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Review

Review on Key Factors of Wireless Power Transfer Technology for Electric Vehicles

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Abstract. Electric vehicles (EVs) have become an alternative option for a clean energy society. A new charging technology which is wireless charging has been developed to satisfy the limitations of EVs which are the electric drive range and battery storage. Companies like Tesla, BMW, and Nissan have already started to develop wireless charging for EVs. This paper presents a literature review on wireless charging of EVs. The existing technologies for Wireless Power Transfer (WPT) system are summarized for different power applications. Coil design plays the most vital role in the WPT system so the different coil design with the transferred efficiency is reviewed. The other important parameters and technical components like significant factors of WPT system, track layout of dynamic wireless charging, foreign object detection method, and position alignment method that are affecting the efficiency of the wireless charging system are also discussed. Lastly, health and safety concerns for human beings and living things are investigated.

Keywords: Charging technology, electric vehicle, future mobility, mutual inductance, wireless.

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1. Introduction

The air pollution problem caused by the emissions from internal combustion vehicles has suffered in every country in the world. The internal combustion engine (ICE) vehicles should be transformed more into electric vehicles (EVs) since gasoline and diesel vehicles emit carbon monoxide gas which is the main reason for the air pollution problem. There are mainly four types of electric vehicles hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), and hydrogen fuel cell vehicles (FEV) [1]. HEV gets the power from both gasoline and electricity and the vehicle's braking system generates the electric energy for recharging the battery. PHEV could be charged the battery not only by regenerative braking but also by plugging into an external source of electrical power [2]. BEV is purely an electric vehicle without a gasoline engine which the battery can be distinguished into an onboard and off-board battery. The onboard battery is inside the vehicle and the size and power rating depend on available space in the vehicle. The electricity is stored onboard a battery with high-capacity battery packs while the electric motors and onboard electronics are driven by the battery power. Off-board batteries are outside the vehicle. Fuel cell EVs use a fuel cell instead of a battery. In this paper, EVs mean battery electric vehicles. EVs are the most effective ones in terms of cost, efficiency, and battery weight [3]. They produce zero emissions, unlike HEVs and PHEVs. EVs can be defined as the future of world transportation. However, the main problem is energy storage. The battery used in EVs requires high energy density. Another problem is where to charge an EV or the charging station. The time required for charging EVs and the shorter driving ranges are limitations for an EV.

The three common ways to charge an EV are conductive charging, wireless charging or inductive charging, and battery swap technology. Conductive charging categorizes into AC charging and DC charging. For AC conductive charging, power needs to be converted from AC to DC to charge the battery [4]. This charging limits the power output due to the size and weight constraints of the onboard battery charger and requires a long time because the charging power is relatively low. AC conductive charging uses an onboard charger and can be used at homes or inside buildings to charge an EV. DC conductive charging is also called fast charging for high-power EV charging. Only the ability of the accepted battery restricts the power output of the fast chargers. However, high investment is needed for the installation of the DC charger which EVs cannot be charged at home. Battery swapping utilizes an off-board charger and switches out the empty battery and replaces it with a full battery. The problem is that EV users must accept not owning a battery. Despite the conductive charging being more beneficial in terms of simple structure and high efficiency, the wireless charger is comfortable to apply and appropriate for all kinds of weather situations. Since wireless charging has no direct electrical contact between the vehicle and the charger, it prevents the risk of an electric shock. Therefore, wireless charging is convenient among the three charging techniques and is even suitable for self-driving cars [5]. Thus, wireless charging technology is reviewed in this paper.

EVs can be charged by three methods of wireless charging technology. They are termed stationary charging, semi-dynamic charging, and dynamic charging methods [6]. Stationary charging system work like an existing plug-in vehicle. In stationary charging, EVs can be parked and charged simultaneously however EVs must be parked in the assigned area for charging. For this reason, it may take a few hours to completely charge the EV. If EV is traveling for a long distance, the drivers might have range anxiety and inconvenience to find the stationary charging stations. In semi-dynamic charging, the charger pads are installed at bus stops, taxi stops, and traffic lights. It gets only a short time for charging in a dynamic environment. In dynamic charging, EVs are charged along the road with driving. The charger pads are installed under the road and EVs can be charged all the time increasing the driving range and consequently overcoming the problem of range anxiety. By dynamic charging, the battery capacity of an EV can be reduced up to 20%, therefore reducing the weight of the EV, and investment in EV should be concerned [7].

2. WPT Technologies

WPT methods can be classified into Inductive Power Transfer (IPT), Resonant Inductive Power Transfer (RIPT), Permanent Magnet Power Transfer (PMPT), Capacitive Power Transfer (CPT), Optic Wireless Power Transfer (OWPT), Microwave Radiation Wireless Power Transfer (MR-WPT) and Ultrasonic Transcutaneous Energy Transmission (UTET) [8].

IPT is almost the same field as RIPT and both are approved by the electromagnetic induction law. Their system efficiency decreases significantly with increasing the air gap between primary and secondary coils [9]. Given the concept, these two methods do not differ distinctly. IPT is applicable for high-power applications which could attain beyond 10kW of output power with larger air gaps [6]. The magnetic interaction of the spinning permanent magnets realizes PMPT. Its low operating frequency and the elimination of the magnetic exposure and foreign object heating make it noticeable for PMPT. But the noise, vibration, and harshness issues are needed to consider attentively for PMPT design development.

CPT is accomplished through electric field interaction between coupled capacitors, and it is also the same field as the WPT method. The accessible area of the devices verifies the coupling performance of such capacitors and thus CPT is only appropriate for low-power applications with limited short air gaps. Therefore, CPT has not been considered appropriate for EV charging since the power capacity is insufficient [10]. These four methods restrict the distance between source and receiver.

