitter or receiver is needed, which could use sensors to determine the degree of misalignment between the coils present in the region of transmission and reception. The position of the receivers or transmitters could be then modified using the proper autonomous control technique until power transmission was restored to its ideal state.

In this chapter, an ideal solution was conceived, created, and developed to solve the fundamental issue of wireless EV charging systems' power pads being out of alignment. A magnetic tracking-based automatic alignment receiver system (AARS) was suggested. AARS is a cutting-edge technique that uses two-dimensional control of the receiver, with a hall effect sensor over the transmitter's magnetic field that has been minimized to automatically align the receiving coil over the transmitter. To determine the increase in alignment efficiency, the outputs of the wireless charging system's electrical circuit analysis, modeling, and simulation were examined in Section 5.2. The recommended system's hardware implementation procedure was detailed in Section 5.3.

The projected AARS system's results, implementation issues, and solutions were covered. For short air gaps with significant magnetic field coupling, inductive energy transfer is a very effective form of wireless power transmission, but it would be difficult to use for greater power wireless charging. Moreover, even a slight misalignment would have a major detrimental effect on the effectiveness of power transfer. Below, electrical research was used to show the degree to which misalignment affected how well wireless power transfer was able to function.

7.4. Analysis of Wireless Power Transfer Efficiency Caused by EV Static Wireless Charging Misalignment

The transformer (which has no core or uses an air layer as a core) and wireless power transfer both operate on the same fundamental principles [260]. Series–series (SS) compensation topology was employed in this investigation. The operating frequency was particular for the constant current operation, where the primary side inductance and capacitance were present. This investigation was done to show the elements directly or indirectly affecting wireless power transmission effectiveness. A general block architecture of an EV wireless charging station was presented. The high-frequency converter, rectifiers, power supply, load, and coupling coils made up the static wireless charging system. To comprehend the connection between the misalignments and the effectiveness of the WPT, simple circuit analysis was carried out, as the alignment between the coils between the transmitter and receiver could alter the coefficient in the coupling.

Consequently, the coupling coefficient had a direct impact on efficiency. Inductance, resistance, capacitance, voltage, and current were the primary electrical properties on the secondary (receiver) side. The primary (transmitter) side included properties such as supply voltage, operating angular frequency, secondary side load resistance, and mutual inductance of the WPT system.

According to Equation (1), the mutual inductance and frequency of operation were connected:

$$M = \frac{V_s}{\omega I_1} \tag{1}$$

According to WPT, Equation (2) described the connection between mutual inductance and coupling coefficient:

$$M = K\sqrt{L_1 L_2} \tag{2}$$

7.5. Two Receiver Coils Were Used in a Novel Wireless Charging System Employed in Electric Vehicles

Most electric vehicle systems are designed around various components to ensure the maximum power and dependability of the automobile. The majority of these components' connections to the charging system are shown in Figure 15. Dynamic wireless power transmission could reduce the cost of onboard batteries in hybrid cars and aid with range anxiety. Pure electric vehicles have long used wireless recharging, enabling charging even while the car is moving. Analysis was difficult, nevertheless, because of the complicated working philosophy of this approach, and the existence of so many different variables and elements. Nevertheless, several characteristics, including the vehicle speed and the shape, volume, and sizes of the coil receivers, were determined by the vehicle's condition, i.e., whether it was in motion or stationary [261]. This study proposed a brand-new technique for enhancing dynamic wireless recharge system performance. The suggested technique for increasing charging power included a dynamic continuous statistical model that could characterize and analyze source-to-vehicle power transmission even when a vehicle was in motion. The suggested mathematical model presented and addressed each of the physical parameters associated with the model. The outcomes demonstrated the viability of the suggested model. Additionally, by placing two coil receivers under the car, the simulation results were validated by experimental testing [262].

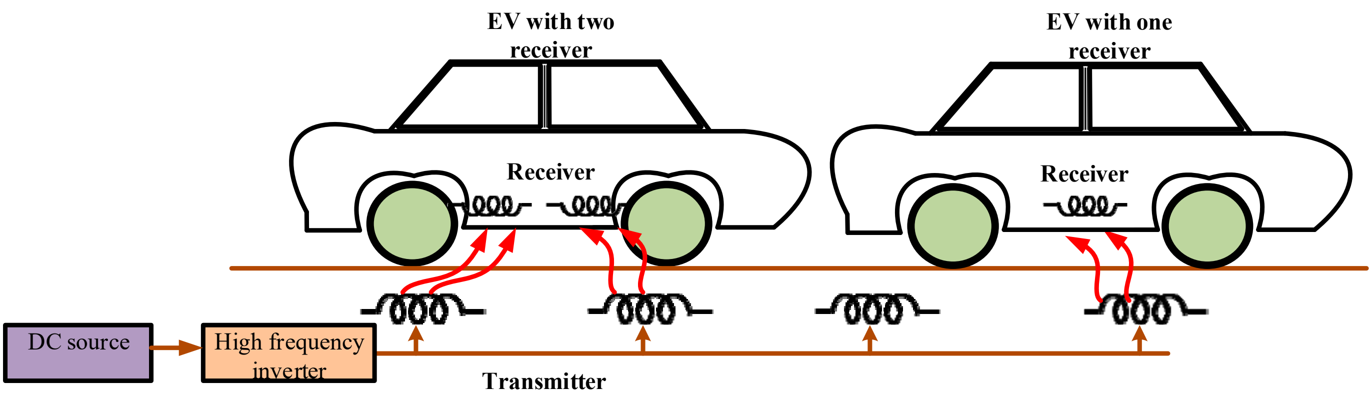

Figure 15. Composition of wireless transmitter system.

