

The development of wireless charging technology in the electric vehicle

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Abstract. Greenhouse gas emissions have caused the global climate to deteriorate, and the consumption of oil resources is becoming less cost-effective. Electric vehicles (EVs) are a good way to reduce this negative impact. However, the energy density of batteries is too low compared with oil, so electric cars need to be recharged repeatedly. This paper provides a comprehensive review of all the wireless charging technologies for EVs. The technology principle of Inductively Coupled Power Transfer (ICPT), Magnetically Coupled Resonant Wireless Power Transfer (MCR-WPT) and Microwave Power Transfer (MPT) are discussed by a comparative analysis between the three technologies. The analysis found that MCR-WPT is the best technology because it has high efficiency and very little radiation. After that, wireless charging is expounded from both static and dynamic perspectives. Next, different national requirements and standards for wireless charging are presented. According to the economic and safety analysis, it is found that wireless charging technology can avoid many security risks, reduce the occupied area and has a longer service life than wired charging.

Keywords: wireless charging, electric vehicle, electromagnetic, microwave.

1. Introduction

Over the years, along with the rapid economic development, industrial pollution and vehicle emissions have continued to rise. From 1970 to 2017, global greenhouse gas emissions increased from 27 billion tons to 53.5 billion tons. Since 2016, 197 countries have been bound by the United Nations Framework Convention on Climate Change (UNFCCC), which ultimately aims to stabilize concentrations of greenhouse gases in the atmosphere [1]. This means that the problem has become a global one. To achieve the purpose, all the countries eventually need to achieve zero emissions. Besides, as a non-renewable resource, oil consumption is huge. Global oil consumption will reach 101.4 million barrels per day in 2022 [2] (China Energy News, 2021). To achieve sustainable development, the world urgently needs to find ways to replace non-renewable resources. How can so many countries live without using oil and producing greenhouse gases? At least for transportation, a viable approach was found --- Electric Vehicle (EV). Unlike traditional fuel cars, EV use storage cells (such as lithium-ion batteries) or fuel cells (such as hydrogen fuel cells) as power supply, which means that EVs don't need to use fuel oil and have no exhaust emissions during driving. However, the promotion of EV is still faced with many difficulties, and the vehicle range is one of the main problems restricting its development. Due to the battery capacity limitations [3], battery energy density has not improved by leaps and bounds. The increase of battery density is becoming more difficult, so people are turning to charge technology, electric vehicle charging technology is becoming a hot topic.

In current charging technology, wired charging is the most common way to charge electric vehicles (e.g.). Electric vehicles get energy from the grid through charging piles, which is extremely

inconvenient for users because they need to wait for the charging to complete. It takes a long time due to its low efficiency.

To overcome the limitations of electric vehicles (EV) driving range, numerous researches have been focused on making better batteries with larger energy density and capacity. Meanwhile, other technologies appeared, like the wireless charging technology of electric vehicles (WEVC), which has immense potential and interest.

Wireless charging is not a new technology. In the early 1700s, Nikola Tesla came up with the idea of wireless charging. Tesla's design used a concept of a charged conductive upper layer in the atmosphere, and he intended to transmit messages, telephony and even facsimile images. This method is based on magnetic induction.

In 2007, MIT professor Marin Soljagic's team designed a magnetically coupled resonant wireless transmission system by adding a resonant network to the transmitter and receiver [4].

The magnetic resonance principle can significantly increase the ratio of the distance between the primary and secondary coils to the diameter, allowing the vehicle's wireless charging [5].

Compared with the low and medium power wireless charging systems, the Qi standard of WPC (Wireless Power Consortium) is mainly adopted, and magnetic induction technology is the main technology. In contrast, magnetic resonance technology is mostly used in the automotive field. The main reason is that magnetic resonance technology supports higher power and a longer transmission distance. When a car is charged with high power, the distance between the chassis and the ground is necessary for close coupling. So magnetic resonance technology is widely used by the car factory.

The most common wireless charging methods used to be inefficient due to the lower transmission power and strict distance requirements. The existing technology adopts efficient antenna design, high-efficiency power conversion technology, so the current wireless charging scheme using magnetic resonance technology can achieve 85-90% of the car charging efficiency, which is quite competitive with 90% efficient magnetic induction technology [6].