OWPT, MR-WPT, and UTET are far-field approaches and have a longer transmission distance. During the power transfer, they contain three processes [11]. In the first step, the electrical energy is transformed into an ultrasonic wave, microwave, or laser. Then the transformed energy is transmitted to the supposed objects. Finally, it is harvested and converted back into electricity. Although OWPT has a high-power density, it cannot be used practically because of safety issues. UTET is proper for multi-device charging with the aid of the nondirective field [12]. MR-WPT can transmit both directive and non-directive power. However, IPT is the best appropriate for wireless charging of EVs. A lot of research has been conducted to achieve higher transfer efficiency with misalignment tolerance. In this paper, IPT technology is mainly focused on and discussed.

Simply, the IPT system distributes power from a stationary primary source to a stationary or movable secondary source throughout a large air gap. EVs can be charged in the parking lots without plugging in any charging cables in the case of stationary or static charging. Another way to charge wirelessly is dynamic charging. The transmitting coils connecting to the power electric cables are covered under the road. These coils transmit electromagnetic fields. The vehicles driving over them pick up the field and transform it into electricity to charge the battery in the vehicles. Dynamic charging gets rid of range anxiety by charging with small packets of energy during long traveling distances so it can improve battery life. Several IPT systems have been established over the last era aiming for charging both passenger cars and public transportation. Generally, these IPT models range from 2kW to 200kW of power and transmit at frequencies around 40-100kHz having an overall frequency of 80 to 95 from AC mains to DC battery. The charging distances (air gaps) are approximately 50mm-400mm for passenger cars and public transport vehicles.

3. WPT Structure

The wireless charging principle is based on inductive coupling using two electromagnetic coils as shown in Fig. 1. The transmitter coil is installed in the charger terminal which is under the road surface connecting to the electricity grid network and it is called ground assembly. On the other hand, the receiver coil is implanted at the bottom EV which is the vehicle assembly.

On the transmitter side, there is a power cupboard that consists of an AC-DC rectifier, a DC-AC inverter, and a compensation network made up the power cupboard [8]. The cascade of AC-DC and DC-AC converters increases the frequency of the main AC supply (50/60 Hz) to a high-frequency AC power lower than 100kHz and energizes the primary coils. The compensation network neutralizes the leakage inductance for magnetically coupled power transfer to achieve higher efficiency. Besides, it reduces the VA ratings of power electronics. Finally, the high-frequency AC is inductively transferred to the receiver coil by electromagnetic induction.

On the receiver side, the induced high-frequency AC is converted into DC by a rectifier for charging the onboard battery after the secondary compensation network provides constant current, constant voltage, or step power to the batteries [13]. An extra voltage regulation circuit could be added between the rectifier and the battery [14].

To ensure the charging process, the data flow is used for reliability and protection and the data exchange is dependent on pairing, information inquiry, and payment systems. The relative communication terminals contain three parts, in-vehicle unit, communication service unit, and wireless charging control and management. The in-vehicle unit is mainly responsible for vehicle-side communication while the communication service unit is for ground-side events. Exchanging information between them is required from time to time for proceeding with the charging process correctly. The charging process will be stopped immediately if any error occurs. Wireless charging control and management make use of monitoring the charging process like a mobile app [15].

4. Significant Factors of WPT

There are several factors which are needed to be considered in dynamic charging for EVs and aimed for the precision of dynamic charging [16]. These factors affecting the wireless charging of EVs will be discussed as follows.

4.1. Speed

The first important factor for charging batteries is speed [17]. The speed must be decreased with advanced technologies, but some organizations rarely restrict it [18]. The transmitters or an electromagnetic system including the power distribution backbone and power supplies are buried under the roadway. EVs with a speed of 120 km/h moving back and forth could receive 20kW. Roads' conditions and categories are issues for speed limits and variable speed limits based on several categories of roads for good charging quality exist. The main challenge for a dynamic charging system is the expense of installation to operation.

