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WIRELESS CHARGING OF ELECTRIC VEHICLE: A REVIEW

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Abstract - *Electric vehicles are today's zero emission vehicular technology which are considered as the future of automotive industry. The batteries of the vehicles get charged in order to drive the vehicle. The methodology of charging the electric vehicle currently is through plug-in method where the charging station charges the battery of an electric vehicle. However, an alternative method for charging the battery of an electric vehicle is through Wireless Power Transfer where it can be as a Static or Dynamic charging systems. Static Charging System can be implemented to charge the batteries of the electric vehicles when the vehicle is parked in static mode. Dynamic Charging System can be implemented to charge when the vehicle is in motion. This method of wireless charging of electric vehicle is done through inductive power transfer where wireless transmission of power is achieved by mutual induction of magnetic field between transmitter and receiver coil. The state of the battery is monitored using Battery Management system (BMS). This paper attempts to review about the difference between plug-in and wireless charging of vehicle, operational principle of wireless charging, types of charging systems, static and dynamic wireless charging, application of dynamic charging system in future and drawbacks of wireless electric vehicle charging.*

***Key Words*: Electric Vehicle, Wireless Power Transfer, Static Charging System, Dynamic Charging System, Battery Management System (BMS).**

1. INTRODUCTION

An electric vehicle (EV) is one that operates an electric motor where the vehicle uses electricity as fuel, instead of an internal combustion engine that generates power by burning fuels and gases. Therefore, such a vehicle is seen as a possible replacement for current generation automobiles, in order to address the issue of increasing pollution, global warming, depletion of natural resources etc.

The development of electric vehicles has gained significant momentum over the past decade. A part of this is based on the desire of cities to push away from petrol-diesel powered vehicles to help provide cleaner cities, given the intense urbanization which is occurring globally, and partly because electric vehicles are becoming more efficient and cost competitive [8]. However, the batteries of the vehicles can be charged wirelessly without plugging in. With wireless charging systems integrated into vehicles, the probability of charging the vehicles by plug – in method in will be reduced. The commuter has to simply park over a coil placed on the ground in order to charge the battery of the vehicle [7]. Dependability, simplicity and adaptability in wireless charging systems has an upper hand over plug-in charging system. This system allows the battery to be charged when the vehicle is stationary as well as in motion. The method of charging the battery of the vehicle when it is in stationary is called as Static charging and when the vehicle is in motion is called as Dynamic charging which is briefly discussed in this paper[1].

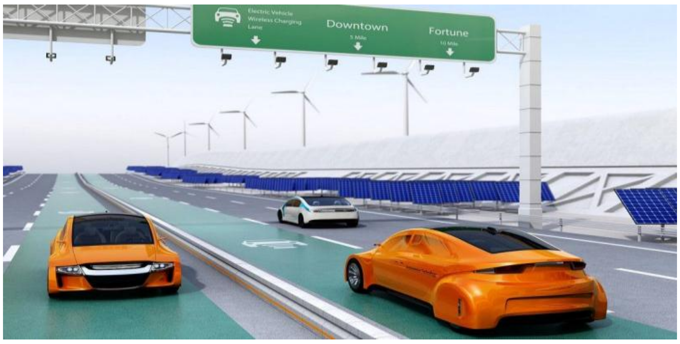

Fig1.1 Electric vehicles driving on the wireless charging lane of the highway.

Automotive industry is working towards standardization of Wireless charging of electric vehicle and they are investing in interoperability as it reduces the need for region specific wireless charging systems, standards such as SAE J2954 are defining the criteria for safety and electromagnetic limits, testing, and efficiency and interoperability targets. The wireless architecture is designed to minimize fields outside the vehicle footprint, which reduces the risk of exposure to humans [8].

