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Wireless Charging Techniques for Electric Vehicles

Mrs. Yogita Shailesh Kadam

Department of Electrical Power Systems, VPM's Polytechnic, Thane

Abstract:
The wireless power transfer (WPT) system has been widely used in various fields such as household appliances, electric vehicle charging and sensor applications. Electric vehicles require fast, economical and reliable charging systems for efficient performance. Wireless charging systems remove the hassle to plug in the device to be charged when compared with the conventional wired charging systems. Moreover, wireless charging is considered to be environment and user friendly as the wires and mechanical connectors and related infrastructure are not required. This paper reviews the methods and techniques used for wireless charging in electric vehicles. First, wireless charging systems for electric vehicles are classified and discussed in depth. Both the stationary and the dynamic wireless charging systems are discussed and reviewed. In addition, a typical model and design parameters of a dynamic charging system, which is a wireless charging system for moving vehicles, are examined. Control system functions of a wireless charging system of an electric vehicle are important for an effective and efficient performance. These are also discussed in the context of better efficiency of power transfer and improved communication between the transmitter and the receiver side of a vehicle charging system. Battery is an important part of an EV as different parameters of a charging system depend upon the battery characteristics. Therefore, different battery types are compared and battery models are reviewed. Findings of this state of the art review are discussed and recommendations for future research are also provided.

Keywords*: Electric vehicle, wireless charging, wireless power transfer, dynamic wireless charging*

1. Introduction:

Wireless power transfer has been considered since the times of Tesla for supplying power to electric devices and equipment, and charging electric vehicles. However, this was not possible at that time because associated enabling technologies were not available. A breakthrough to this end was achieved in 2007 when researchers lit up a bulb from a wireless power source at a distance of two meters [1]. Much advancement in this field has been made since this major success [2, 3]. Electric vehicle (EV) charging is one of the many other areas where the option of wireless power transfer (WPT) has good potential and is being actively explored due to its many advantages [4, 5]. The traditional wired or plug-in charging systems are also called conductive charging systems. There are a few problems associated with these wired charging systems. For example, they require heavy charging wires and connectors. Furthermore, the charger should be manually connected to the electrical supply and the device to be charged [6]. The wired charging system is also not user and environment friendly [7]. If there is a short circuit or breakdown of the insulation of the charging wire due to reasons, such as high temperature, friction with the ground or the charging device itself, then this can cause an electric shock which can be fatal [8]. To reduce the charging time, and hence potential hazards associated with it, a large number of batteries can be used or the drained batteries can be swapped with the charged batteries when needed [9]. For example, if a vehicle can run a certain distance in a single charge with a given number of batteries, then the travel range can be increased by using a higher number of batteries. Alternatively, the vehicle batteries can be swapped with the charged batteries at charging stations during travel. However, the batteries have their own set of problems [10]. The batteries have heavy weight and a high initial cost but short life. Due to their weight, it may not be possible to carry a large number of batteries beyond a certain number. Future innovation in the energy storage devices may help overcome these problems. However, another possible method to overcome the problems associated with the batteries is the WPT [11]. For example, heavy and large size batteries can be avoided and the initial cost can be reduced by using the dynamic wireless power charging system [12]. Furthermore, the WPT method is convenient and user friendly as it removes the hassle of wires and connectors associated with the manual plugged in charging systems [13, 14].

WPT and its practical implementations are being widely investigated due to their potential use in a variety of industrial and engineering applications. Some of the applications where WPT can be used include EVs, electronic gadgets [15, 16], industrial plants [17], underwater vehicles [18], lighting [19], implanted medical devices [20], solar powered satellites [21], unmanned aerial vehicles (UAV) [22] and smart grids [23]. The WPT has also been investigated for long distance power transmission in the grid [24, 25]. A grid connected wireless power transmission system has been deployed as well, and is being tested [26].

WPT system is safe, easier, adaptable, position free, flexible and enables mobility. By using this technique, the battery powered devices can be charged dynamically. This technique is also favorable during rainy weather as there are no wires involved and electric shock hazard is reduced.