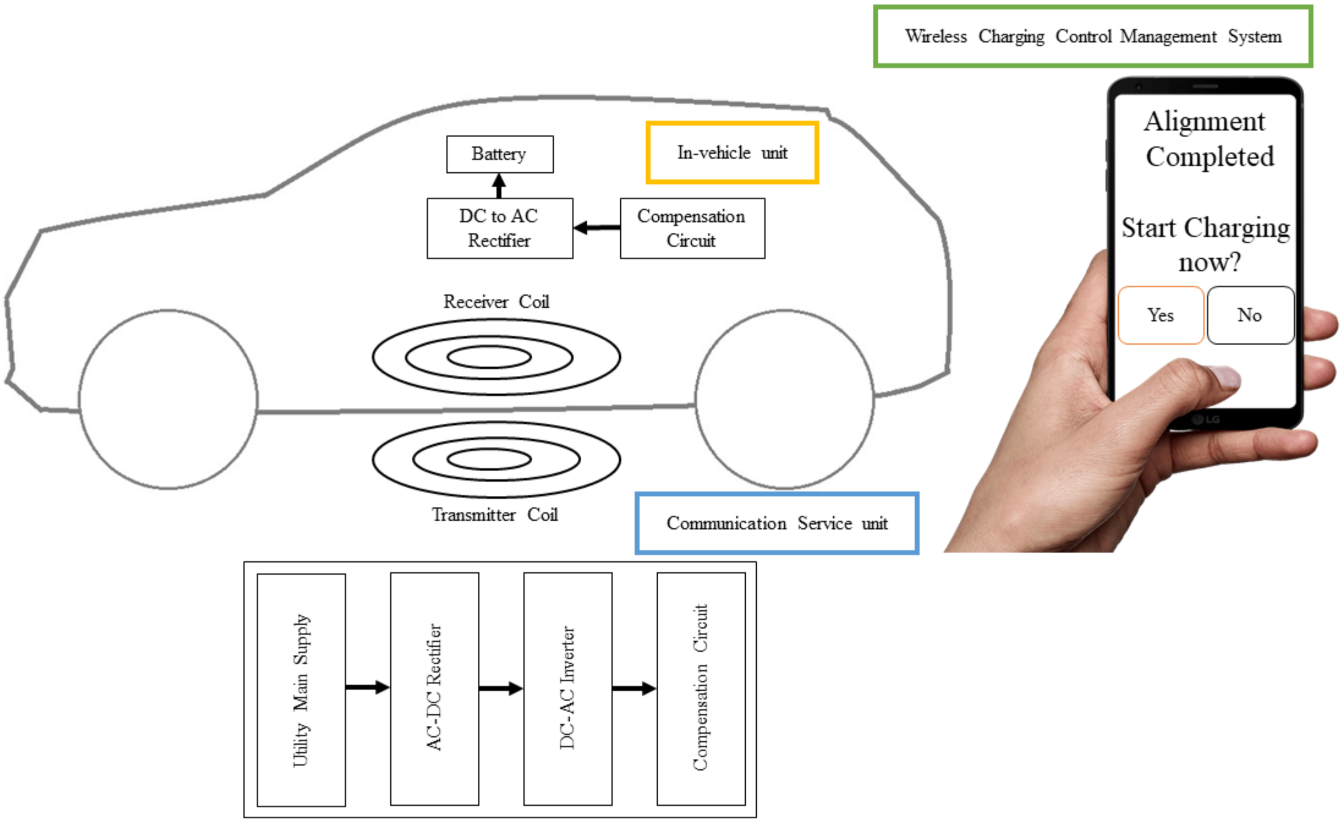

Fig. 1. Structure diagram of typical WPT system for EVs.

4.2. Positioning

Dynamic charging influences positioning while EV is moving. EV must be situated at a certain position on a charger where EV can be feasible charging levels to its maximum amount while it is traveling. Then the power can be reached to the battery of the EV efficiently. Thus, the second important factor is the position of the EV above the charger [19]. When an EV is located near the exact or expected position above the charger pad, it could obtain 80% of its charging capacity. If not, the charging levels will be likely decreased to 30%.

4.3. Distance between Primary and Secondary Coils

The third factor is the distance between two charger pads, and it is a key factor for the rate of charge per unit time and for determining charging intensity as shown in Fig. 2. Besides, it is also crucial combining with the above two factors [20]. While EV travels, the secondary charger must be at the nearest distance of around 50cm to the primary charger [21]. Distance also in fact depends on the categories of roads and alters with gradients and curves of roads [22]. Moreover, the EV must go directly above the charger while traveling. The wasted energy could be restricted if these three factors are organized efficiently by EV charging management.

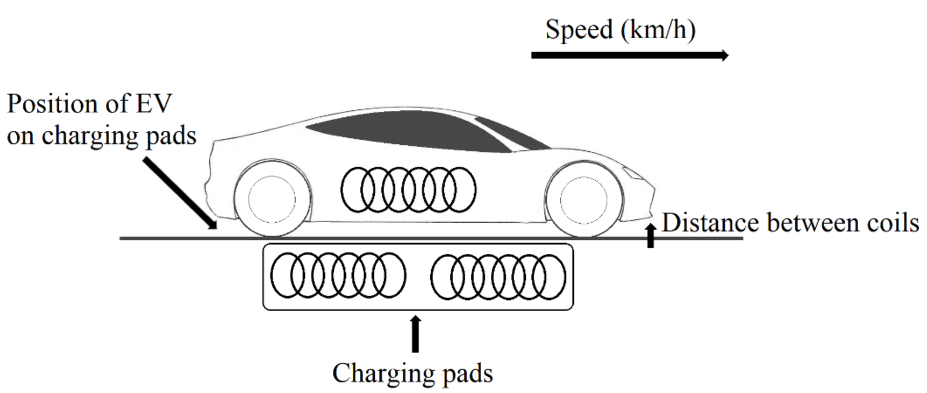

Fig. 2. Three factors of Wireless Charging of EV.

4.4. Traffic

Another thing required to be considered is that EV travels near a few other vehicles. Some roadways may have low, average, or high traffic. The battery charging levels could be different for the reason of traffic if the wireless chargers are existed on the roadway and EVs pass over the areas [17].

4.5. Number of Stations and Coils

Another considerable factor is the detection of the number of stations in a city. The charging pads' arrangement being a measurable factor could be calculated after certain on-site work. If the areas point to higher traffic, more charging pads could be arranged [23]. On the other hand, passive stations or fewer charger pads can be set in fewer traffic areas. The main purpose of considering the number of charging pads is to achieve the greater system's power competently and avoid lost power. The number of coils is crucial to the wireless charging system and fluctuates according to the gradient of the road [24]. Moreover, coil design, transfer medium, and flux leakage decide the power transfer efficiency.

4.6. Mathematics Road Gradient

The coil pad arrangements also depend on the road gradient as shown in Fig. 3. The higher number of coils could be fitted for a slope since the vehicle takes time to drive over a charger. If the road has no gradients, it only needs a lesser time. The two parameters: distance between coils and road conditions can reduce the charging time [21]. According to gradients, a greater number of coils can be installed if the EV takes more time or a lower number of coils if the EV takes less time [25]. Besides, the number of coils depends on the matching frequency for saving energy [26]. Thus, it can be concluded that the transfer distance between transmitter and receiver and road conditions are crucial to consider.

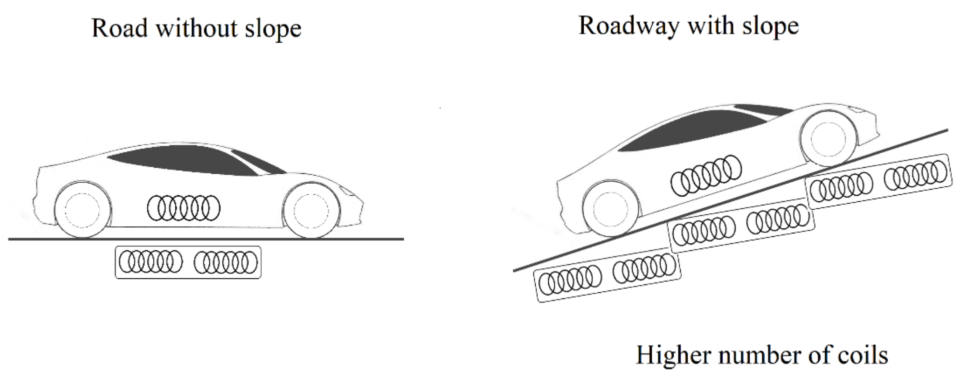

Fig. 3. Difference between Coils on a Roadway with and without a gradient.