According to a survey done by International Energy Agency, the use of electric vehicles will grow from 3 million to 25 million by the year 2030. That is almost 41 times of what it is today, with the increasing demand of fossil fuel and problems with pollution. Owing to that, all major IC engine car manufactures like Ford and General Motors (GM) are slowly turning their attention towards the electric vehicles. The market and consumers are in need for a cheaper personal transportation, whereas the government has started supporting electric vehicles through its policies. Considering all these facts it is pretty much evident that very soon electric cars will be zooming all around the roads.

Fig1.2 A practical example of wireless charging of lane in UK.

2. PLUG IN V-2G AND WIRELESS V-2G

Plug in V-2G technology for electric vehicle is basically done through a bi-directional charger to switch between the home and grid network. The vehicle is charged using the AC socket. To produce the DC source, the AC is converted to DC. The converter DC current is supplied to a battery via BMS and other converters. The drawback of this process is that it demands a direct contact and physical handling to ensure the charging and discharging in electric vehicle [11].

Fig 2.1 Plug-In V2G

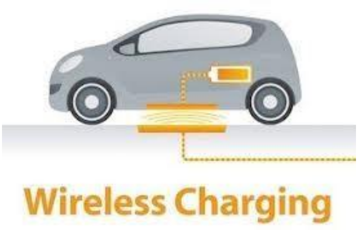

Fig2.2 Wireless V2G

On the other hand, by using the wireless V-2G, the primary coil is placed on the concrete road and the secondary coil is placed underneath the electric vehicle.

This device is completely self-governing and provides extra confinement between the receiver side and the source through the wireless transformer. Here, it consists of the transmitter and the receiver coil where the AC current from the transmitter coil is transmitted and the receiver coil receives the AC power through mutual induction and the received AC is converted to DC using the power converters and charges the battery [12].

Table-1: Comparison of Wireless V2G and Plug-In V2G

FEATURES	WIRELESS V2G	PLUG-IN V2G
Method	Wireless Power Transfer	Traditional Conductive
Operating Sensitivity	82-89Khz	18-102Khz
Air-Gap Sensitivity	Moderate to high	N/A
Position Sensitivity	Moderate to high	N/A
Power Transfer efficiency	>89%	>89%
Electric Shock Hazard	Low to Moderate	Moderate to high
Suitability	Very high	Moderate

3. PRINCIPLE

The basic operating principle of wireless charging is similar to transformer working. Wireless charging system consists of transmitter and receiver coils which is embedded with AC-DC and DC-AC converters. The AC mains from the grid is converted into high frequency AC and it is transferred through the transmitter coil which creates alternating magnetic field that cuts the receiver coil and receives the production of AC power output in receiver coil [1]. But the important factor to be considered here is that for efficient wireless charging, the resonant frequency has to be maintained between the transmitter and the receiver coil. To maintain the resonant frequencies, compensation networks are added at both sides of system. The AC power at the receiver side is rectified and filtered to produce stable DC, which is further utilized for charging the battery through BMS [7].

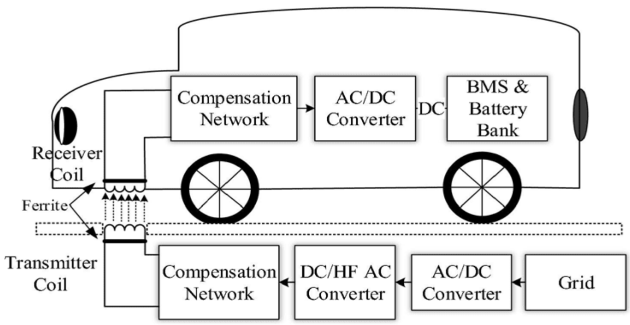

Fig3 Blockdiagram of wireless charging system.

A simple rule of thumb for designers is:

$$P_o \cong k\sqrt{VA_{primary}VA_{Secondary}}$$

where Po is the output power, k is the coupling factor between the ground and vehicle magnetic pads, and VA represents the Volt-Ampere product.

