Recent Advances in Wireless Power Transfer Technologies for Electric Vehicles

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Abstract. With the advancement of innovative technology in the contemporary world, wireless power transfer technology is also playing an increasingly important role in electric vehicles. In the past, there did not have enough electric products and spaces to apply to this wireless charging technology so the use of it by humans is limited to some levels of understanding of the technology, such as one or two technical classifications contained in wireless power transfer (WPT). However, people have more in-depth research on convey of power wirelessly and charging for the electric vehicle nowadays. By reason of this situation, this paper focuses on the three technologies in the WPT system, which are magnetic resonant coupling, capacitive coupling, and inductive coupling. Meanwhile, the compensation network that is associated with three technologies is also illustrated directly in it. Additionally, it compares those technologies in a clear table with advantages and disadvantages. Eventually, it summarizes all the previous content and proposes a vision for the future improvement description.

Keywords: Wireless power transfer, compensation network, electric vehicles, technology.

1. Introduction

Nowadays, the global environmental pollution problem is becoming increasingly serious. Various types of pollution permeate human life, such as air, water, light, and other forms of pollution. Among them, the vehicle exhaust and the energy required for charging are significant sources of pollution. The use of various energy shortages and polluting energy is increasing year by year. Therefore, using the wireless power transfer technology is a correct way for relieving and even solving this trouble. Wireless power transmission requires high energy transmission efficiency to meet the demand for power transmission, while increasing the transmission distance of the energy loaded by wireless radio waves. It has become widely used relies on its flexibility transmission, break free from the constraints of location range and other advantages [1]. Moreover, the research of it is focused in the future development. From late 1800 to early 1900, Nikola Tesla conducted extensive research on wireless power transmission. He discovered the electromagnetic induction coil. He mainly converts low-frequency high voltage into high-frequency current, and transmits high-frequency current through air as a medium. Next, Maxwell established a complete system of electromagnetic theory. During the second world war, wireless power transfer (WPT) started in that time researchers used curved reflectors to concentrate energy into one small area [2]. Around the mid-2000s, researchers began exploring resonant inductive coupling as a more efficient method for wireless power transfer, which allowed for greater spatial freedom and improved power transfer efficiency compared to traditional inductive charging. In recent years, many companies and institutions continue to develop and refine various wireless charging methods for numerous applications, including medical devices, automobiles with electricity and so on [3].

To analyze below working technologies of a WPT system, the construction of it can be divided as the circuit topology in Figure 1. There are two main types, one is acoustic and one is electromagnetic field. Among the electromagnetic power transfer field, two categories that are coupled and uncoupled about it. The inductive coupling and capacitive coupling technologies in the coupled aspect. But, radio frequency and laser power transfer are the uncoupling technology [4].

This paper mainly reviews three typical technologies of wireless power transfer, introducing coupling that is via magnetic resonance, capacitance, and induction technologies, as shown in Fig. 1.

In the next section, it provides a detailed explanation of the complete compensation network. Then, compare these technologies and conduct a clear analysis of them. In addition, the future application and progress space of wireless charging technology were also proposed. Finally, the entire paper provides a summary and proposes a beautiful vision.

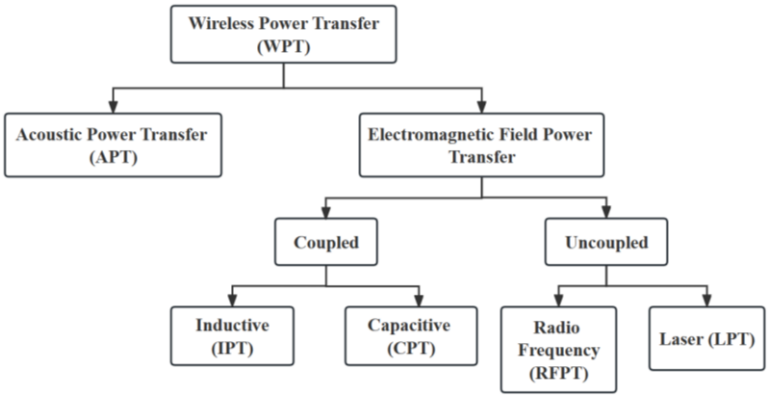


Figure 1. The wireless power transfer system's architecture [4]

2. Fundamental Working Technologies

2.1. Magnetic Resonance WPT

The theory of magnetic resonance is that of a rotating fork that is oscillating. When a coil vibrates, other coils which are nearby the same natural frequency are activated and generate energy. It happens when the transmitter and receiver coils attaining resonance [5]. It has two distinct parts to this resonance. Firstly, the self-inductance and self-capacitance of the coils regulate, which is self-resonance. Secondly, its own inductance and installed capacitance of the coils control, which is outside and stimulated syntony [5]. The similar circuit about the magnetic resonance coupling is in the Figure 2. It indicates that several LC circuits with impedance and the mutual inductance L_m.