WPT can be accomplished in three different ways i.e. static or stationary wireless charging system (SWCS), semi or quasi dynamic wireless charging system (QDWCS) and dynamic wireless charging system (DWCS) [27, 28]. In SWCS, the WPT is used for the charging of a stationary EV. The semi or QDWCS employs the WPT to charge an EV when a vehicle stops for a short duration during its travel. For example, an EV may stop at a traffic signal where WPT is used to charge the EV. Dynamic charging systems seek to charge an EV while it is in service and is moving.
This article comprises ten sections. Section 1 gives a brief introduction to this research study. In the Section 2, general techniques for the electric power transfer using wireless medium are discussed. The section 3 reviewed and compared the IPT and the CPT. Section 4 introduces the EV wireless charging.. Section 5 reviews on EV charging techniques. Section 6 concludes this article.

2. Wireless power transfer

In a WPT system, the electrical energy may be transferred from the source to the destination using near field and far field transmissions [31]. The medium used for far field WPT may be acoustic, microwave or optical. For the near field, capacitive or inductive coupling technique that is non radiative electric, magnetic or electromagnetic field is usually used. Microwaves may be employed for transferring energy using frequencies in the range of 1 GHz to 1000 GHz [32]. In the optical method, power is transferred by a laser beam [33]. Both microwave and laser can be used for power transmission over long distances. However, both require a clear line of sight between the transmitter and the receiver. These are potentially harmful to humans and biological life also. Some work for EV charging using microwave [34, 35] and laser [36] has also been done. However, these are not being used commercially [37] as yet. WPT using mutual coupling is an effective wireless charging technique [38]. In this method, the mutual coupling can be capacitive or inductive. Capacitive coupling employing capacitors forms the basis of the CPT, and the inductive coupling using inductors results in the IPT. CPT based wireless charging produces low power levels and the charging gap is also small when compared to the IPT based wireless charging [29]. Therefore, the IPT based wireless charging techniques are considered better and are being used for commercial deployment [39]. In an inductive coupling based WPT, the current is produced by means of mutual induction [40]. A pair of coils is used for the transfer of electrical power. One of the coils is the primary and may be considered as an antenna for the transmission of power. The other coil can be thought of as secondary serving as the receiving antenna. A time varying voltage applied to the transmitter side coil results in a magnetic field in the near field of that coil. Due to this magnetic flux, a voltage is induced in the receiver side coil that is present in the near field of the first coil. This is due to the mutual induction between the coils. The inductive coupling based WPT system may additionally be augmented by a magnetic resonance network between the primary and the secondary sides [41, 42]. At the resonance frequency, the coupling wave has its maximum, and therefore, it results in an efficient power transfer. Performance of the system may be affected by a number of parameters which include the operating frequency, resistance, turns of coils and the diameter of the coils [43]. So, these parameters should be considered and tuned while using this technique. The process of inductive coupling based WPT is illustrated with the help of Fig. 2. In the IPT technique, the energy is transferred using flux that is produced by the transmitter [44]. If a large amount of flux is received by the receiver, then this means that the coupling between the coils is good. The distance between the coils has a direct impact on the system efficiency [45], as it limits the transmission of flux from the transmitter to the receiver [46,47]. If the distance between the coils increases beyond a certain limit, the coupling decreases and consequently, the working efficiency of the power transmission reduce. Of the three methods used for the WPT described in this section, only the mutual coupling is employed for the wireless charging of EVs at present [30], and will be the focus of discussion in the remainder of this article. A comparison of the aforementioned power transfer methods on the basis of cost, output power, distance and biological effects on humans is provided in Table 1 [48, 49].

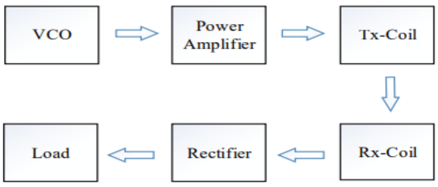

Fig. 1 Inductive coupling is employed for wireless power transfer over a short distance. Mutual induction between a pair of coils is used for the transmission of power. The primary coil acts as the transmitting antenna, whereas the secondary coil serves as the receiving antenna.