3.1 TYPES OF WIRELESS CHARGING SYSTEMS

Based on operating techniques wireless charging of electric vehicle can be classified into four types:

1) Capacitive Wireless power transfer (CWPT)

2) Permanent Magnetic Gear Wireless power transfer (PMWPT)

3) Inductive Wireless power transfer (IWPT)

4) Resonant Inductive Wireless power transfer (RIPT)

3.1.1 CAPACITIVE WIRELESS POWER TRANSFER (CWPT)

This power transfer technique uses advanced geometric and mechanical structures of the coupling capacitor and makes it very useful for low power applications such as portable electronic devices and cellular phone chargers. The transfer of energy between transmitter and receiver is accomplished by means of displacement current caused by the variation of electric field.

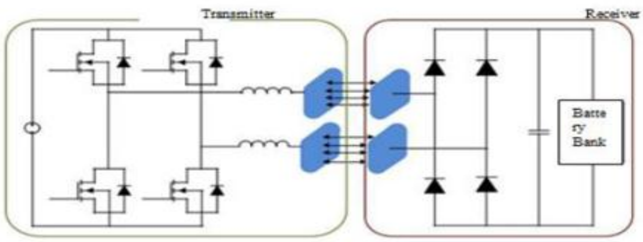

Fig 3.1.1 Schematic Diagram of Capacitive Wireless Power transfer.

A series resonant circuit based CWPT is shown in the figure. This technology uses coupling capacitors to transfer power instead of coils or magnets usually four metal plates are used in a CWPT system to form capacitive coupler. The AC voltage is first supplied to power factor correction circuit to improve efficiency and to maintain the voltage levels and to reduce the losses while transmitting the power. And then the voltage is supplied to H-bridge network for high frequency AC generation. A few inductors are added in series to coupling capacitor to reduce impedance between transmitter and receiver. On the receiver side, the received AC voltage is converted to DC through rectifier and filter circuit and fed to the battery through BMS. Operating frequency of the system is 100 to 600Khz [7].

The main advantage of this technology is negligible eddy currents, low cost and weight excellent misalignment performance. The power transfer efficiency depends on the size of the coupling capacitor and the distance between them. Application of CWPT for electric vehicle is limited due to large air gap and high-power requirements. Ideas have been proposed to use car's bumper as receiver to reduce air gap and increase efficiency [4].

3.1.2 PERMANENT MAGNETIC GEAR WIRELESS POWER TRANSFER (PMWPT)

This technology is different from CWPT and IWPT which I mentioned above. The block diagram is shown in figure. Here transmitter and receiver each consists of armature winding and synchronized permanent magnets (PM) inside the winding. At transmitter side, when the AC current is passed to transmitter winding it induces mechanical torque on transmitter magnet and causes its rotation. Due to the magnetic field change in transmitter, permanent magnet field causes torque on receiver's permanent magnet which results its rotation in synchronous with transmitter magnet. Now change in receiver permanent magnetic field causes the AC current production in winding i.e receiver acts as generator which is the mechanical power input to the receiver's permanent magnet converted into electrical output at receiver winding. The coupling of rotating permanent magnets is referred as **magnetic gear**. The generated AC power is converted to DC at receiver side and is fed to the battery after rectifying and filtering through power converters. A laboratory prototype of 1.6 kW of the MGWPT was developed and is capable of delivering around 150 mm air gap distance [1].

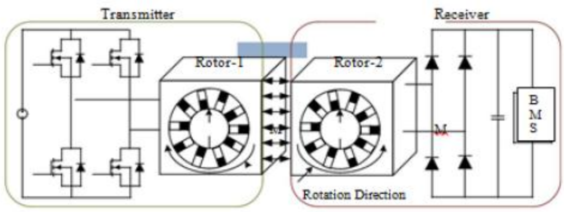

Fig 3.1.2 Schematic Diagram of Permanent Magnetic Gear Wireless Power transfer.

However, this technique has many challenges associated with incorporating the technology into static and dynamic applications. The power transfer capability is inversely proportional to the axis-to-axis separation between the primary and secondary PMs as the coupling between the two synchronized windings reduces abruptly. As a result, MGWPT is suitable for stationary WEVC but challenging for dynamic charging systems [3].