In this paper, it is argued the WEVC in many respects. In principle, it can be divided into three categories. After expounding the three basic principles, dynamic charging and static charging are analyzed. Then the WEVC standards of different countries are compared. Finally, there is a comparative and safety analysis. This paper is provided a preliminary and comprehensive information of WEVC, put forward some problems existing at present stage, having reference value for relevant practitioners.

2. The development of wireless charging technology

2.1. Technical standards and principle

In principle, wireless charging works much like wired charging. Both of them convert the power supply voltage to direct current (DC) and charge the battery. Besides, Power Factor Correction (PFC) is used in wireless electric vehicle charging (WEVC). Power factor refers to the ratio of effective power to total power consumption. PFC is a technology that can improve the power factor of electrical equipment. Unlike wired chargers, WEVC uses current isolation transformers based on the main power supply's charger, which is the essential difference between wired and wireless chargers [7]. The effect of the isolation transformer is to protect personal safety and isolation danger voltage, more than that, the high frequency loss of the core can be used to suppress the high frequency clutter in the control loop, provides a pure power supply voltage to the electrical equipment. In addition to changes in equipment, WEVC has three different technologies, Inductively Coupled Power Transfer, Magnetically Coupled Resonant Wireless Power Transfer and Microwave Power Transfer. Their specific principles are as follows.

2.1.1. Inductive coupling

For the domain of electric vehicle wireless charging, electromagnetic induction is one of the main principles [8]. Inductively Coupled Power Transfer (ICPT) technology is based on electromagnetic

induction. It uses loosely coupled transformers to achieve power transmission. The structure diagram of ICPT is shown in Figure. 1.

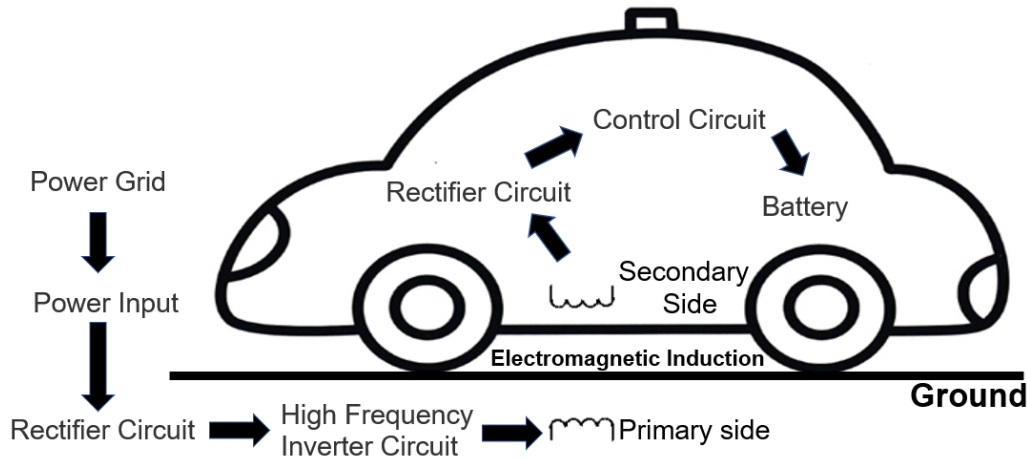


Figure 1. Electromagnetic induction system structure

The power input terminal is installed under the ground, and the primary coil side and the induction secondary coil side is located inside the electric vehicle. Primary, the power received from the power grid is the power input, which will be rectified and then flows into the primary of the induction coil through the high-frequency inverter circuit. Next, an induced current is generated on the secondary coil side because of electromagnetic induction. Then the current is rectified and filtered by the internal rectifier circuit and control circuit. After the power regulation, the battery can be charged [9]. When ICPT technology is used in wireless electric vehicle charging, the distance between the primary and secondary sides should be considered. Usually, the distance between two induction coils should be controlled within 0.1m, and the induction coils of two sides should be aligned as much as possible to guarantee efficiency. The energy conversion efficiency of electromagnetic induction charging is high, reaching 99 % at close range. However, its disadvantages are also obvious, such as large transformer loss, too short transmission distance, rapid reduction of transmission efficiency with the increase of the distance, and small tolerance of horizontal line deviation [10].