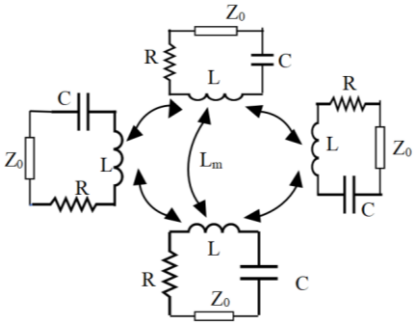


Figure 2. The equivalent LC circuit about the magnetic resonant coupling WPT [4]

Importantly, take out a portion for analysis. The interconnection equations illustrate a couple of ports at reference planes T_1–T'_1 and T_2–T'_2 are $V_1=j\omega Li_1+j\omega L_m i_2$, $V_2=j\omega Li_1+j\omega L_m i_2$ with the circuit explanation in Figure 3.

According to the figure 3(a), the voltage decreases under the influence of the inductance. The Figure 3(b) is an substitute version of this diagram above. An impedance inverter with the formula $k=L_m$ is used to express the magnetic link between the two resonant loops. If the electric wall in place of the symmetrical dimension T-T' is supplanted, the electric wall frequency is $fe = 1/(2\pi\sqrt{(L - L_m)C})$ and magnetic wall $f_m=1/(2\pi\sqrt{(L + L_m)C})$, so the final resonant frequency is $f_o=\sqrt{f_e f_m}$. After that, the coefficient of the magnetic coupling is $k_m=(f_e^2 - f_m^2)/(f_e^2 + f_m^2)=L_m/L$ [6].

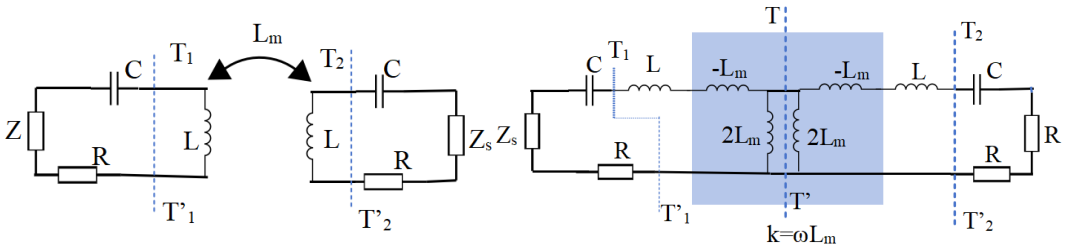


Figure 3. Magnetic resonant coupling WPT. (a) The equivalent LC circuit about the magnetic resonant coupling WPT (b) A replacement to the circuit diagram shown. [4]

2.2. Capacitive Coupling WPT

The capacitive coupling technology is recently added to the electric vehicle wireless charging. Under this technology, the terminal is made up of metal sheets and its main side and secondary side are all featuring insulation coverings. Power will be transferred because the high frequency inverter could activate the terminal of the coupling region, then creating an electric field and permits the passage of the current. The capacitive coupling system method diagram is in below Figure 4. It shows that a high frequency inverter converts a direct current voltage into an alternating current voltage and then given to two main metallic sheets [7]. The proximity of these sheets is what causes the motion of movement current produced by the electric field. After that, the AC voltage is subsequently changed to DC by the rectifier [7]. However, the capacitively coupled contactless power transfer (CCPT), which differ most from inductive power transfer (IPT) systems in that they send energy by an electric field opposed to a magnetic one, have the ability to penetrate through metal substrates that are present in the transmission line [8].

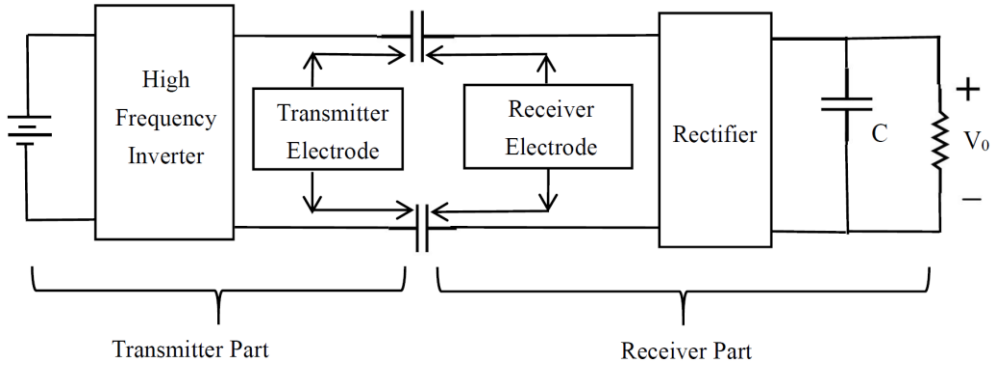


Figure 4. The method diagram of capacitive coupling system [4]