3.1.3 INDUCTIVE WIRELESS POWER TRANSFER (IWPT)

The basic principle of IWPT is Faraday's laws of electromagnetic induction. Initially, inductive power transfer technique was developed by Nikola Tesla in 1914 to transfer power wirelessly. This power transfer technique has been tested and utilized to transfer power wirelessly in wide range of applications [3]. The wireless transmission of power is achieved by mutual induction of magnetic field between transmitter and receiver coil. When the main AC supply is applied to the transmitter coil, it creates AC magnetic field that passes through receiver coil and this magnetic field moves electrons in receiver coil causes AC power output [6]. This AC output is converted to DC using the power converters to charge the battery and it is monitored through BMS. The amount of power transferred depends on frequency, mutual inductance and distance between transmitter and receiver coil. Operating frequency of the system is 19 to 50KHz. The disadvantage of this method is slower charging, more expensive etc [2].

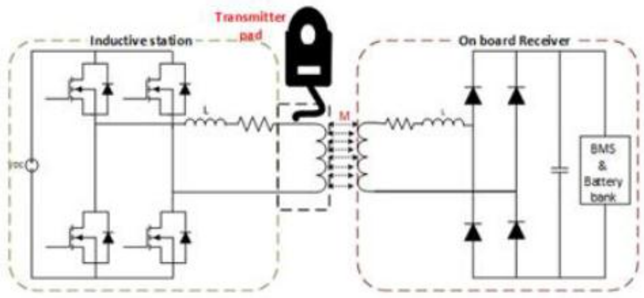

Fig 3.1.3 Schematic Diagram of Inductive Wireless Power transfer.

3.1.4 RESONANCE INDUCTIVE WIRELESS POWER TRANSFER (RIWPT)

This power transfer technique is an advanced version of the traditional IWPT, in terms of designing power electronics and wireless transformer coils. Basically, resonators having high quality factor transmit energy at much higher rate. So, by operating at resonance, even with weaker magnetic fields we can transmit the same amount of power as in IWPT.

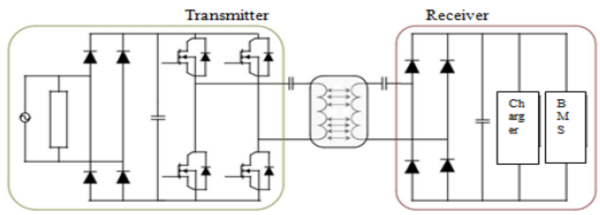

Fig 3.1.4 Schematic Diagram of Resonance Inductive Wireless Power transfer.

Fig shows the schematic diagram of the RIPT for EVs. Like other power transfer techniques, the main AC voltage is converted into high frequency AC and supplied to the transmitter or primary winding. The receiver or secondary coil receives power via varying magnetic fields. The received power is converted to DC by rectifier and filter circuits and battery is charged through BMS. The power can be transferred to long distances without wires. Maximum transfer of power over the air happens when the transmitter and receiver coils are resonant matched. So, to get good resonant frequencies, additional compensation networks in the series and parallel combinations are added to the transmitter and receiver coils. The value of coupling coefficient in RIPT varies from 0.2 to 0.3 due to the minimum height clearance requirement of the EVs, which is 150–300 mm. The compensation networks also reduce additional loses. Operating frequency if the system is 10 to 150Khz [1].

$$f_{r(p,s)} = \frac{1}{2\pi\sqrt{L_{p,s} \cdot C_{p,s}}}$$

Where fr is resonant frequency of coils, and L and C are the self-inductance and resonant capacitor values of the transmitter and receiver coils, respectively.

Table -2: Characteristics of various wireless power transfer methods.