The paucity of fossil fuels and environmental concerns indicates new energy challenges. Traditional transportation accounts for a sizable share of global oil use, which generates substantial emissions [263]. The investigation and development of electric vehicle (EV) technology, as a solution to these issues, is essential and will continue to impact the automotive industry as a whole. Electric power storage is now a very popular field of study [264–266]. Electrical energy storage technology improvements have increased the power and mass of energy generated, making it possible to meet automotive demands [267–269]. The primary shortcoming of these storage options is the high cost of manufacture [270]. To minimize the overall cost of EVs, experts have been working to develop effective storage solutions and improve their reliability and charging strategies. This sector has seen the development of numerous storage systems that have been successfully incorporated into the electric power train system, improving their performance [271–275]. Therefore, losses relating to vehicle power systems could be reduced by controlling the main grid, engine, or even the rechargeable battery system flawlessly. The designers of [276] studied several control techniques to increase system efficacy. Numerous studies on the internal structures of batteries have been done to boost overall production. Numerous approaches were implemented to increase the energy efficiency of E-transportation systems [277–279]. These solutions were included in current iterations of electric cars and now have a proven track record of independence. Some researchers have concentrated on charging equipment, seeking to maximize overall performance to increase vehicle efficiency and autonomy.

In contrast, the authors presented a unique wireless charging method in [280–283]. The hybrid recharging system, which also used two types of internal power sources for the automobile, received additional consideration [284]. Additionally, PV systems have been integrated into vehicles to supply power from several sources, including blended power sources [285–289]. The main goals of the problems, addressed in the models above regarding shading impact, charging remedies, and vehicles' extra structures, included PV recharging and hybrid techniques and their remedies [290]. Research has been done on wireless charging techniques to discover more reliable and practical solutions. Accordingly, based on the literature relating to recharging strategies, more researchers have demonstrated that two components must be used, a receiver and transmitter, in parallel, for this method to be very effective.

The whole machine's performance would be constrained if the two sections were to move apart by a few inches [291]. As a result, the analysis could only be correct if the two pieces were aligned correctly and stable (i.e., not in motion). The precision of the analysis would change if one of these were still moving. Inductive power transfer, magnetic gear wireless power transfer, capacitive wireless power transfer, and inductive coupling link wireless power are just a few of the wireless energy transfer methods discussed in the literature. Of these, inductive coupling link wireless power has proven to be among the most popular. Numerous representations emerged in the literature due to the extensive discussion surrounding mathematical expressions and their representations of this recharging tool. In [292], the authors looked into static modeling to increase the effectiveness of a 50 kW, 22 kHz, 70 kHz and 85 kHz wireless charging system range for electric vehicles. This concept was only evaluated when the receiver and transmitter coils were overlaid, and it was based on mutual inductance among primary and secondary coils. The authors of [67] looked at a dynamic setting to comprehend the connection between the receiver and transmitter coil orientation deviations. Calculations were made to determine the output voltage and total efficiency factor so as to build an integrated computational framework similarly to other fields [293,294].

The analysis and mathematical model considered internal factors, including the inductance, resistance, and pitch angle among the two coils. The specifications of each of the two prior approaches were examined in [24], which also contrasted and examined the two methods. These evaluations were performed using a single receiver coil without considering the significance of the divergence speed between the receiver coils and transmitter halves. The issue, involving a two-receiver system, was not adequately examined in any current research, and its dynamic yield has not been examined.

Pitch elevation angle, resistance, coil size, inductance, spacing among the coils, and the displacement speed present in the receiver coil were assessed in the newly presented model in connection to the efficacy of the coil's recharging tool. This model helped specify the proper number of wireless coils to completely power the car while it was on a charged road. The recharging process was described in detail using a detailed mathematical model. It also offered intriguing data, showing how the physical equations worked. The tests were performed under two different circumstances: when the car was stopped and when it was in motion.

Two wireless receivers were tested in the vehicle as part of this investigation, and the outcomes demonstrated the value of the suggested model. The authors considered where the receiver was in relation to the transmitter and when the vehicle's speed changed. Additionally, the effects of the autonomous driving system were discussed. Current approaches were contrasted with these findings. The results of this study showed the benefits of two receivers below the car. The suggested concept underwent experimental testing utilizing a prototype, and the findings were confirmed.