3. Comparison of capacitive and inductive power transfer techniques

Both CPT and IPT, which are the two main techniques for the WPT, have pros and cons. An overview of the comparison between the CPT and the IPT techniques is provided in Table 2 [29, 49, 50]. Both these techniques are further discussed in this section. While the CPT is suited only to low power systems, the IPT is considered to be appropriate for both high and low power applications [29, 51]. As an EV requires high power in the range of KWs for charging, the IPT may be preferred over CPT for EV charging applications [52]. IPT works on the same principle as that of a transformer. Without a physical connection, the energy is transferred between the coils. Therefore, mutual induction and coupling play an important role in an

IPT system [53]. To achieve a good coefficient of coupling, the gap between the transmitting primary and receiving secondary coils should be appropriately adjusted. In a regular transformer, efficient transmission of high power is not possible by utilizing this approach alone. Therefore, a compensating circuit must be used that provides high voltages at the input and the output for the transmission of high power [54, 55]. Based on the combination of the capacitor and the coil in the compensating circuit, the IPT can be subdivided into different categories. The compensating capacitor can be either in parallel or in series with the coil. Therefore, four combinations are possible [56]. These combinations are,

- parallel-parallel (PP)
- parallel-series (PS)
- series-parallel (SP) and
- series-series (SS).

Simplicity is the key advantage of this approach. However, all these combinations do not support all the load conditions [56, 57]. Efficiency can be compromised by variations in the load [58]. Moreover, there should be an alignment between the coil and the capacitor so that the power level is maintained. To resolve this problem, different methods, such as, double sided LCC compensation methods have been proposed [59, 60]. In the double sided LCC compensation method, one inductor and two capacitors are attached on both the sides. For both the input and the output, the resonant tank behaves as an energy source using this approach [61], and the current at the output is not affected by the load conditions. One of the problems associated with the IPT technology is related to the coefficient of coupling [40, 62]. When the coefficient of coupling is low, the reactive power is high and the efficiency of power transmission is low [63]. Compensation tank helps improve the efficiency and reduces the reactive power [64]. As a result, the load and the coupling coefficient are invariant of the resonance frequency. This is one of the main advantages of the IPT technology.

Table 1
Comparison between WPT methods [47, 48]

Microwave	**Laser**	**Mutual Coupling**
Costly method	It is also an expensive method	Relatively cheap
Used for long distance	Used for both long and short distance	Used for short distance
Harmful for human beings	Also harmful for humans	Not harmful for humans
High output power	High output power	Low output power as compared to the other methods

Table 2
Comparison between IPT and CPT [29, 49, 50]

Inductive Power Transfer IPT	**Capacitive Power Transfer CPT**
Used for both high and low power applications	Used for low power application
Magnetic field is used for power transfer	Electric field is used for power transfer
High efficiency	Low efficiency
Compensation circuit consisting inductor and capacitor is used.	Compensation circuit consisting inductor and capacitor is used.
Can transfer power at large distance	Can transfer power at small distance
Installation of system is expensive.	Installation of system is relatively inexpensive.