Wireless Power Transfer Methods	Capacitive	Permanent Magnetic Gear	Inductive	Resonance Inductive
Efficiency	Low/ Medium	Low/ Medium	Medium/ High	Medium/ High
EMI	Medium	High	Medium	Low
Frequency range (KHz)	100-600	0.05-0.50	10-50	10-150
Size volume	Low	High	Medium	Medium
Complexity Of design	Medium	High	Medium	Medium
Power levels	Low	Medium/ low	Medium/ High	Medium/ low
Suitability for WEVCS	Low/ Medium	Low/ Medium	High	High

4. STATIC AND DYNAMIC WIRELESS CHARGING

Wireless charging system of an electric vehicle charges the vehicle by electromagnetic field to transfer the energy. This methodology of charging the electric vehicle can be classified into two categories:

1. Static Wireless charging.
2. Dynamic Wireless charging.

4.1 STATIC WIRELESS CHARGING

In this type of wireless charging system, the batteries of the vehicle can be charged autonomously while the vehicle is being parked in static mode where the transmitter enclosed with the primary coil is installed underneath the ground along with additional power converters and its circuitries. Here, a very high frequency AC is transmitted from the transmitter coil. The receiver coil which is enclosed with the secondary coil is mounted on the underside of the vehicle receives the AC. The received energy is converted from AC to DC using the power converter and is transferred to the battery bank. For safety measurements, the receiver coil is enclosed with battery management system (BMS) and power control with a wireless communication network to receive any feedback from the primary side [10]. The charging duration of an electric vehicle depends on their charging pad sizes, power supply level and distance (air gap) between the transmitter and the receiver. The distance between the transmitter and the receiver coil is approximately 150-300mm.

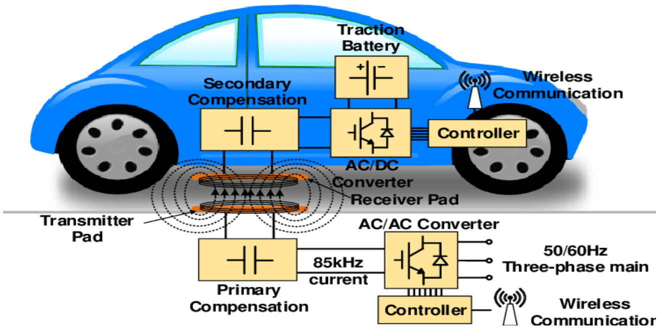

Fig 4.1.1 Typical structure of Static Wireless Electirc Vehicle Charging System (SWEVCS).

This concept of wireless charging can be well suited for mass transit applications, where it can be used at parking areas at shopping mall, garages, commercial buildings etc. An implementation of this system can be done by installing an automatic guidance system in the vehicle to help the driver align the vehicle directly above the primary charging pad. The transmitter end of the charging station and the receiver coil of the vehicle can exchange data using the inductive link or through short range communication methods. This feature allows the charging stations to adjust the charging procedure according to the condition of the battery and according to the driver's preference [9].

Fig4.1.2 Static Wireless Charging Infrastructure setup.

4.2 DYNAMIC WIRELESS CHARGING

In static wireless charging, sufficient amount of charge must be present in the vehicle before starting. So, in order to store the charges, bigger batteries are required to provide constant power to the vehicle. But use of bigger batteries results in system inefficiency. Revolution in wireless charging motivated researchers to use dynamic wireless vehicle charging [13]. In this type of wireless charging system, the battery size is reduced and vehicles are charged while they are in motion, where the transmitter is enclosed with a primary charging pad which is installed beneath the concrete of the road along the pathway with high frequency AC along with its circuitries and the receiver enclosed with a secondary coil is placed below the front of the vehicle with power converter and battery management system which converts high frequency AC into DC and charges the battery bank[10].

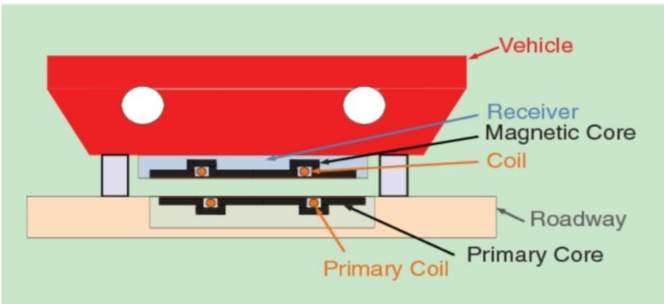

Fig 4.2 An illustration of dynamic Wireless charging concept.