4.7. Battery Size and Coil Position

The charging capacities differ with various EVs as the battery sizes are different. If the battery size is bigger, EV can travel longer and it needs more charging time [27]. The battery size does not matter for this purpose since the roadway has a dynamic charging system. Also, the receiver coil position of the EV is significant to accomplishing charging rates greater [28]. For charging if EV is not positioned accurately in the exact place, it needs additional time or will not even charge since it is off from the boundary of a radius of charging [29].

4.8. Day Time

The time depending on traffic is also an important factor while charging. It was developed from the National Renewable Energy Laboratory (NREL) and Oak Ridge National Laboratory (ORNL) research. Roads in the cities may have more traffic in the daytime [11]. For that case, these roads could be installed with dynamic wireless charger pads [30]. Likewise, the electric buses can be charged in garages or charging stations during unoccupied hours. The power supply should be scheduled to deliver power and it also needs to construct an effective dynamic charging system to conserve energy for various times of the day.

5. Coupled Structure or Coil Design

In a wireless charging system, a minimum of two magnetic couplers is used for transferring power wirelessly. One is the primary coupler on the transmitting side and the other one is the secondary coupler or pick-up coupler on receiving side. The transmitting magnetic coupler can be designed in the form of a pad or a track based on the applications [31]. For the system having a high coupling coefficient k and quality factor Q, the wire used for the coils will be thicker, and more ferrite must be used. Higher transfer efficiency could be obtained if the dimensions and materials are increased but that option is not reasonable. It would be better to design with the minimum dimensions, cost, and increased frequency for higher k and Q in high-power EV WPT applications.

Besides the frequency, coupled structure or coil design is essential since the power is transferred through the air gap from the ground to the chassis of the EV. Different coupling coefficients will be affected by the different coil designs with comparable dimensions and materials. Moreover, the parameters of the air-core coil are responsive when there is an object in the vicinity between the ground and the chassis, so it is the main challenge. RIPT systems having a frequency less than 100kHz commonly apply ferrite as a magnetic flux guide and an aluminum plate to shield for this issue [32]. The coupling can also be increased by reducing the air gap length between two coils. The application of EV charging and restricted coil size defines the air gap length. Applying the equally sized coils could increase the coupling and decrease eddy currents induced in the receiver and reduces magnetic field leakage around the coils too. In this paper, commonly used coil designs will be reviewed. First, for all the coil designs, the power must be nearly as high as conductive charging. Then k value should be high so the magnetic flux lines will be strong enough. Finally, the operating temperature will be increased, and radiation will be leaked so they must be precisely controlled within the safety range [33].

The magnetic coupler can be categorized into double-sided and single-sided types due to the distribution area of the magnetic flux. In the double-sided type, there is flux on both sides of the coupler [34]. An additional aluminum shielding is placed to avoid eddy current loss in EV chassis [35]. Choosing a double-sided coupler is not best because of the high shielding loss. In a single-sided type, the majority of flux goes to only one side of the coupler. The main flux path flows through the ferrite and there is only a leakage at the back in a single-sided coupler. That is why the shielding is not significantly affected in a single-sided type. On the other hand, half of the main flux goes to the back. A single-sided pad generally contains three layers. The coil is on the top layer. A ferrite layer is introduced to enhance and guide the flux below the coil layer. A shielding layer is at the bottom. The two pads are set in proximity with coil to coil for the power transmission. Most of the high frequency magnetic flux can be kept between the two pads by the shielding layer.

The circular coil shape is the most used coil design due to the simple construction, structure, and minimal eddy currents. Coil size affects the magnetic flux distribution and the transferred efficiency. As shown in Fig. 4, it lessens the usage of ferrite and thus higher flux density is achieved. Circular coils produce their maximum magnetic field at the center of the coil and it falls drastically with offset because of a low non-directional misalignment tolerance. The circular pad performs similarly in the matter of offset tolerance in all directions of EV. To increase the anti-offset capability in a particular direction, oval and rectangular pads are developed. Circular pad design is still common for stationary wireless charging systems in which the coil performance is extended by applying multi-objective development processes. A circular coil is prone to large leakage fields and results in decreased overall transmission efficiency. The rectangular coil is more prone to eddy current losses because of its increased inductance at corners and creates hotspots but it has a better misalignment tolerance and increased efficiency than circular designs.

Fig. 4. A Circular Pad Structure.

An advanced design called a Double-D pad (DD pad) is developed by combining two rectangular coils with smooth curved edges generating flux perpendicularly with minimal edge leakage fluxes as shown in Fig. 5. The coupling, transmission distance, and misalignment tolerance are enhanced by the concentration of magnetic field alongside a single path in the DD pad compared with the same size of other coil geometries. The charging area of the DD pad is four times larger than that of CP with the same material and dimension. Also, the tolerance in the y-direction is quite good in the DD pad [32]. So, the DD pad is chosen as the best solution for dynamic charging since the driving direction is along with the y-axis with an efficiency range of 88.3% to 90.4% at a 5 km/hr speed [36]. However, DD coils couple only the horizontal flux components so there will be approximately 34% misalignment in the x-direction [9].

A quadrature coil (Q coil) is added to the DD pad to improve the x-direction tolerance [37] as in Fig. 6. This multi-coil design is called Double-D Quadrature (DDQ) pad. The amount of copper used in DDQ and DD pad is two times larger than in circular pad since DDQ and DD pad uses two combined windings and generates the double flux height compared with circular coil [38]. Besides, the charging area can be improved five times larger than the circular design if the DD coil is used as a transmitting pad and DDQ as a receiving pad. However, the drawbacks of the DDQ pad are the higher number of coils, the infrastructure cost, and higher system flexibility than different coil configurations.