Moreover, in Figure 5, the capacitive coupler internal capacitance C_{in1} and C_{in2} interact with the others C_{ex1} and C_{ex2} in the compensation systems so that $C_1 = C_{in1} + C_{ex1}$ and $C_2 = C_{in2} + C_{ex2}$, so $k_C = C_M\sqrt{C_1C_2}$. After that, change representation of some components. Add a suffix eq after the name of each components as shown in the below figure. Among them, using parallel-connected conductance GC_1 and GC_2 to express the power losses of capacitance. Similarly, GL_1 and GL_2 describe the inductance respectively. Meanwhile, in this approach, the circuit configuration is not a factor [9]. Therefore, the efficiency of it is

$$\eta=|V_{C2}|^2G_{Leq}/|V_{C1}|^2G_1 + |V_{C2}|^2G_2 + |V_{C2}|^2G_{Leq} \quad (1)$$

Because, $G_1=GC_1+GL_1$, $G2=GC2+GL_2$, the efficiency is changed to below with the equivalent conductance G_{eq} and G_{Leq} is the the output load R_L is expressed in equivalent conductance.

$$\eta=1/((G_2 + G_{eq})^2/\omega^2C_M{}^2).(G_1/G_{Leq}) + G_2/G_{Leq} + 1) \quad (2)$$

And through the formula with k_C calculation, the efficiency is below.

$$\eta=1/((\alpha + \frac{1}{\alpha} + 2)/k_C{}^2Q_1Q_2 + 1/\alpha + 1) \quad (3)$$

So that the maximum of efficiency is

$$\eta=k_C{}^2Q_1Q_2/(1+\sqrt{1+k_C{}^2Q_1Q_2})^2 \quad (4)$$

And the peak value of α is $k_C{}^2Q_1Q_2$ [10].

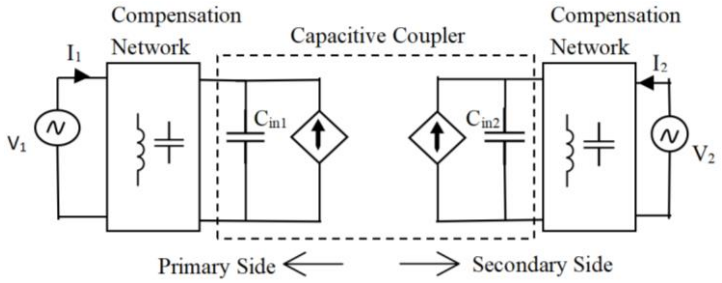


Figure 5. The general model of a CPT method with the compensation network [4]

2.3. Inductive Coupling WPT

A secondary and primary coil are magnetically coupled together in a typical system, which is powered by an alternating current. The connection of the two coils, which is determined by the coupling factor km, creates a coreless transformer. Adapting to Ampere's law, an alternating magnetic area is caused by an alternating current moving via the principal coil. Depending on the law of Faraday induction [11], the additional coil's fluctuating magnetic flux induces an electromotive force, which is known as the inductive coupling. The coupling factor $km=M/\sqrt{L_1L_2}$ from both coils, as well as the resistive coil wastage play a significant role in efficiency. Meanwhile, subscript m operates according to the fundamentals of alternating magnetic fields. According to the below figure and formulas, the mutual inductance appears to diminish as the distance extends and the coupling also decreases significantly, which represents that the scope of WPT through inductive connection is quite severely restricted. In the below Figure 6, it has a ac source, two coils L_1 and L_2 and resistor R_L. Also, the rectifier, DC to DC regulator, and DC load are all taken into account in this equivalent AC load.

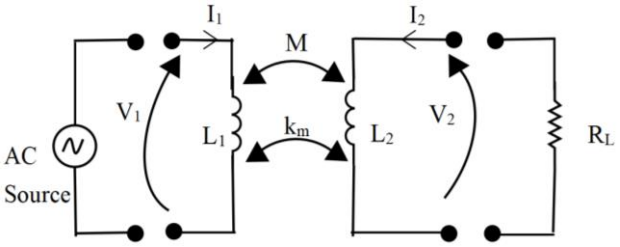


Figure 6. An inductively linked the simple circuit of WPT method [4]

The link indicates the attachment between the secondary and the primary coil power, so it should be maximized. With the goal of enhancing performance in a strongly coupled system, the AC load can be considered as follows to $Q_1=\omega L_1/R_{L1}$, $Q_2=\omega L_2/R_{L2}$, $\alpha=\omega L_2/R_L$, Q_1 and Q_2 are meant as the quality factor of the elementary and subprime network for each, so the maximum is below.

$$\alpha_{max}=Q_2/\sqrt{1+Q_2{}^2+k^2Q_1Q_2} \quad (5)$$

Because of security concerns, particularly regarding the potential for electric field flowing, which increases the possibility of an arc and voltage dissolution, as well as the necessity to run in megahertz and massive inductance, the CPT system is not suited for EV wireless powering. Consequently, the IPT system is able to vary the power over a wider air gap distance [12].