But the primary charging pad which is installed on the vehicle moving path, can be classified into two categories:

1. Lumped charging pad (Single coil design)
2. Segment charging pad (Multiple coil design)

4.2.1 LUMPED CHARGING PAD

In lumped charging pad, one single winding coil is used as the primary coil of the transmitter side. This technique is basically used for static wireless charging because when the displacement occurs the mutual inductance of the primary and the secondary coil will change which will result in deflection of the magnetic flux. In this case of dynamic charging there should be a control strategy which will correct the flux deflections. The number of power converters and controllers used are less in lumped type. Due to this, the power transfer capability is limited [9].

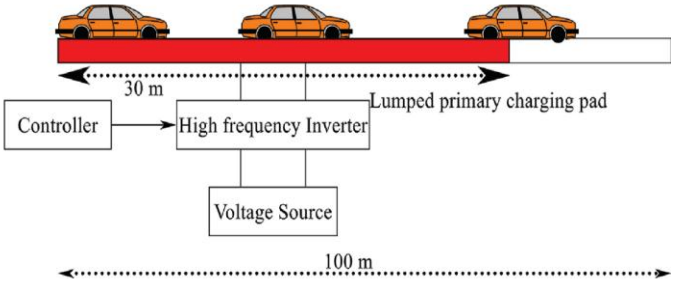

Fig 4.2.1 Block Diagram of Lumped Charging Pad.

4.2.2 SEGMENT CHARGING PAD

In segment charging pad, the primary winding of the coil is divided into segments and placed throughout the pavements of the road for power transfer. A particular segment is energized when vehicle moves over the segment. During this process, the remaining segments which is not energized remains in off state. This reduces the power loss of the system. But disadvantage of this process is that individual inverters and controllers are employed for each segment which increases the complexity and cost of manufacturing the system. As the vehicle moves on the pavement there is chance of misalignment between the transmitter and receiving pads which affects the system performance. Various controlling methods have to be proposed in order to overcome it [9].

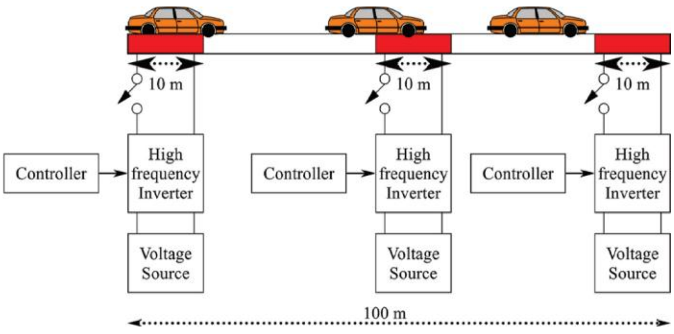

Fig 4.2.2 Block Diagram of Segment Charging Pad.

Two different methodologies of installing the primary charging pad has been mentioned above. On a higher note, the future holds the self driving cars, it is efficient and practical for the transmitter unit to be aligned beneath the concrete in a pre-defined route. This application can be incorporated in electric buses, rails and rapid rails. Initial cost of installing would be high but on a broader prospect it is efficient.In order to know the development prospect of dynamic wireless charging system, the table has been mentioned below.

Table -3: Development Statistics of a Dynamic Wireless Charging System.