2.1.2. Magnetic resonance

Resonance refers to the energy oscillations between the magnetic field and the electric field for magnetically coupled circuits. The basis of magnetic resonance is still the principle of electromagnetic induction.

A given primary current I_1 produces a loss of $I_1^2 R_1$ in the primary winding and induces a voltage with the RMS value of $\omega M_{12} I_1$ in the secondary winding. This induced voltage will apply on the impedance $R_2 + R_L + j\omega L_2$ in the secondary side. So, the induced current will be largely restricted by the reactance of the secondary winding. Suppose the reactance of the secondary side impedance could be compensated, for example, by connecting a capacitor C_2 in series with the secondary winding and cancelling out the reactance as shown in Fig. 2. In that case, a larger load current and a higher load power can be transferred to the load.

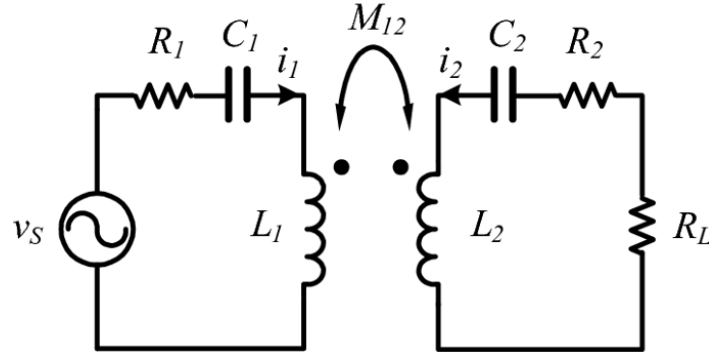


Figure 2. Coupled inductors with compensating capacitors connected in series with the windings

$$\omega L_2 - 1/(\omega C_2) = 0 \quad (1)$$

With the same input current in the primary winding, the output power is increased. Thereby the power transfer capability and efficiency are improved. On the primary side, $j\omega L_1$ should be also compensated by using capacitors to minimize the required VA rating of the system, i.e., a lower input voltage is required to generate the same input primary winding current. Therefore, primary compensation also improves the power transfer capability of a WPT system.

One of the basic operation principles of magnetic resonance WPT is to compensate both the primary and secondary reactances. Thus we have resonance in both the primary and secondary sides. A series-compensated primary and secondary system is shown in Fig. 3. There are two L-C (inductor and capacitor) resonators in the circuit. This forms a basic magnetic resonance WPT system.

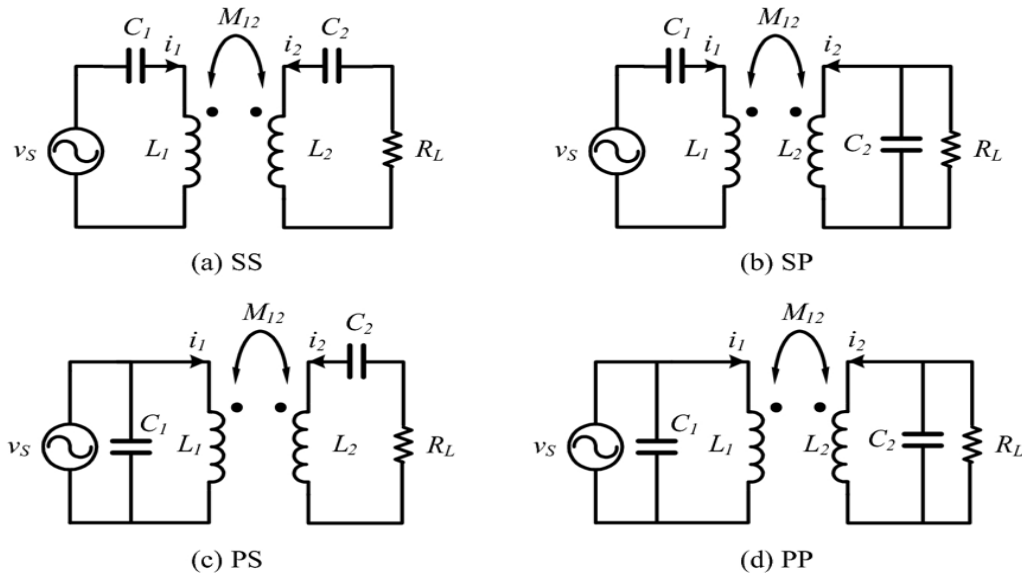


Figure 3. Four basic compensation topologies [11]