Another high flexibility configuration called bipolar pad (BP) is introduced by the University of Auckland [39]. The two coils are partly overlapped making an internal quadrature coil exclusive of an extra coil as in Fig. 7 and both coils require a synchronized independent converter. BP can decrease the usage of copper, system complexity, and cost compared with the DDQ pad. BP also could transfer power using about 25% less wire material than the DD pad [40]. BP configuration is fit for multi-mode secondary pad design having a potential for wireless charging of EV. Both BP and DDQ designs are primarily intended for receivers. But they can only be used as transmitters since their coils can be independently controlled and energized in various modes that are producing parallel, vertical, and compound flux patterns and in that way allowing them to energize various on-board coil types. By using a bipolar pad design, the coupling between transmitter and receiver pads could get around 0.15 to 0.3 with a suitable size at a 200 mm air gap for an EV. An efficiency greater than 90% could probably be obtained with this coupling level as shown in. In [41], the author proposed sensitivity analysis to reduce the coil design variables, improve the optimization results and reduce the computational time of different design coils such as circular Pad, DD pad, DDQ pad, bipolar pad, tripolar pad, hybrid solenoid coupler, intermediate multi-coil, and three-phase bipolar winding pad. The properties of popular wireless charger coil designs are listed [42]. Table 5.1 shows the efficiency of different coils designs with the works of literature.

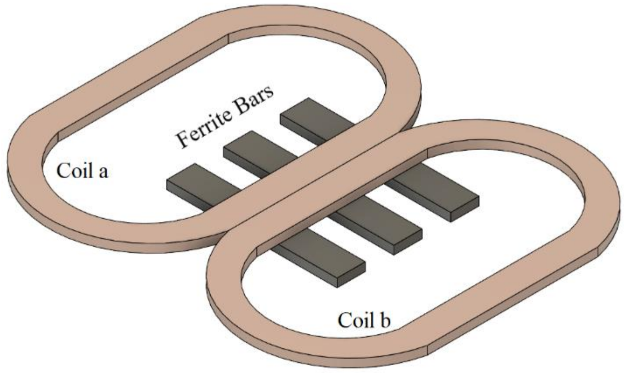

Fig. 5. Double-D Pad.

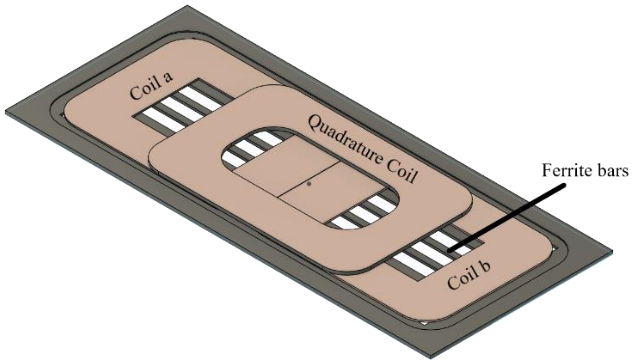

Fig. 6. Double-D Quadrature coil design.

Table 5.1. Coil Design and Transferred Efficiency.

Reference	Coil Design	Efficiency	Common Use in WPT applications	Transmission Distance
[45]	Circular coil design	91.5%	Transmitter	Low
[46]	Rectangular coil design	89.2%	Transmitter and Receiver	Low
[47]	DD coil design	95%	Transmitter	Medium
[48]	DDQ coil design	97.5%	Receiver	High
[49]	Bipolar coil design	>90%	Receiver	High

6. Track Layout of Dynamic Wireless Charging

The system layout mainly on the primary side influences the system performance just as so the design of the charger pads. For a stationary charging system, an EV needs plenty of time to charge and traveling ranges are not acceptably long [50]. Besides that, the EV must be parked during the charging process. However, in a dynamic charging system, an EV can be nonstop charged while it is driving thus the size and weight of batteries could be reduced in the EV at the same time not only the driving range but also the consumers' convenience is increased. A problem with dynamic charging is that the time for transmitting and receiving pads interacting with each other and transferring power is a short period [6]. As EV passes over the transmitting pads, the receiving coils induce the magnetic flux causing the magnetic coupling changes. In that case, the power and transfer efficiency fluctuate therefore charging pads of the system should tolerate a high degree of misalignment. Dynamic charging of EVs can be employed using two kinds of electrical tracks.

6.1. Single-coil Long Transmitter Track

A single-coil long transmitter rail in Fig. 8 is easier to control due to its simple configuration and constant power output, current, and mutual inductance between track and pickup coil while EV driving on the track [51]. A single power supply is used to power a long transmitter track in dynamic charging and therefore the ratings of all components are increased. The whole system must be shut down if an error occurs within the system so the system reliability is decreased. Since the receiver inhabits a small proportion of the track and the whole track must be always active even where no EV passes over it, the efficiency is low in part-load operation, and it is not efficient to use a single long coil track [52]. It is also required to suppress the produced electromagnetic field for reducing destructive radiation.