8. Wireless Charging System—Composition

This research looked at the wireless power transfer system, which had two main parts: one on the road and one within a car. On the road, the stationary part was referred to as the transmitter. The second part, placed below the vehicle, was called the moveable receiver. Each of the two halves utilized an electronic system and was isolated from the other by a vacuum. The transmitter block generated a magnetic flux with a maximum frequency. This magnetic flux was converted into electrical energy whenever connected to the receiver coil, which was then used to recharge the EV battery. The other had two receivers, whereas the first has just one [295].

As seen in Figure 16, the transmitter component was installed on the road and coupled to various electrical components to ensure the receivers and the AC power supply were compatible. It provided the initial energy, AC power coupled to the AFE converter, which created a controlled DC voltage. This part of the transmitter block was updated by a PFC block, which kept track of the reactive power going from the source to the transmitter to preserve grid stability. After that, a strong excitation current was delivered to the transmitter coil using a high-frequency (HF) full-bridge inverter [296]. Two variables significantly influenced the entire system's profitability. The first element had to do with the compensating technique that ensured the accuracy of the current and voltage waves. The second crucial element was how the coils were made, specifically whether or not the transmitter coil surface was mainly related to the coil form's circularity. More information on these factors has been provided in the two following subsections [297].

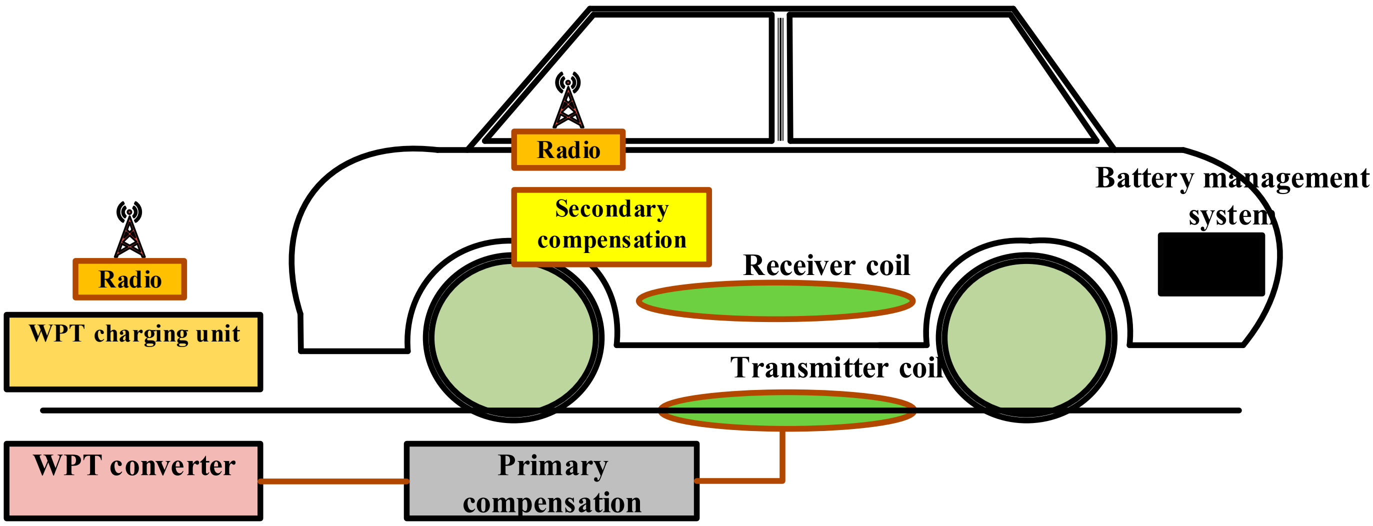

Figure 16. Two instances of electric vehicles.

8.1. Topologies for Compensation

A wireless power system transmission (WPT) system might use four resonant circuit topologies. After placing the capacitor on either side, that was indicated. The types of topologies are: series–series (SS) method, series–parallel (SP) method, parallel–series (PS) method, and parallel–parallel(PP) method, assuming that the connection and interconnection can be in series (S) type or parallel (P) type with the coil. Figure 17 provides an illustration of these plans. More information regarding these methods was provided in [298–300]. For management of the filter, the values of the first and second inductances and the capacitors (L_1, L_2) and (C_1, C_2) are fixed. To increase the transmission of power, one must reduce the apparent power supply and ensure the distribution of the active energy to the load; the coupler's primary and secondary circuits—and perhaps inductance and capacitance—are used [301]. The authors of [302,303] researched various topologies and used a few working prototypes to demonstrate their system concepts.