Besides using series compensation in both the primary and secondary sides, which is usually called series-series (SS) compensation, parallel compensation is also (denoted with letter P). Consequently, there are totally four basic compensation topologies, i.e., SS, SP, PS, and PP [11], as shown in Fig. 3. For example, PP means both primary and secondary sides use parallel compensation. Regardless of the different connections, series and parallel compensations aim to eliminate the reactances in both the primary and secondary circuits. So, the following analyses will focus on SS topology. Similar studies can be extended to the other three topologies.

The circuit model of the SS WPT system is given by

$$(R_1 + jX_1)I_1 + j\omega M_{12}I_2 = V_S \quad (2)$$

$$(R_1 + jX_1)I_1 + j\omega M_{12}I_2 = V_s$$

Where $(R_1 + jX_1)I_1 + j\omega M_{12}I_2 = V_s$, $i = 1$ or 2 , is the reactance of Resonator- i , i.e., Here R_i include both the winding resistance and the equivalent series resistance (ESR) of the compensating capacitor.

2.1.3. Microwave

Microwave wireless power transmission (MPT) is the key technology of solar power satellites and aircraft in near space. It could also be applied in charging the wireless sensors and electric cars, harvesting the ambient electromagnetic power. In fact, Tesla came up with the idea of using radio waves to transmit energy back in 1899 and tried to verify it in the experiment. Still, unfortunately, his experiment did not leave detailed data. In the 1960s and 1970s, the U.S. Dr Brown's research team was based on microwave-driven helicopters, near-space communication relay platforms and solar-powered satellites and did many experiments on Microwave Wireless Power Transmission (MPT) technology [12]. In 2007, the US Defense Advanced Research Projects Agency (DARPA) proposed the reconfigurable Satellite System concept, which is a combination of the near-space communication platform and the solar satellite. The reconfigurable satellite system consists of several functional modules (small satellite 1), which can reduce manufacturing and maintenance costs, and one module is dedicated to providing power for the other modules through MPT technology. An American company called Escape Dynamics is developing an innovative new space shuttle that is powered by microwaves from the ground and could into a single stage orbit without fuel [13].

The efficiency of Microwave Wireless Power Transmission (MPT) direct current to direct current (dc-dc) could be divided into three parts, the efficiency of transmitting direct terminal current to microwave (dc - mw), the efficiency of receiving end microwave to direct current (mw - dc) and microwave beam catch efficiency. National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL) had reported some experimental data of an MPT system with a distance of 170.2 centimetres. The transmitting terminal DC to microwave, the transmitting and receiving efficiency is 69%, 95% and 82%, respectively. The output DC power is 495 W, and the DC continuous conversion efficiency is about 54%. However, outdoor experiments with long-distance MPT technology are far from achieving this efficiency. For example, JPL's outdoor experiment at a distance of 1.54 km [14] showed a system efficiency of only 6, 7%, mainly because the microwave beam capture efficiency was only 11.3%.

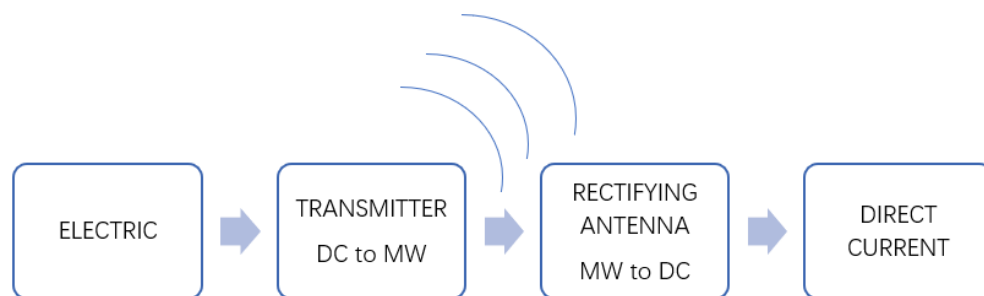


Figure 4. MPT system

With the development of planar printing technology, the microwave to direct current conversion efficiency of the rectifier antenna unit can reach 82%, the efficiency of the subarray is more than 70%, and the efficiency of the large-scale rectifier antenna array can reach 65% [15].