R&D Institutions	Pick up Power (kW)	Operating Frequency (kHz)	Air–Gap (mm)	Efficiency (%)
University of Auckland	21-30	13	450	84
Japan Railway Technical Research Centre	55	11	7.7	85
Oak Ridge National Lab	21	23	130-180	89
Flanders Drive	84	21	110	87-89
Nissan Research Centre	1.1	89	110	>89

5. APPLICATION AND FUTURE INFLUENCE OF WIRELESS CHARGING OF ELECTRIC VEHICLE

Wireless Charging of Electric Vehicle, approach revolutionizes the changes in electric vehicle Industry.In the last few years, trends suggest a rise in interest among the common masses for electric cars in comparison to electric two-wheelers and internal combustion engine vehicles or petrol/diesel cars.

At a fundamental level, electric cars comparatively offers a lower operating cost compared to conventional internal combustion engines. On average, electric vehicles are 75-80% cheaper from fuel and maintenance perspective, which is an important factor for many consumers who have high usage. This reality holds true across factors because it's materially cheaper to charge a battery compared to refueling a conventional liquid fuel tank [3]. The electric vehicles comparatively induced with dynamic wireless charging technique takes lesser time than the electric vehicles which are charged statically. With reduced new battery capacity using dynamic wireless charging system electric vehicles can be charged under motion. Comparatively, with wireless charging system range and cost are the setbacks plug-in charging systems are facing currently. With the growing impact of fuel-driven vehicles on the environment, electric taxi fleets in congested urban streets is critical in cutting transport emissions and cleaning up the air. With more people opting for electric mobility, the new technology can also be rolled out broadly for public use. This in turn would help everyday drivers of electric cars charge more conveniently on the go. However, the time taken to charge wirelessly could reduce a taxi driver's earning potential, a problem which is known and being worked upon [1].

6. DRAWBACKS OF WIRELESS ELECTRIC VEHICLE CHARGING SYSTEM (WEVCS)

1. Inefficient transfer of electricity: The energy efficiency via wired charging of the electric vehicles is somewhere between 90 – 93%, which makes it obvious that efficiency from wireless charging of EV will be much less. However, with time the efficiency is likely to be improved [3].

Table -4: International Society of Automotive Engineers standards for wireless charging of electric vehicles.

Wireless Power Transfer Levels	WPT-1	WPT-2	WPT-3	WPT-4
Maximum Input Power	3.7	7.7	11	22
Minimum Target Efficiency	>84%alligned			
Operating Frequency (KHz)	85 (Band: 81.39-90)			

2. Health and safety issues: As wireless charging of electric vehicles works in high voltage and current levels, safety concerns become most important. We definitely need strict monitoring in order to transfer so much electricity wirelessly without having adverse effects on the living organisms. Besides that, the long-term effect of the electromagnetic field can also affect the living organisms which needs to be inspected thoroughly. However, it also comes with three important potential health and safety issues namely electrical, magnetic and fire hazards. Sometimes due to breakdown of devices or physical damage or by environmental conditions it can also produce electrical shocks [3].

While working at higher power levels, it is possible for magnetic flux to exceed the minimum value given by the standard authority. In such cases, flora and fauna becomes vulnerable and are exposed to a probable danger. Since there is a high-power transfer from the transmitter to the receiver charging pads at substantially big air gap of about 150 to 300mm at some kilohertz to some Megahertz. As a result, high frequency leakage fluxes are generated due to air gaps. The level of such exposure fluxes must be below or must follow the guidelines set by standard organizations [1].

7. CONCLUSION

Wireless charging of electric vehicle has the potential to revolutionize the road transportation from the automotive industry. With the advancement of electric vehicle technology, wireless charging technique is expected to increase significantly by next decade. The main agenda of this paper is to give an overview of various wireless charging techniques out of which inductive wireless transfer has proven to be the best method of wireless charging. This paper also attempts to review about the application of static and dynamic wireless charging and how battery plays an important role in the electric vehicle. Here, the battery size is effected by wireless charging techniques which lowers the overall cost of the electric vehicle. The electric vehicle batteries which were to take quite a lot time to charge up to the rated value will be charged within less time comparatively as their battery capacity is reduced. However, simplicity and minimum driver intervention are key features that win out time-and time again and when these features are coupled with high power transfer efficiency, wireless charging of electric vehicle is a winning combination.

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