For an efficient transfer of electric energy from the primary to the secondary side coil in an IPT system, the frequency should be high [65, 66]. For this purpose, the low frequency AC current that is supplied by the grid is first converted into DC. After this, it is changed in high frequency current by using DC/AC converters [67]. Next, the power transfer takes place as a result of the magnetic induction. The voltage induced on the secondary side is then rectified and converted to DC, and is utilized by the EV battery [40]. To transfer high power and to achieve high efficiency, compensation capacitors are used on both sides [65]. Choice of the compensating elements is made by taking into consideration the mutual inductance and self-inductance of the coil in case of static inductive charging [68]. The use of such compensating elements should be carefully evaluated in the dynamic inductive charging systems because the inductance value changes with respect to the motion of the EV [69]. Though the IPT has advantages for charging an EV, the CPT method is also being investigated for EV charging [70]. In addition to the consideration for EV charging, the CPT method is mostly used in low power applications, such as universal serial bus (USB), lamps and small robots [71]. The main limitation of the CPT method is that the transmitted power is low and the distance over which it can be transmitted is also small [38]. The CPT method can also be categorized based on the type of the compensation circuit used. For a series resonant circuit, a series inductor is used with the coupling capacitor. The capacitance is usually large as compared to the inductor [72]. Another method in CPT is the use of class E converter. However, its power and efficiency are limited due to the high frequency converters For the transmission of capacitive power, PWM converters are used. Other topologies are also possible, such as LCLC in which two inductors and two capacitors are used on both sides. However, there is a loss of power due to a leakage electric field in case the air gap is large.

4. WPT systems and charging in electric vehicles

The WPT systems used for the wireless charging can be divided into the following three categories with respect to the state of motion of the EV,

(a) Stationary WPT (SWPT),
(b) Semi or quasi dynamic WPT (QDWPT),
(c) Dynamic WPT (DWPT).

SWPT	QDWPT	DWPT
Stationary	Semi or quasi dynamic	Dynamic
EV charging stations may be installed in urban areas.	Installed at bus and the taxi stands for short term charging.	EV charging is done using wireless medium while vehicle is in motion.
Vehicle has to be stopped.	Temporary stop	No need of stop and wait for the charging.
Achieved using IPT or CPT	Achieved using IPT or CPT	Achieved using IPT or CPT

Commercial scale deployments, at present, use the IPT due to its higher power transfer ability with a larger gap between the transmitter and the receiver when compared with the CPT [73]. However, the IPT based SWPT, QDWPT and DWPT are bulky and heavy due to large copper coils with ferrous cores. On the other hand, CPT based prototypes and implementations [72, 74, 75, 76] use simpler structures are not only lighter, but also cost effective due to plates and foils. However, power transfer levels are lower and the air gap is also quite small. Due to the simplicity and cost effectiveness, research is underway [70, 77, 78] to overcome these shortcomings of the CPT based SWPT, QDWPT and DWPT charging systems.

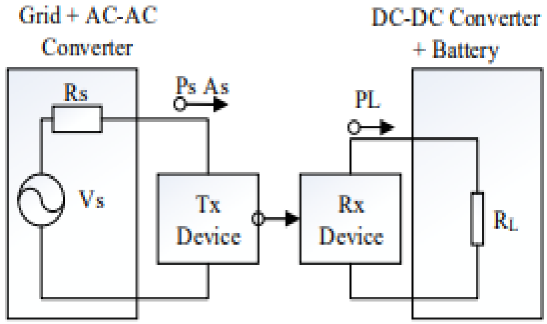

Fig. 2. A general depiction of a wireless charging system for an electric vehicle. There is an air gap between the transmitting and the receiving sides, and the power transfer between the two sides is due to the coupling between them.

5. Electric vehicle charging techniques

The techniques used for the charging of an EV may be broadly categorized as wired or wireless. The wired conductive charging may be further subdivided into three different levels, which are level 1 (L-1), level 2 (L-2) and level 3 (L-3) [78, 79]. Likewise, the wireless charging techniques may be divided into two main categories, which are, the CPT and the IPT. The IPT is considered to be the preferred technique for wireless charging as compared with the CPT method [29, 51, 52]. The wireless charging techniques may also be subdivided into the static and the dynamic methods. These different techniques and their further division are shown in Fig. 3 [29, 78].

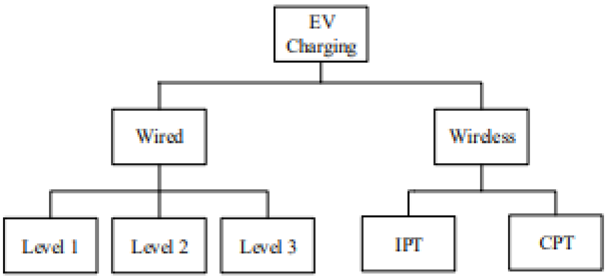

Fig. 3 An EV can be charged using wired or wireless methods. These techniques are divided into further categories depending upon the level of charge or the charging methodology.