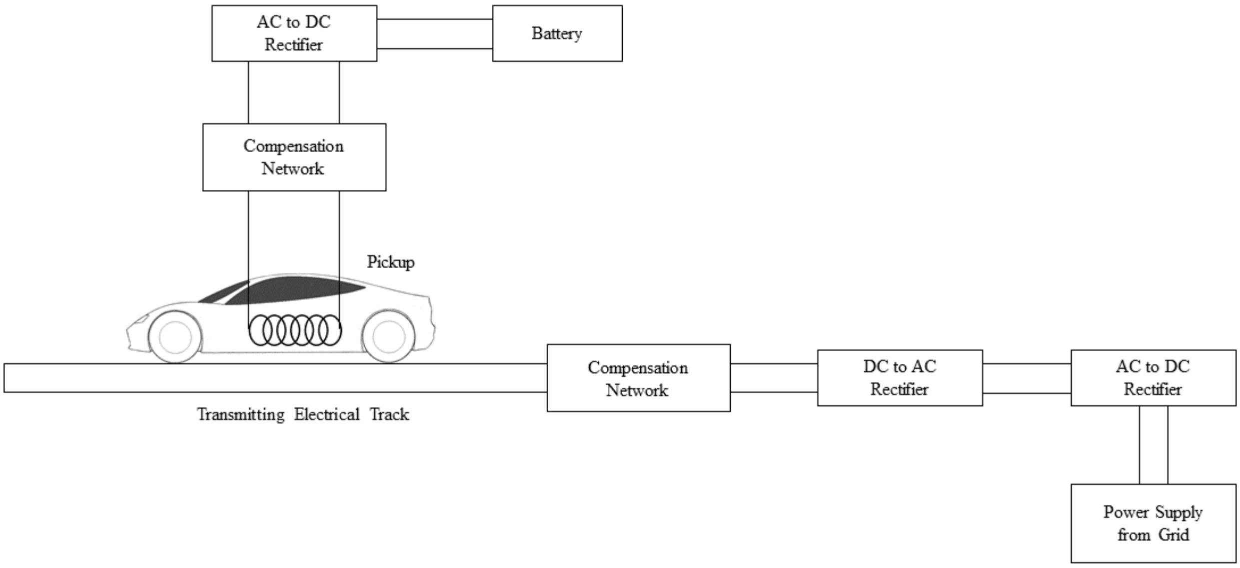

Fig. 8. Single-Coil Long Transmitter Track.

6.2. Multiple Segmented Pads

The segmented coil track structure as shown in Fig. 9 can solve all the problems of a long transmitter track [52]. Every pad has its own compensated topology, power source, and high-frequency inverters since every pad must be connected separately. One high-power inverter with switches connecting to transmitting pads is also possibly used to connect multiple-segmented pads instead of using numerous inverters [53]. It can choose which segment pad to excite by locating an EV and when the EV leaves, the transmitting pads are switched off. By doing this, the reduced coupling and the system efficiency improves, and EMF radiations could be suppressed. Even though a fault occurs within one segment, the charging system still operates. Besides, the system arrangement is simplified due to each pad having a compact low weight. Nevertheless, this configuration increases the infrastructure cost and complicates the control scheme to get higher efficiency and lessens grid impact because of power fluctuations. Another considerable factor that affects the system performance is the inter-pad spacing: the space between each transmitting pad [54]. When the pads are placed too near, there will be the coupling between the transmitting coils generating negative current stress, and a high number of pads are required. This coupling between transmitting pads can be decreased by arranging them far from each other but in that case, discontinuous power transfer making negative effects on the grid network will result in the end.

Fig. 9. Multiple Segmented Coils for Dynamic Charging.

7. Foreign Object Detection

Foreign Object Detection FOD is essential for a complete wireless charging application. Foreign objects cover metal and non-metal objects. If metal is detected between the charging pads, an eddy current will be induced to metal because of the high-frequency AC magnetic field. The results can be declined efficiency and increased temperature even leading to combustion. Therefore, the system needs to switch off instantaneously and stop power transfer to avoid heating of metals/ conductive objects for safety risks. And non-metal objects could be living matters (people and animals) that can expose to magnetic fields or combustible objects causing fire hazards. Technically detecting foreign objects and shutting down the power transfer immediately could prevent system losses when EV is not situated over the transmitter pads.

Detection of metal objects can be achieved by using inductive or capacitive, optical, and mechanical sensors. Another way instead of using sensors is to employ system parameters. The presence of metal objects can be verified by employing the quality factor of secondary coils and impedance of primary coils and this method can be used in stationary systems including alignment systems [55]. These aforementioned methods can be applied only if the EV and the transmitting charger pads are perfectly aligned. The quality factor of the receiver changes when pads are misaligned. Also, in a dynamic charging system, the receiving coils are always moving so the quality factor changes constantly. Qi standard approves the efficiency comparison (specifically power losses variant) method as a metal objects detection method [56]. However, the losses generated are very small to detect since high power is transferred in EV wireless charging. Another approach is using an additional device. As shown in Fig. 10(a), the overlapped coils are reversely linked on the ground assembly and each loop cancels out the induced voltage if the metal object is not detected. However, the output voltage of each loop has shown zero yet if the metal occurs at the intersecting point [57]. It is labeled as a blind zone that can be removed by a two-layer structure design as in Fig. 10(b).

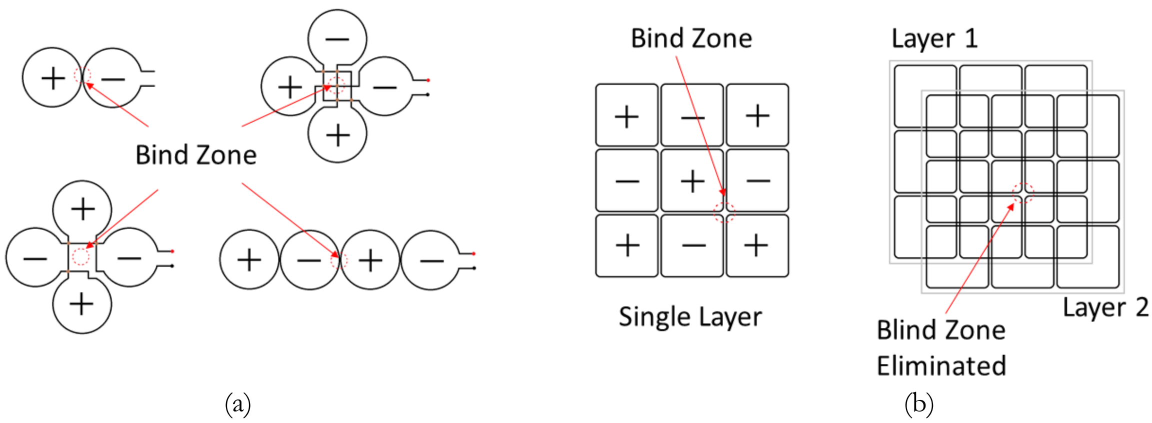

Fig. 10. (a) Single-layer, (b) Two-layer structure of Overlapped coils configuration.