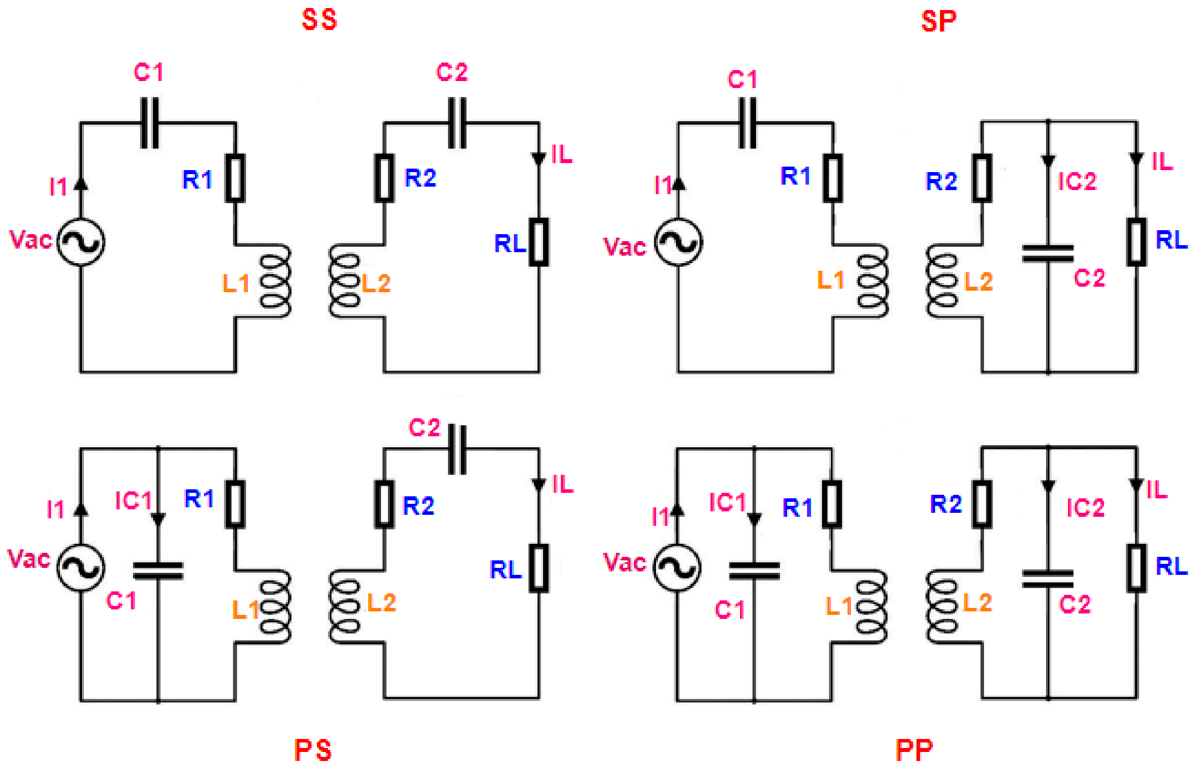

Figure 17. Compensation topologies for primary and secondary resonant circuits.

Compensation is crucial in a resonant inductive power transmission system. The system's VA ratings must consistently be decreased whenever the coupling coefficient falls under 0.3. Both parties' compensation should be reasonable and capable of performing. In the case of parasitic capacitance, the network's architecture prevents the system from resonating or receiving compensation. Additional reactive parts, like inductors or capacitors, are required to change the operating resonant frequency.

Mono resonant topology refers to the primary and basic fundamental compensation that may be achieved by interconnecting the single capacitor in series or parallel. A kind of compensation known as multi-resonant compensation affects several reactive elements. On the other hand, improper compensation results in greater reactive power and current. Reactive current enhances conduction and semiconductor losses, especially on the inverter side.

The main goals of compensation are:

- decreased reactive power;
- the feasibility of operating with a gentle duty cycle;
- avoidance of bifurcation and segmentation;
- the creation of a system able to tolerate severe misalignment; and
- to achieve optimum efficiency, bifurcation tolerance, a compact design, and cost reduction.

An automatically coupled voltage power source inverter and series compensated transmitter's coil is possible. An inductor transforms a paralleled compensatory coil winding of the inverter into an inverted current source utilizing an inductance. Secondary compensation is utilized to reduce the coil's VA rating. It is possible to offset the series network's secondary side by converting the transmitter coil's continuous output on the current side of the series network of a transmitter coil to an input source voltage.

Primarily on the secondary side, parallel networking rectification creates a current source [304]. To reduce the coil VA, Zero's Phase Angle(ϕ)(ZPA) criteria would need to be enhanced. This situation would only be feasible if the voltage, as well as the current, were in phase. This can be accomplished by fine-tuning the main capacitor using predetermined load and coupling characteristics. The primary side compensation, like the secondary side compensation, aims to achieve zero switching current (ZCS) or zero switching voltage (ZVS) if it retains a small portion of reactive or active power demand [305]. Compensation schemes can. be adjusted to the resonance frequency, also known as the ZPA frequency, due to abrupt changes in some parameters. This bifurcation occurs in the RIPT system, and the resulting parameter specification is referred to as the critical parameter. The electrical properties are modified by bifurcation. Electronic components could suffer harm as a result.