3. Compensation Network

In WPT system, compensation network is connected with the main and another sides which under the electrical resonance. Since the final terminal load of the WPT is always a battery, this needs the unchanged charging current at a low state of charge until the state attaches about 85% before becoming constant voltage charge [13]. Because the couplers only have the inductance, a enormous number of the reactive power is requested to achieve the goal. All of this extra power has to be provided by the inverter, which severely restricts the system's capacity to convey actual power. Therefore, applying compensation network is important to provide the reactive power. As shown in Figure 7, there are four types about the compensation network with inductance and capacitance, which are series-series (SS), series-parallel (SP), parallel-series (PS) and parallel-parallel (PP). Firstly, series-series that is simply called SS, this tuning structure is the only arrangement whose resonant frequency is unaffected by alignment or coupling factor [13]. Then, SP is proved in the constant voltage system no matter what the load resistors are [14]. But, the type of SS and SP have some shortages. For example, the primary inverter's observed impedance reduces in situations involving dislocation or in the absence of a secondary coupler, and the primary DC-link voltage lacks control, the impedance of it will be reduced and even large current is flowing. However, this problem can be solved by the way of PS and PP connection, which only influences in the perfectly alignment [13]. Meanwhile, LCC and LLC configurations are committed to maintain the constant primary coil current so that the secondary voltage is reached. Moreover, these two designs decrease the intricate nature of the control system and the need for feedback communication [15].

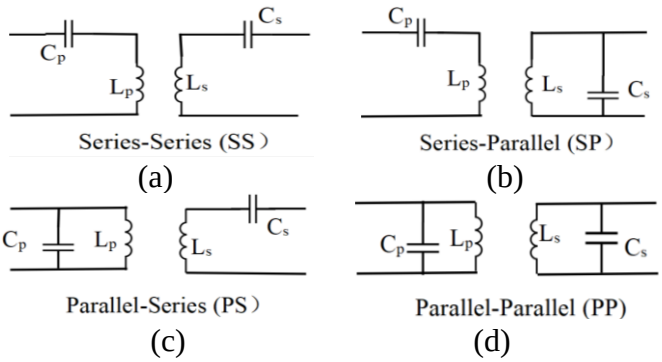


Figure 7. Different compensation network [4]. (a) SS type. (b) SP type. (c) PS type. (d) PP type

Table 1. The comparison of virtues and shortages of three technologies

Technology	Advantages	Disadvantages
IPT	· High efficiency in short-range. · Simple design. · Limits electric field.	· Short distance within a few centimeters. · Limited power transfer.
CPT	· Reduced protection against electromagnetic radiation in hazardous areas. · Reduced size · Cost-efficient. · Great conductivity.	· Difficult construction in heavy capacitors. · Parasitic capacitors will influence the performance of the wireless chargers.
MRC	· Enables more extended ranges of power and data transfer. · Higher power transfer efficiency.	· Design complexity. · Large volume. · More expensive in cost.

4. Comparison

There are some merits and demerits about above three WPT technologies that showing in Table 1. Because the space between the two plates of the capacitors, where the electric field is contained, with regard to magnetic components, capacitive wireless chargers offer superior security. In capacitive WPT, limited electric field that only affects the area where the plates are. This is protecting its emission in the hazardous areas. Also, the cost of it is low and its size is smaller than resonant wireless charger so that it can be more convenient to use. But, it is difficult to build capacitors strongly, especially in the vehicles. In inductive WPT, the design of it is easy, the cost is also low and always needs one orientation power flow. The drawbacks of it is that restricting power transfer. In magnetic resonant WPT, it can convey from hundreds of meters to kilometers distances and within high efficiency. However, it is complicated and expensive to be designed [16].

5. Future Development

The improvement of the WPT technology will be in a high level in the future and its application will also be more common in the every corner of life. For example, on most roads such as lanes and parking lots, wireless charging boards are built in to allow electric vehicles to be directly charged during waiting or parking processes or even not stopping, without worrying about the problem of low battery or short driving distance. But until relatively recently induction charging required closely. So in the next advancements, the distance between induction charging vehicles will be increased, so that electric vehicles can be sensed and charged in advance from a distance away from the area. Besides, smart WPT is becoming a new trend nowadays. The system is combined with clean and renewable energy, combined with energy encryption technology and internet information exchange, to form an increasingly complete block chain in society. Thus, connecting more renewable energy in emerging modern markets and enabling intelligent WPT technology to provide cleaner and safer services for green and smart cities.

6. Conclusion

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