All in all, MPT is an attractive technology for wireless power transmission over long distances. To further improve the efficiency of the DC-DC system, some key technical problems need to be overcome, which can be considered from the following aspects. The first problem is the distance. As for now, this technology cannot afford long distance transmit. The second problem is how we can cover all the roads and air space and how much it would cost. The efficiency of capture microwave beam needs to be rise which is the third problem.

2.1.4. Comparison of the three transport technologies

Compared to the other two, the cost performance of MPT is lower [16]. Mitsubishi Heavy Industries has developed an electric vehicle charging system based on microwave wireless power transfer, with an energy conversion efficiency of only 38% [10]. Besides, another experiment based on MPT has been developed by Kyoto University in collaboration with Nissan Motor Company at 2.45 GHz, with a transmission distance of about 10 cm, and the maximum efficiency was 5% [17]. Therefore, MPT is not suitable for EVs because the energy efficiency of MPT is too low to support the vehicles. For ICPT technology, the most serious problem is that the transmission distance is small, which is not greater than 15 cm in general. However, the prerequisite for WPT application in electric vehicles is that the transmission distance should not be less than 20 cm [18]. Apart from that, the lateral offset tolerance of the technology is small. When the transmitting coil and the central coil are not aligned perfectly, the transmission efficiency of the system will decrease rapidly. Therefore, ICPT is also difficult to apply widely to EVs. For MCR-WPT technology, Sesung—Hwan Lees' lab shows that under the working frequency of 3.7 MHz and transmission distance of 30 cm, the wireless energy transmission of 3 kW is realized, and the efficiency reaches 95%. So, MCR-WPT is probably the most suitable technology for widespread application in EVs.

2.2. Progress of wireless charging in various countries

Since the late 19th century, magnetic resonance has been the cornerstone of wireless power transmission (WPT). MIT developed magnetic resonance in 2007 [4]. It overcomes the shortcomings of magnetic induction and microwave to transmit power within a few meters. In South Korea, the OLEV running in the Kumi City is based on resonance coupling and uses DWC charging for EVs [19] [20]. This DWC uses the SMFIR technology developed by the KAIST. In 2020, Dubai's Road Transport Authority (RTA) successfully conducted a dynamic wireless charging test for electric vehicles and buses in operation by SMFIR. Global automobile companies, such as Tesla, Toyota and Nissan, use magnetic resonance coupling for WPT [21]. In terms of wireless charging methods, it can be divided into two main methods: dynamic charging and static charging.

2.2.1. Dynamic charging

The DWC (Dynamic wireless charging) proposed by Bolger could charge the EV during driving. Since 2009 [22], the development of DWC has been led by a research team at KAIST. The project addressed a number of major issues, such as continuous power transmission, high frequency current control inverters, and different EMF features [23]. DWC overcomes most of the problems with EVs, such as range anxiety, battery size, and battery cost. The existing model of DWC is based on the inductive WPT method [24]. This technology relies on the magnetic coupling between the coil mounted under the road surface and providing high-frequency current to generate an electromagnetic field and the pickup coil mounted in the EV.

DWC depends on the speed of the vehicle. As the position of the secondary coil changes, the flux also changes. In this regard, Zhang, X., et al. analysed the coil coupling and variation of transmission efficiency [25] and proposed a dispersed coupling structure called grouped periodic series spiral coupler. The charging system can selectively turn on or turn off charging during vehicle driving.