In RIPT system circumstances, basic resonant topologies exhibit bifurcation and primary level-type capacitance.

8.2. Mono-Resonant Compensation Networks

Based on the capacitor connection, there are four different compensation topologies. The two letters can then be used to address them because of the series/parallel link. As shown in Figure 17, the first sign denotes the connection of the primary side, while the subsequent (second) symbol denotes the interconnection present on the secondary side. Series–series type (SS), series–parallel type (SP), parallel–series type (PS), and parallel–parallel type (PP) are the four variations. QS must be established as a secondary quality criterion in order to get major reimbursement $Q_s = \frac{\omega_0 L_P}{R_L}$ for series-type compensation, and $Q_s = R_L/\omega_0 L_P$ for parallel-type compensation, where *inω_0* represents the frequency in resonance. The quality factor (QF) is the proportion of reactive power to active power. Table 8 displays the primary capacitances of fundamental compensatory techniques.

Table 8. Requirements for averting the basic compensations' bifurcation occurrence.

	SS	SP	PS	PP
Primary Capacitance	$\frac{1}{\omega^2 \cdot L_p}$	$\frac{1}{\omega^2 \cdot L_p \cdot \frac{M^2}{L_S}}$	$\frac{L_P}{\left(\frac{\omega^2 . M^2}{R}\right)^2 + L_p^2 \omega^2}$	$\frac{L_p - \frac{M^2}{L_s}}{\left(\frac{R.M^2}{L_S^2}\right)^2 + \omega^2 \left(L_p - \frac{M^2}{L_s}\right)^2}$
Bifurcation	$Q_p > \frac{4Q_s^3}{4Q_s^2 - 1}$	$Q_p > Q_s + \frac{1}{Q_s}$	$Q_p > Q_s$	$Q_p > Q_s + \frac{1}{Q_s}$

Because they increase performance, compensations like SS-type and SP-type are frequently employed in these applications. The capacitance levels are not impacted by changes in load thanks to the their compensatory networks. Additionally, SS compensation is unaffected by the main coupling coefficient of the network's capacitance. Owing to the uniqueness of the network's coupling coefficient, this leads to reduced susceptibility to misalignment. This requirement is typically included in the approach known as DWPT. Additionally, as SP compensation type is dependent only on some of the available coefficients of the coupling range, a higher primary capacitance value is required for solid magnetic coupling [306]. In an SP topology, the mutual inductance squared equals the main side transmission impedance. In this circumstance, putting DWC into practice is rather tricky. Two additional networking topologies, namely the PP type and PS type, have different properties, based only on the compensation network's resistive load and coupling coefficient range. Current source converters power these systems. The primary capacitance value needed for PP topology is higher than for PS [307]. Table 9 shows the analysis of the review study of the resonant power transmission.

Table 9. Analysis of review study on resonant power transmission.

Complication to be Resolved	Involvement in This Paper	Resolution	Performance
A single base station for power delivery and data collecting in WSN	Fully automated recharging of mobile vehicles.	The driving assistance (automotive vehicle) travels along defined routes according to the blueprint, and OPT-4 transfers electricity to the necessary nodes.	OPT-5 OPT-1
Multi-frequency	Multi-frequency unwired power transmission system.	Certain electrically-powered equipment could only receive electricity from a predetermined frequency channel.	—
The transmitter circuit's nearby and reserved loads each received the same amount of energy.	Technique for electrical circuit separation matching of impedance	Employment of several repeaters and resonators to create arithmetic derivations was suggested.	Power division method

For series–series compensation, the PF is the low coupling coefficient that causes unity and maximum accuracy. In the presence of a receiver, the associated impedance only goes to zero at the resonance frequency. However, the rated current is constrained by parasitic impedance [308], which makes operation potentially dangerous. Additionally, SP-type compensation is influenced by the more extensive primary (main) capacitance ranging value, and the coupling coefficient is required for robust electromagnetic coupling [309]. In adding more topologies, such as PP and PS types, coupling coefficient ranges and load resistances dictate capacitance values. In such systems, current source converters are employed. SS-compensating secondary sides have become a well-liked alternative for bidirectional wireless chargers due to their symmetry, which facilitates the construction of identical control topologies. The overall impedance for the four topologies is shown in Table 10. Research [310] claimed the following to be possible descriptions of the mutual inductance between two coils:

$$M = \pi \mu_0 r^4 N^2 / 2D^3 \tag{3}$$

where μ_0 represents the vacuum permeability, the spacing between the two coaxial coils is shown by the letters D, N, and r, which represent the coil's radius, turns, and number. The load is given, by transmitted power, as:

$$P = \frac{\omega_0 M^2 Q_s}{L_s} * I_p^2 \tag{4}$$

Table 10. Overall impedance of compensation topologies.