5.1. Capacitive power transfer technique for charging

In a CPT system, the electric power is transferred using an electric field. When passing through the electrically isolated metal barriers, the electric field shows only small power losses [80]. Therefore, it is considered suitable for the charging of EVs [70]. Transmission of power is done by using the capacitors. These capacitors are formed by using metal plates that are cheaper. For example, the Aluminium plates can be used as these are good conductors, have light weight and are low cost. The alignment of the vehicle and the charging pad is important in a charging system. If there is a misalignment of position, detuning cannot be avoided in the CPT charging method [81]. The structure of a CPT charging system is simple, as metal plates are used instead of coils. Two capacitive couplers for the transmission of power are formed using four metal plates. These plates are placed horizontally and vertically depending upon the application. The CPT wireless charging system is suitable for short distance applications which typically require low power [82]. Usually, the distance is as small as 1 mm, which limits the applications of the CPT charging system [29]. In addition to the EV charging, some of the additional applications include, robot charging, light emitting diode (LED) driver, and excitation of synchronous motors [62]. The circuit topologies employing coupling capacitors in a CPT system are a cause of the distance limitation. A CPT circuit topology is classified either as a resonant topology or a non-resonant topology [60]. The non-resonant topology uses the PWM for the conversion. To supply smooth power to the circuit, a coupling capacitor is used as a power storage component. In a resonant topology, class E converter and series resonance converter are used [83]. A compensation circuit is used in which the coupling capacitor resonates with an inductor [77]. As a result, the coupling capacitance can be reduced while the resonant inductance and switching frequency are high. However, self-resonant frequency limits the inductance and efficiency, whereas power capability of the converter limits the switching frequency. Another limiting factor of this topology is that it is sensitive to parameter variation which may be caused by misalignment.

5.2. Inductive power transfer technique for charging

A typical IPT system may be subdivided into two main parts i.e. the primary side, which transmits power and the secondary side, which receives power. In an EV charging system using the IPT, the primary side of the IPT system may be placed on or under the road while the secondary side is mounted on the moving vehicle [84, 85]. Primary side transfers power to the secondary side. The power source is mainly application dependent or the power requirements of the device used. If the device being charged is power hungry, then a single or three phase system can be used while on the other hand if the power requirements for the device are small, then small batteries can suffice [86]. To convert low frequency to high frequency, an inverter is used [87]. The power transfer between the primary coil and the secondary coil of an IPT system takes place due to the mutual coupling between the two coils. A physical contact between the EV and the charger is not required in an IPT system, as coupling technique with a small gap between the coils is used for the wireless transfer of power. Therefore, the IPT is considered to be the prime method for the wireless charging of an EV [29, 51, 52, 88]. The working principle of an IPT system is the same as that of a transformer. An IPT system may use resonance for an efficient power transfer. The power transfer capability can be directly influenced by the magnetic coupling. Leakage may result if the coupling is not optimum. The leakage flux is that magnetic flux which does not take part in the power transfer in an IPT system. International Commission on Non Ionizing Radiation Protection has a guideline that the leakage magnetic flux density should not be more than 27 micro Tesla when exposed to human beings as it is harmful beyond this threshold [89].

5.2.1. Static charging

All EVs have battery related problems. Wired chargers are fixed, and therefore, a vehicle has to stop at a charging station for the purpose of charging. Moreover, the mechanical connectors should be maintained routinely. Handling the wires and the mechanical connectors is dangerous especially in wet and dry conditions [92]. These issues can be resolved by adopting a wireless charging system. In a static wireless charging system, an EV still has to stop for charging, but there is no hassle of maintaining and connecting mechanical connectors.