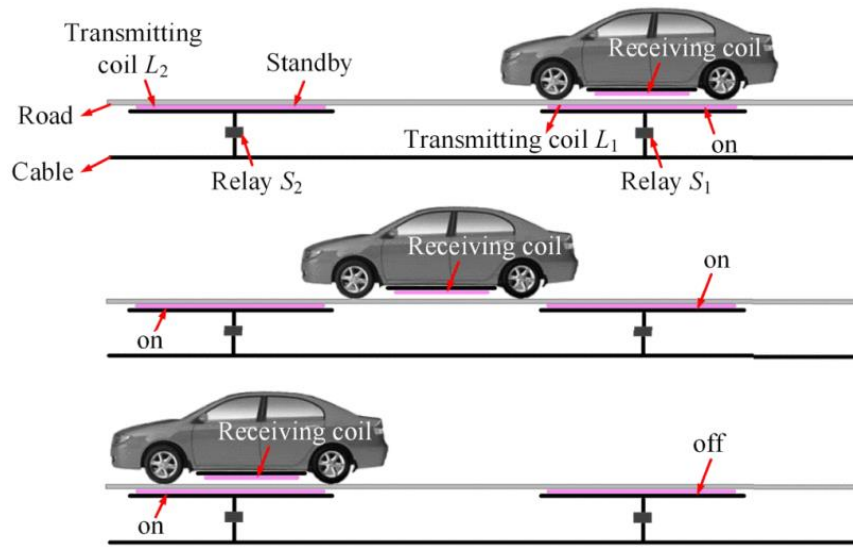


Figure 5. Selective charging system

Mou, X., et al. also proposed a new V2V charging technology to solve the problems caused by the limited number of charging stations [26]. The angle offset analysis in wireless V2V system is proposed, and the effects of different transmitter coil structures on system efficiency are compared [27].

2.2.2. Static charging

Static wireless charging technology can be divided into electromagnetic radiation type, electric field coupling type and magnetic field coupling type according to the transmission mechanism [28]. The radiant radio energy transmission technology uses the far field to transmit energy, mainly radio waves, laser, etc. It is suitable for long-distance wireless transmission, but the efficiency is very low, and the transmission power of microwave and radio wave is very small. Laser radio energy transmission technology cannot be put into use at present. Electric field-coupled and magnetic field-coupled radio energy transmission technologies utilize near-field to realize the transmission of electric energy. The electric field coupling type uses the capacitor's electric field for energy transmission, while the magnetic field coupling type uses the alternating magnetic field for energy transmission. Due to the great influence of electric fields on the human body, there is little research on electric field coupling. Comparatively, magnetic field coupling has been paid more attention, and has been widely used in static wireless charging of electric vehicles. Magnetic field coupled radio energy transmission technology can be divided into induction type and resonance type. Inductive transmission has high power and high efficiency in a short distance. Still, it is sensitive to coupling coefficient because of the law of electromagnetic induction, so it is only suitable for short distance transmission. The utility model is suitable for medium distance transmission. The electric energy transmission is not affected by the non-magnetic obstacles in space [4], which has more advantages in the static radio of electric vehicles [29].

2.3. Development of wireless charging standards

The establishment of standards plays an important role in the practical application of WEVC technology. At present, there are three major organizations in the development of WEVC standards—the International Electrotechnical Commission (IEC), the Society of Automotive Engineers (SAE) and the International Standardization Organization (ISO) [3]. Unlike SAE specifically designed for the Americas, ISO and IEC standards have membership in dozens of countries, designed as references for most countries. The wireless charging standard IEC61980 developed by the IEC is one of the most widely referenced WEVC standards. It includes three parts: general requirements, communication protocols and special requirements. For the part of the general requirements, IEC 61980–1 was published in July 2015 and subsequently revised in January 2017. After that, the second edition was

published in November 2020. This part covers the structure requirements, material strength, safety requirements, performance requirements, electromagnetic compatibility and other provisions [30]. The second part, IEC TS 61980-2 was published in June 2019. When connected to the supply network, it regulates the communication between EV and wireless power transfer (WPT) systems. Besides, the standard about WPT equipment provided by field storage systems (such as buffer batteries) at standard supply voltages is also included. The third part also was published in June 2019. It shows the specific requirements for the magnetic field WPT systems.

The SAE TIR J2954 standard for plug-in Hybrid Electric Vehicles (PHEV) is one of the widely referenced standards for wireless charging of EV. The standard was revised for a second time in April 2019. Apart from that, ISO 15118-1/2/3 were published between 2013 and 2015, which provide relevant regulations on communication protocols for electric vehicle charging. After that, in January 2017, ISO 19363 was published, which sets out safety and interoperability requirements for WEVC.