Symbol Representation	Equation
Z_{T-SS}	$\left[R_P + J\left(\omega L_P - \frac{1}{\omega C_P}\right)\right] + \frac{\omega^2 M^2}{\left[R_S + R_L + J\left(\omega L_S - \frac{1}{\omega C_S}\right)\right]}$
Z_{T-SP}	$\left[R_P + J\left(\omega L_P - \frac{1}{\omega C_P}\right)\right] + \frac{\omega^2 M^2}{\left[R_S + J\omega L_S + \frac{R_L}{1 + JR_L C_S \omega}\right]}$
Z_{T-PS}	$\frac{1}{(R_P + J\omega L_P) + \frac{\omega^2 M^2}{\left(R_S + R_L + J\left(\omega L_S - \frac{1}{\omega C_S}\right)\right)} + J\omega L_P}$
Z_{T-PP}	$\frac{1}{\frac{1}{(R_P + J\omega L_P) + \frac{\omega^2 M^2 (1 + JR_L C_S \omega)}{(R_L + ((R_S + J\omega L_S)(1 + JR_L C_S \omega)))} + J\omega C_P}}$

Misalignment reduces mutual inductance, which changes the impedance range of the entire system. Thus, according to Equations (1) and (2), the power transfer enhances power production and effectiveness and is approximately proportionate to the transmission signal. The total compensation, at the most basic level, and how they relate to mutual inductance, misalignment, and whole impedance, including current mutual inductance for output power and beneficial transmission effects, were discussed.

The average total impedance falls when the ratio of current to load rises under both the series–series-type topology and the series–parallel-type topology compensatory design. Thus, the total value of the impedance rate would progressively grow along with the misalignment under the topologies of parallel–series type, as well as the parallel–parallel type compensations, resulting in a sudden reduction in the value of the current [311]. PS-type and PP-type coils' compensations would offer a maximum power factor value (PF) value and very high efficacy at low mutual inductances, and thus, the broader value spectrum of mutual inductance variations and load fluctuation [312]. Table 10 shows the detailed symbol representation of the topologies.

The value in the power factor (PF) of the PP-type layout is minimal; at the same time, the parallel main (primary) loads require a maximal current rate; primary parallel loads require a maximum reference voltage [313]. The primary side input impedance range produced by series-type compensation, presenting mostly on the secondary side of the network connection (SS-type or PS-type), has a significantly and comparatively minimal value compared to that produced by compensation for parallel networks (mostly on the secondary side in the network connection (SP-type or PP-type) [56]. A quick comparison of many fundamental network topologies is shown in Table 11. The positives and negatives of each strategy are listed.

Table 11. Comparison table of the Network Topologies.

Characteristics of Topology	SS-Type Topology	SP-Type Topology	PS-Type Topology	PP-Type Topology
The primary compensation capacitance found in the load condition, which a significant impact on topology.	-	-	Interdependent	Interdependent
The circuit equivalent impedance at resonance	Minimum	Minimum	Maximum	Maximum
The AC power supply type that will be utilized to transfer a large amount of power	Voltage power source	Voltage power source	Current generator or power source with very high voltage	Current generator or power source with very high voltage
At the stable current source (SS, SP), energy is transmitted (PS, PP)	Lower	Higher	Lower	Higher
Peak performance of efficiency	High	Low	High	Low
Power factor tolerance for changing frequency	Lower	Greater	Lower	Greater
The capability of power transmission	Maximum	Maximum	Minimum	Minimum
As a function of distance, power factor sensitivity	Minimum	Minimum	Medium	Medium
Alignment tolerances	Maximum	Maximum	Medium	Minimum
The impedance range at the resonance state	Minimum	Minimum	Maximum	Maximum
Suitability for use in electric vehicles (EV)	Maximum	Maximum	Medium	Medium

8.3. Coil Design

WPT makes it possible for electrical power to go from the source to the receiver by utilizing an air-core wireless transformer architecture [1].

In Figure 18, many planar coil designs for WPT systems are depicted, including rectangular, circular, and hybrid forms. These are applied to boost output and fix transmitter and receiver misalignment problems similarly to structural issues [314]. Additionally, each model's associated benefits and drawbacks are listed in a similar table [315]. The literature review assessed several WPT architectures' viability and magnetic coupling for automotive applications. These studies mainly concentrated on circularly-shaped structures. Inductive power transfer for a 2 kW circular planar construction was recently tested in [316,317]. It was proven that this model's null zone was the lowest. This design was chosen for this research as a result. Two coils, attached and allowing for the transmission of electricity through a magnetic field, made up the system's core component for wireless power transfer (WPT). In WPT systems, an electrical current discharge among the principal (primary) side coil creates a changing magnetic field over time. Whenever the secondary winding of the coil, which is in the reception (receiving) part, is near to that same primary (main) side coil, present in the propagation (transmitter) section, voltage is produced as the magnetic field is halted. Several variables, including the separation among the two winding of coils, the intensity of the electromagnet field, and the number of coiled turns provided throughout the time, affect the expected size of the induced emf voltage. Due to this voltage, the secondary coil of the receiver will have current flowing through it.