In metal object detection, vehicle detection is considered one of the detection methods, principally used to switch on the transmitting pad when the receiving pads are present and off when absent. The variation of magnetic flux on the transmitter coil can be detected by using non-overlapping coil sets. An induced voltage of the non-overlapping coil sets determines the position of the EV when the pick-up coil arrives on the power supply coil without any power losses. The method consists of two coil sets aiming one for lateral direction and the other for longitudinal direction [58]. The system utilizes high material on account of the extra coils.

Many vehicle detection systems exist and an approach is using a multi-coil system [59]. There are two detection coils in the transmitting pad including an offset in the travel direction and a single coil in receiving pad that is energized to induce a voltage in the detection coil of the transmitting pad when EVs pass over the charger. Owing to the longitudinal offset of the coils, the difference in voltage and phase could be employed to identify vehicles. However, this method can only detect when vehicles approach along the direction of travel. Another common approach is to decouple the neighboring transmitting pads for the reason of decreasing the adverse impact on transfer efficiency. Though the coupling between pads is very small and insignificant depending on the pad configurations. But this small coupling can detect the coming vehicles in this system [60]. As EV is coming near the transmitting pads, the coupling is influenced by the ferrite of the receiving coils and a voltage following the transmitting coil. A measured current flow is used to detect the vehicles when the primary pad is resonated with its tuning capacitor. Although the transmitting pad already contains the current sensor, the system is only valid for dynamic wireless charging systems with multiple segmented pads where the transmitting pads are placed closely. Other methods use the phase difference between voltage and current in transmitters [61] or RFID (Radio-frequency identification) [62]. But these systems have a limitation on an EV per pad and vehicle speed. Living objects are also detected by similar technologies using capacitively coupled pads. The coupling is also differed by the living objects, and careful sensor tuning is required for small variation.

8. Position Alignment Method

Another important factor in wireless EV charging is a position alignment system. The charging process will start only when alignment tolerances of both longitudinal and lateral directions are satisfied as defined by SAE J2954. In stationary charging, if the EV is not parked aligned, the magnetic coupling of the system will be declined decreasing efficiency. Many researchers have proposed the methods such as the optimization of coil design [63], magnetic flux guidance by ferromagnetic core [64], adaptive frequency control [65], and utilization of resonant tank [66] to solve the misalignment problem. However, these methods still have the challenge. Consequently, an auxiliary positioning system and automatic alignment for autonomous vehicles are developed to align EVs perfectly while charging [67].

The position alignment system contains a two-step procedure. At first, the direction and magnitude of misalignment are attained. The first step is categorized into two kinds since the vehicle side generates the signal from an additional device or magnetic field of primary couplers. For the second step, the position of the EV is self-corrected by closed-loop control. In the previous, the system used GPS, RFID, optical alignment [68], and so on but these approaches still require misalignment tolerance and the installation cost and system complexity are high [69]. The recent method is using two sensing loop coils attaching symmetrically to a secondary coupler [70]. When the misalignment is detected in a lateral or longitudinal direction, the drop or disproportion of magnetic flux density around the secondary coupler is measured by the sensing coils and produces a dependent variable voltage of direction and magnitude of misalignment. Similarly, the four directions (forward, backward, left, and right) of the EV side are fixed to confirm faultless alignment in a four-coil positioning system in which the output voltage is observed [71]. The misalignment of all three directions in 3D can be measured but the hardware costs are higher in comparison to the two-coil system. In these two-positioning approaches, the primary coils are used as an energy source without an extra primary device like independent RF sources. Moreover, the foreign object detection system can be properly combined into a position alignment system for dual-propose or multi-purpose systems [72].

The dynamic charging system also requires a position alignment system. When the accurate alignment is confirmed between transmitter and receiver, the range anxiety can be reduced by charging the EV battery more rapidly. An online autonomous coil alignment system is developed to correct the misalignment of vehicles [73]. Figure 11 is an improved alignment system that is easier to install the autonomous coil for more applications [74]. If the secondary coil is misaligned to the left or right side where B2 or B1 magnitude is dominant, the difference in voltage phase of the sensor coil is around 180 degrees thus the direction of misalignment is easily displayed. The secondary coil receives 26% of more energy in this system.

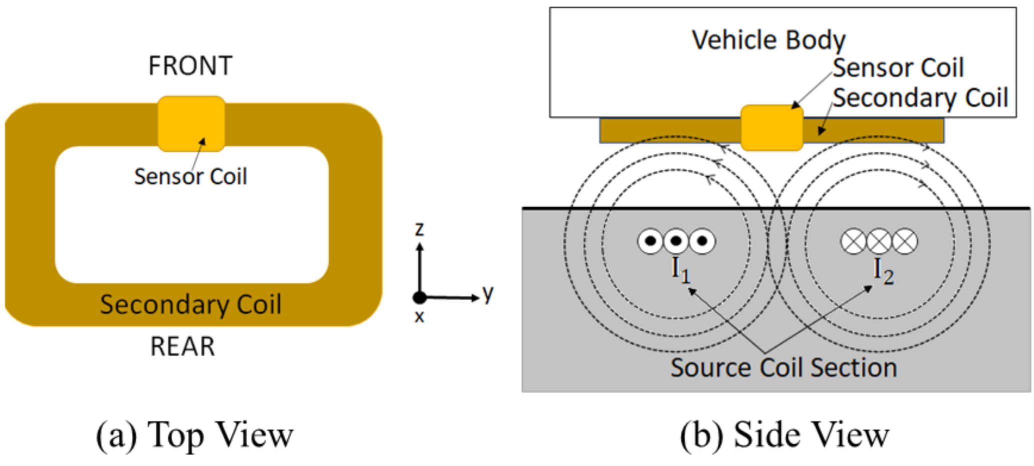

Fig. 11. Advanced autonomous coil alignment system using one sensor coil.