Table 1. The standards of wireless charging for EV

Organization	Standard Number	Date Published	Description
SAE	J2954_201904	2019-04-23	Wireless Power Transfer for Light-Duty Plug-In/ Electric Vehicles and Alignment Methodology
	J1773_201406	2014-06-05	SAE Electric Vehicle Inductively Coupled Charging
	J2847/6	2015-08-05	Communication between Wireless Charged Vehicles and Wireless EV Chargers
	J2931/6	2015-08-27	Signaling Communication for Wirelessly Charged Electric Vehicles
IEC	IEC 61980-1: 2015/COR1: 2017	2017-01-25	Corrigendum 1-Electric vehicle wireless power transfer (WPT) systems-Part 1: General requirements
	IEC TS 61980-2 Ed.1.0	2019-06-13	Part 2: Specific requirements for communication between electric road vehicle and infrastructure with respect to wireless power transfer (WPT) systems
	IEC TS 61980-3 Ed.1.0	2019-06-13	Part 3 Specific requirements for the magnetic field wireless power transfer systems
ISO	ISO 15118-1/2/3	2013~2015	Road vehicles - Vehicle-to-Grid Communication Interface
	ISO 19363	2017-01	Electrically propelled road vehicles - Magnetic field wireless power transfer - Safety and interoperability requirements

Table.1 lists the main international wireless charging standards for EV. In general, the establishment of basic standards for WEVC has been relatively complete, which basically satisfied the requirement of the industries. However, the compatibility between different standards is regrettable because different institutions have different research emphases on WEVC [3].

2.4. Economic and safety

Conventional charging use plugs connected to sockets for charging, which still have safety loopholes, contact loss and inconvenience. In contrast to these limitations, wireless power transfer(WPT)has many advantages, such as reducing battery weight, realizing mobile dynamic charging, adapting to a variety of harsh environments and climate, saving spaces of charging piles, lower battery expenses and higher charging efficiency. As for the economy, it's a burden for the government, which would be a huge investment in infrastructure construction because thousands of coils must be buried under the road. EV should be modified with coils associated with coils under the road. Meanwhile, lower costs of batteries could make the price of EVs more affordable.

Table 2. Researches of static wireless charging for EV

Institutions	Year	Power/kw	Transmission Distance/cm
Oak Ridge National Laboratory	2018	120	15.7
Momentum Dynamics	2018	200	30.5
University of Auckland	2017	1	15-20
University of Michigan	2017	3	15

Power of conventional charging EV could be chosen among 30 kw, 60 kw, 100 kw, 150 kw, 200 kw, and we can see that power of some wireless charging with particular coils could somehow catch up with that number in cable charging. As for safety, China has implemented GB/T 38775.1, GB/T 38775.2, GB/T 38775.3, GB/T 38775.4, four national standards about wireless charging system of EV. The standards have extremely strict regulations about electromagnetic radiation came from wireless charging, and also electromagnetic shielding technology will be used in wireless charging as double security. Wireless charging could effectively solve some potential safety hazards like quality problems of charging piles, the high density of charging piles if one pile's outbreak of fire probably leads to chains reactions and serious fire catastrophe, the shock of touching electric piles, and save floor spaces of charging piles making the land a high use efficiency.

3. Conclusion

This paper argued three different principles of wireless charging, Inductively Coupled Power Transfer, Magnetically Coupled Resonant Wireless Power Transfer and Microwave Power Transfer. According to the analysis of the cost performance, energy transfer efficiency and transmission distance, it is found that MCR-WPT is the most suitable technology for EVs application. Besides, the current status of wireless charging technology research in various countries is briefly introduced. Then wireless charging technology is introduced from dynamic and static aspects. After that, the standards for wireless charging technology are listed. Three organizations currently developing WEVC standards are introduced — the International Electrotechnical Commission, the Society of Automotive Engineers and the International Standardization Organization. An analysis of the economic and security aspects of wireless charging and wired charging is shown at the end. Wireless charging technology for electric vehicles has been widely studied, and some progress has been made. However, there are still some problems that need to be solved, such as the cost of the transmission equipment, the efficiency and the distance of energy transmission. In conclusion, WEVC has strong adaptability to the requirement, based on different principles, it can achieve different effect. Compared to wired charging, WEVC has no physical damaged with high safety, more in line with sustainable development, to meet the requirements of people's lives. Therefore, WEVC will definitely become a dominant charging method of EV age.

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