To charge an EV using the IPT static wireless charging technique, the vehicle is parked on the charging pad at a charging station. The vehicle or the battery need not have a physical connection with the charging system. Misalignment between the assembly installed on the EV and the charging pad is acceptable to a certain degree [93, 94, 95]. This technique is appropriate for shopping malls and offices as the vehicle is parked for a specific time interval. Large battery pack is required in this technique as previously seen for conductive charging systems [96]. Dynamic charging system helps to overcome the problem of large battery [97].

5.2.2. Dynamic charging

Dynamic wireless charging is an ideal candidate for the WPT methodology, as this allows the vehicle to be charged while it is in motion. This also increases its travelling range [98], saves driver and passengers' time and improves their safety. The maintenance costs are also reduced, as the mechanical connectors are no more needed for charging [99, 100]. Roadway powered EV is one way to employ dynamic WPT. With this method, the EV is charged dynamically by the WPT and does not require a long time for charging. By using this technique, the public transport can be charged even on stops when the passengers get down or board the bus or taxi [101]. This idea can also be used on highways. Certain paths can be consistently powered to charge EVs [102]. This will reduce the size of the battery pack, initial cost, complexity and weight of the vehicle. Range also increases by the use of this technique [103]. Two types of magnetic couplers are used for dynamic charging [104, 105]. In the first type, a single longitudinal coupler is laid down while in the second type, the coupler is divided into segments. The segmented coupler is more advantageous as compared to the longitudinal coupler [106]. In the segmented coupler approach, only that segment is energized where the receiving system of the vehicle is currently present. This helps reduce power losses [107]. The challenges involved in this technique are high initial cost, installation is to be distributed possibly along highways and complex management for scheduling. This technique is still being developed and only a few dynamic charging systems are available.

A commonly used wireless charging system is proposed in [108], which is based upon the IPT mutual inductance model. In the mutual inductance model, a two port network is obtained by transforming the T type transformer. It is the most commonly used and simple model. Likewise, in [60], a double sided LCC compensation technique is proposed. In this technique, the transmitting and the receiving sides use external capacitors and inductor. This technique is not affected by the changing voltage of the battery in battery charging applications [109]. This is possible due to the resonant circuit. In this technique, unity power factor is achieved and, therefore, it has high efficiency. In [62], a topology which uses the CC and the CV charging modes with double sided LCC technique is proposed. Flaws of the IPT charger can be overcome by using this technique. Another model to dynamically charge an EV is proposed in [110]. This model is described and discussed in Section 6.2.2.1 as a typical example. One of the major disadvantages of dynamic wireless charging is low efficiency [111, 112]. For the purpose of high efficiency of power exchange, various systems have been proposed, such as, compelling pickup tuning, pickup voltage strategies, proficient pickup modules [112, 113] and resonant inverters [114] for wireless power exchange.

6 Conclusion

We have discussed and reviewed charging of electric vehicles using wireless power transmission. Wireless charging is considered a better alternative to traditional wired charging systems as it is user and environment friendly. Furthermore, it eliminates the need for wires and mechanical connectors, and therefore, avoids the associated hassles and hazards. Wireless charging systems also reduce the range anxiety and enhance the system efficiency. The wireless power transmission, in general, takes place using microwave, laser or mutual coupling. However, only mutual coupling based techniques are generally used for wireless charging. The mutual coupling based techniques, inductive and capacitive power transfer are employed for contactless power transfer and charging of electric devices. Both these techniques are discussed, compared and contrasted, and it is concluded that the inductive power transfer has advantages and is the prime method for wireless charging of electric vehicles. For this purpose, static, semi or quasi dynamic or completely dynamic methods of wireless charging can be employed. These modes of wireless charging of electric vehicles are explained in this article. Roadway powered EV is one way to employ dynamic WPT. With this method, the EV is charged dynamically by the WPT and does not require a long time for charging. By using this technique, the public transport can be charged even on stops when the passengers get down or board the bus or taxi [101]. This idea can also be used on highways. Certain paths can be consistently powered to charge EVs [102]. This will reduce the size of the battery pack, initial cost, complexity and weight of the vehicle. Range also increases by the use of this technique [103].

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