In wireless charging, the electrocution threat is evaded from the contact of the physical charger. However, transferring high power wirelessly generates enormously strong AC magnetic fluxes. By these AC fluxes, a voltage will be induced in any metallic objects or electronic system in proximity resulting in temperature rise and circuit fault [75]. Besides the large air gap between two couplers increases the leakage field decreasing the system efficiency [32]. The leakage magnetic field must be controlled within safety standards since it is harmful radiation to health. The risks include electromagnetic field exposure (EMF), electrical shock, and fire hazards [76]. Among them, EMF exposure is the most important concern and must be controlled under both normal and unusual conditions during irregular operation, the occurrence of a human under the vehicle, potential abuse, etc. Under the condition of the driver and passengers inside the EV, the metal shielding of the EV chassis lessens the radiation hazard [77]. But if humans or animals are under EV, there is still a chance of exposure to high levels of electromagnetic radiation. The riskiest radiation zone is between the two coils.

For human exposure to electromagnetic fields (EMF), the two international groups assign standards. One is the International Committee on Electromagnetic Safety (ICES) under the Institute of Electrical Electronic Engineers (IEEE) [78], and the other one is International Commission on Non-ionizing Radiation Protection (ICNIRP) [79]. In IEE standard C95.1-2005 [78], only the electrostimulation limits are applied below 100 kHz, only the thermal limits are employed above 5 MHz, and between 100kHz to 5MHz, both limits are applied. IEE recommends basic restrictions (BRs) referring to limits in situ electric field or internal fields inside the human beings and maximum permissible exposures (MPEs) values deriving from BRs and referring to limits on external fields outside the human body. Safety factors defined in MPEs are higher than those in BRs. Therefore, if the external fields are within MPE limits, BRs are also satisfied automatically. Between 3 kHz and 5 MHz, MPE limits are 163 A/m for magnetic field strength (H field of rms value), and 0.205 mT for Magnetic flux density (B field).

There are two recommendations: Basic Restrictions and Reference Levels in the ICNIRP standard. The reference level in ICNIRP is as same as the maximum permissible exposure (MPE) values. While ICNIRP consists of only one general limit for BR, the ICES (IEEE) has various limits for different parts of body tissue such as the brain and other tissue. Basic restrictions are the key factors in both ICNIRP and ICES. For public exposure to EMF, the ICNIRP reference level is defined as 6.25μT [79] and is much lower than the ICES level. Thus, the ICNIRP level is defined as the most referenced level to confirm the safety issues in wireless charging of EVs.

Another two safety concerns are electrical shock and fire hazards. 100 kW or more of power, large voltages (240 VAC), and high currents (up to 100 A) are delivered in EV charging wirelessly [76]. The voltage potentials between primary and secondary coils could even be higher than the supply voltage. To avoid the contact of humans and animals with the conductors, the magnetic coils must be shielded. Because the wireless charger is permanently mounted under a garage floor or parking space, the electrical risks may happen at any time by larger power charging. The fire threat is also possible due to the fault of insulation and failure of other electrical components. The current flow or excessive heating must be electrically monitored for the reason of faults, shorting, poor energy transfer, arc or ground faults, or other events leading to any fire hazard [76]. The evaluation of the performance of insulation materials used in the charging coil construction is also required for a long-term perspective because the temperature elevation and materials degradation could create a fire hazard.

9. Conclusion

EVs can be more persuasive in the future with wireless charging technology. People find that charging for EVs is frustrated and the range anxiety is also a disturbance for using EVs. But all these problems will be solved by wireless charging technology.

The power converters and control system are also critical in the WPT system to achieve system efficiency. The basic control strategies such as frequency control, phase-shifting control, changing circuit parameters, and phase-locked loop control are studied in [80].

A near-field electromagnetic field is used in the WPT system. When the high-frequency alternating current flowing through the transmitter coil creates an alternating magnetic field and induces the electric current on the receiver coil. The interaction between transmitter and receiver coils must be adequately close to obtaining the high transferred efficiency. Additional compensation capacitors are required to compensate for the leakage inductance since systems with only inductive coupling have lower efficiency than inductive power transfer systems with the resonance [81]. Compensation topology improves the transfer power and reduces the Volt-Ampere rating (VA rating) of the power source achieving a soft switching of semiconductors [82].

The Society of Automotive Engineering (SAE) regulates the operating frequency of 81 to 90 kHz for light-duty electric vehicle wireless charging. The resonant frequency is chosen based on the load. Four basic compensating technologies are Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP). SS topology transfers the best efficiency among the four topologies. There are also hybrid topologies (LCL-LCL, LCC-LCC) that show high transferred efficiency, but the control complexity and the costs are higher than the SS topology. The compensation topologies are not studied in detail in this review.

A comprehensive review of wireless charging of EVs is presented in this paper. More benefits can be achieved by wireless charging than by wired (conductive) charging. Eventually, the market of EVs can become larger when the dynamic charging infrastructure is installed under many roads. First of all, the recent applications for charging EVs are comprehensively investigated as well as stationary and dynamic wireless charging. Additionally, WPT technologies are thoroughly reviewed then IPT technology which is the most commonly used technology for wireless charging of EVs is mainly focused on. Then the charging procedure of the IPT system is discussed in detail in three parts that are transmitter side, receiver side, and data flow between them. Furthermore, the significant parameters for dynamic charging of EVs are also studied. Moreover, the most important part affecting the power transfer efficiency of WPT which is coil design is also revised. Four renowned coil designs which are circular pad, DD pad, DDQ pad, and BP pad are reviewed with benefits and drawbacks and recent coil designs of an orthogonal coil are also described. The track layout for the primary side of dynamic wireless charging is discussed and the multiple segmented pad layout is suitable to suppress produced electromagnetic field and system reliability. The foreign object (metal and non-metal) detection method is also analyzed with various methods. Besides, the position alignment method to improve the power transfer efficiency and reduce the misalignment problem is investigated. Last but not the least, health and safety considerations for electromagnetic field exposure to human beings are discussed since the WPT system produces high transfer power and high EMF field.

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