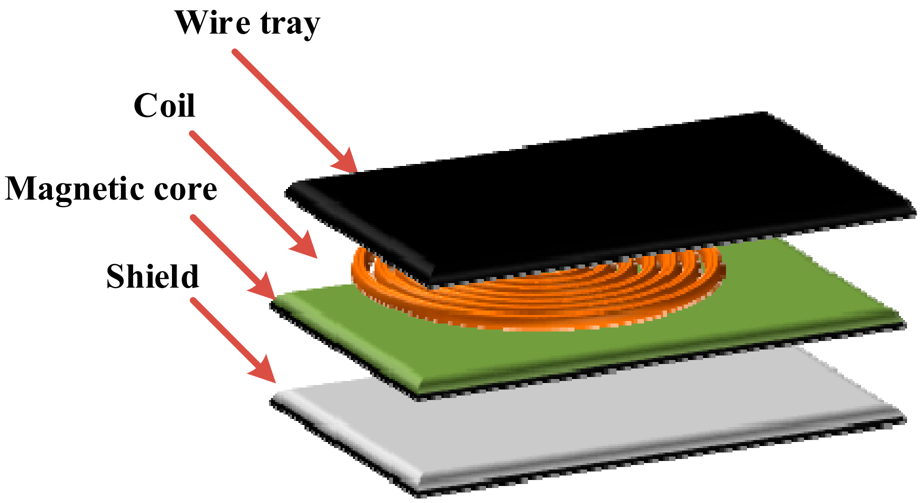

Figure 18. Exploded view of the power pad.

Power transmission resistance may not have been provided by the permeability and electrical flux channel that linked the coil that had the windings used to create the transformer's loosely coupling coil. When every coil was interconnected via the appropriate compensating communication network, the resonance movements enhances the electrical charging current, which traveled on the coil side. The Q factor of certain coil winding and the availability of coefficient in coupling (k)—which were connected toward the optimum permitted tolerance to boost the wide-angle length of aperture and lateral displacement in the longitudinal/lateral interfaces—were important criteria utilized for the overall process of designing the coil pads included within the primary (active) and secondary (passive) coils.

Another way to improve coil design in the coupling is to progressively increase coil size or decrease the air gap size of the aperture. Thus, the width present in the air gap, or the size of the coil, is determined by the implementation, and EV charging is prohibited. The coupling coefficient can be enhanced utilizing same-sized coils, e.g., a mutual inductance range for a 0.1 m aperture measurement vs. the proportion of the receiver coil (Rx) to the transmitter coil (Tx) radius.

In an EV application, with utilization of coils of the same size, both the current in the eddy coil to the vehicle chassis and the permeability of the magnetic field around the coil field are reduced [318]. When the volume and size of the receiver's coil are lessened, it is easier to install and more suitable for use in vehicles. There are more advantages in terms of weight reduction, size, and dimension when automobiles are equipped with a secondary side circuit. Additionally, each pad costs less, since less ferrite is used. These pot designs are consequently shifted to discs, rods, or plates that are evenly distributed across the coil [319]. The pad architecture created by Budhia et al. saved ferrite while maintaining the crucial connection between the circuits' primary (main) coil and secondary coil [157,320]. The authors, Budhia et al., separated the coils present in the winding to produce two different coils, interconnected in series mode. Better coil topologies have been studied and investigated due to their capacity to create a unidirectional flux. The DD and DDQ pads [321], bipolar-type pad [321], tripolar-type pad [322], and zigzag design [323] are well-known examples. The structural component of the core's top and also the side faces are wrapped in the shape of a round helical coil to form an electrical flux pipe-like pad known as a DD-type pad. This creates paths in the electromagnetic flux, which then turns away from the coil winding formed around the core material and returns to its initial position. Moreover, the backside of the coil creates zero magnetic flux with this arrangement.

The formation of the flux in the electromagnetic field connecting the main coil side accessible in the primary (active) and the secondary (passive) side available in the reception (receiver) pad is caused by the coefficient in the coupling between most of the two coils housed on a single pad.

Dimensions of the flux pipe need to be constructed in order to evaluate the coupling effect. Thus, only lateral flux is combined in the DD design, which is a downside. The quadrature coil described in [324] could be connected to the vertical parts to create the DDQ structure. The DDQ pad is another example which calls for extra wires, because it joins two windings to create a circular coil with nothing more than a double flux height. According to the authors, Bosshard et al. [325], the parameter performance of the DD charge methods and rectangle approaches were distinct. In contrast to the two independent coils utilized in a DD pad, tripolar design variants needed three separate coils associated with the DDQ coil. In an egg-like shape and size, three different kinds of coils imbricated and detached from each other. It was feasible to separate the coils by diminishing the magnetic flux in the neighboring coil winding and altering the fabricating region [326]. This kind of coil winding pad offered a wide quasi-misarrangement tolerance and, as a result, a more effective and appropriate design space for distributing the chosen, rated amount of power, by allowing significantly more winding of coils [327].

Moreover, the leakage field was somewhat decreased compared to a circular pad. The requirement for a complex control strategy design, however, was a significant drawback. A separate inverter used each coil independently, which resulted in a very high cost. An alternative layout was proposed that used three kinds of coils for each pad, with one larger group of magnetic coils twisted into a rectangle next to smaller rectangular coils [328]. The smaller coils were able to precisely and uniformly control the magnetic flux.

The load condition received power from the coil and made tiny adjustments across a significant misalignment region. Most of the time, a considerable amount of wire cable was needed. In order to increase the transmission distance, inter-junction coils could be placed concurrently among the transmitting coils' main side and the receiving winding coil [329]. Additionally, this investigation did not understand the future coils or outsourcing [330]. Whenever the layout design was separated in the power utility grid, the conclusion of the comparison of the achievability of different coil designs (Table 12) was that there was zero tolerance for the misalignment rate or the altitude of the magnetic flux path. This is crucial for any further innovations in the system [331] or cyber-resilience [332–334]. Additionally, other data-driven processes for design and optimization must be considered [335,336].

Table 12. Comparative evaluation of various coils' design methodologies.

Design Specification of Coils	Rate Range of Misalignment	Tolerance for the Flux Path's Height
Circular type	Zero at 40–50% range in diameter.	1/4 amount of a coil's diameter
Magnetic Flux pipe/flat solenoid	A great step toward tolerance.	1/2 amount of a coil's length
DD coil type	Null at 35% of the length of the pad (x-direction).	1/2 the amount of the coil's length
DDQ coil type	Around 96% of the length, null (x-direction).	2 circular times
Bipolar coil type	Approximately 96% of the length was null (x-direction).	2 circular times
Tripolar coil type	Non-symmetrical type of tolerance.	N/A
Zigzagcoil type	No null and empty values are present in this.	1/(2.5) amount of the coil's length

8.4. Batteries and Electric Vehicles

Wireless charging gives EVs, both pure and hybrid, greater independence. As such, it has become much more prevalent on motorways. Additionally, since a battery-powered electric vehicle (BEV) cannot currently be charged when moving, advancements in wireless recharging methods might be helpful. Hence, it will be crucial for manufacturers to disclose BEV's interior designs. The basic variants for the primary electric motor consist of battery systems coupled to an inverter [160]. The entire system is managed or supervised by a control unit. Because specific current systems do not allow for wireless charging, the preceding mention solely refers to the vehicle-to-grid (V2G) classification's basic form. The size of the motor must be maximized in recently- and soon-to-be-introduced EV models, battery technology must progress, and several easy charging methods must be supported in order to contribute to the reduction of pollutants [337–339]. It is commonly known that the battery, which supplies the necessary energy to run the system, is among an electric car's crucial components (EV). This component type was modeled in this work to examine power flow and demonstrate how well wireless recharging tools work [340,341]. The charging/discharging voltage of lithium-ion batteries is determined by devices comprising a DC voltage source and a series of variable resistance. It is influenced by several factors, as shown in the Equations and the recommended methods, considering related assumptions, that must be adopted in order to optimize battery function and performance. [342–344].

9. Conclusions

In this work, we compared and contrasted several types of power pads utilized for the wireless charging types of electric vehicles. Thanks to mutual induction, electric vehicle batteries may be charged wirelessly, without physical connections. Critical obstacles to EV wireless charging include power transmission frequency, power pad design, space between transmission of coils, and alignment of transfer coils. These were reviewed in this paper. This paper also discussed power pad design, involving economic analysis, in addition to optimization of the coil and core size, material, and shape for rapid prototyping.

The article evaluated existing coil shapes and designs, using a ferrite core across the coils, to create a powerful power pad for wireless EV charging. Because of the unusual way the flow was distributed, analysis was done using the 3D FEA. Only three kinds of coils—D, DD, and DDQ—were used to examine the impact of the magnetic ferrite core. The comparison was based on data imported from various findings, and magnetic flux patterns and simulation results were evaluated. The magnetic configuration of the power pad coils was simulated using Ansys 3D Maxwell simulation software. The findings showed that the DD model coil had the largest coupling coefficient, best magnetic fields, and greatest tolerance for misalignment, as explained in detail in this paper. The ferrite core, inserted across coils, somewhat improved the coupling coefficient and aligned the magnetic flux pattern, which was also discussed.

The development of EVs and HEVs is inevitable, as a result of growing worries over the energy crisis and energy usage. While an overview of new technologies could be helpful to many stakeholders, many fascinating innovations that have been developed in the previous few decades were also discussed herein. This paper sought to provide engineers, researchers, and academics eager to pursue their interests in this field with a place to start. The latest EV/HEV models, electrochemical energy sources, wireless charging infrastructures, and electric vehicles, in general, represent some of the major subjects covered in this article. As such, this work was designed to give readers a road map, so they may start their own fieldwork.

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