

Energy Efficiency in Inductive Wireless Charging Systems for Electric Vehicles

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Abstract. With the massive appearance of electric vehicles (EVs) around the globe, the demand for more handy ways of charging is increasing sharply, and wireless charging turns out to be one of the most promising solutions. However, the low energy efficiency is one of its crucial limits that impedes its massive application. This passage justifies the significance of improving the energy efficiency of inductive wireless power transfer (IWPT), and then summarize the factors which affect the energy efficiency and ways of improvement through analysis of past literature, reasoning and calculation. It is found that the main influencing factors of energy efficiency include the relative location of coils, the frequency of alternating current which is sent into the primary coil, the design of coils, and the degree of matching between system load and the impedance of secondary coil. Possible ways to improve energy efficiency include decreasing the difference in positions through the use of an automatic device, using alternating current with the appropriate frequency, modifying the design of primary coil, choosing the proper coil, matching of impedance, compensation, using an array of coils, and using a static charging system.

Keywords: Electric vehicle, Inductive wireless power transfer, Energy efficiency.

1. Introduction

With the gradual retirement of traditional fuel cars and the promotion of renewable energy, electric vehicles (EVs) have gained widespread adoption in China and a number of other nations. EVs also own features which fuel cars don't have, such as lower noise, zero pollution, automated driving and the ability to support high-power electronic devices. Overall, EVs require lower cost of energy and maintenance than fuel cars because of simpler engine design and reuse of energy that were wasted by fuel cars when braking. The hot market for EVs brought demand for ways of charging which are more efficient, reliable, safe and convenient than before [1].

Among many possible solutions, wireless charging got the attention of many EV makers. If EVs support wireless charging, users do not need to plug in and out the power plug each time, and therefore problems such as the damage of sockets, electrocution, and pulling lines apart accidentally can be avoided. In the meantime, EVs which support wireless charging do not need physical charging sockets. This offers more space for other important components and decreases the difficulty to manufacture the outer framework of the car.

Despite these benefits, current-existing EVs still rely heavily on wired charging and are equipped with the physical charging socket. One of the factors that impedes the promotion of wireless charging is its relatively low energy efficiency, which leads to waste of energy and increase in the cost of using an EV. As the number of EVs are very large, the waste of energy will increase the burden on national electricity grid. Spontaneously, as EVs are often used by people on a tight budget or used as taxis, the increase in cost might decrease the competitiveness of EVs. The lower energy efficiency may also increase the time spent on charging so decreasing the freedom of using EVs. Thus, energy efficiency must be improved before wireless charging can be massively applied on EVs.

Prior studies have explored numerous strategies for optimizing the energy efficiency of wireless charging systems. However, these may not focus on EVs, and some solutions such as using an array of coils are not universal since other electronic devices have significantly different sizes from a car. In this passage, the basic principle of inductive wireless power transfer (IWPT) is shown first. After that, the importance of improving energy efficiency is justified through calculation. The main factors

that influence energy efficiency, such as the relative location of coils are then discussed. Ultimately, possible ways of improvement, including modifying the design of primary coil, are shown and analyzed. This research is intended to provide a foundation for improving the energy efficiency of EV IWPT technology.

2. The principle of IWPT

Currently, IWPT is the most frequently used category of wireless charging. It is based on electromagnetic induction. The hardware required to achieve this consists of a charging base which is put on a flat plane, the secondary coil and related circuits in EVs. In the charging base, a transformer transforms the alternating current (AC) with common frequency (50~60Hz) from the electricity grid into direct current (DC). The DC is transformed into AC with very high frequency (50~150kHz) by an inverter. This AC pass through the primary coil and a constantly changing magnetic field is generated around the primary coil. In the meantime, electric energy is transformed into the energy in magnetic field. The device which receives energy (EV here) have a secondary coil, in which electromagnetic induction happens, and an induced electric potential is generated because of the change in magnetic flux. Meanwhile, energy in the magnetic field is transformed back into electric energy. After this, another transformer transforms the induced AC into DC with proper voltage, which is charged into the battery after passing through a charging and battery management circuit. In short, this is a process in which the energy undergoes many times of conversion (common frequency AC to DC to high-frequency AC to magnetic field to induced AC to DC) and finally charge the battery. In Figure 1, the rough structure of this system is shown.

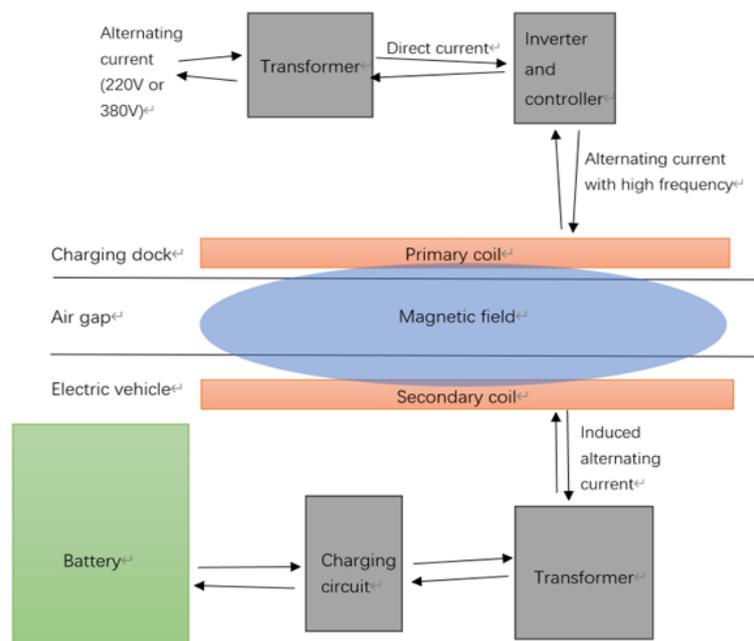


Fig 1. The principle of IWPT

In this passage, energy efficiency refers to the ratio of energy received by the secondary coil to energy sent into the primary coil. The magnitude of energy efficiency is decided by the proportion of energy loss in the coils and during wireless transmission.

3. The importance of improving energy efficiency

Theoretically, the energy efficiency of wireless charging for EVs can reach 90% [2]. However, this may not be reached in practice because of factors such as the misalignment of coils and the imperfect design of coils. In order to measure the influence of energy efficiency roughly, the simplified model below is set up and used for calculation.

Assume that during the whole process of charging, the energy efficiency remains constant. 0.6CNY/kWh is taken as the cost of electricity. 240 kW is used as the power input of the primary coil. If an EV need 120kWh of electricity, the data contained in Table 1 can be got through calculation. Some ideal situations are included.

Table 1. The energy loss and financial loss when charging an EV

electricity needed by the car/kWh	the power input of primary coil/kW	energy efficiency/%	effective power of charging/kW	time spent on charging/hour	energy input of primary coil/kWh	electricity fee/CNY	energy loss/kWh	money spent on the lost energy/CNY
120	240	100	240	0.5	120	72.00	0	0.00
120	240	95	228	0.526	126.316	75.79	6.316	3.79
120	240	94	225.6	0.532	127.660	76.60	7.660	4.60
120	240	93	223.2	0.538	129.032	77.42	9.032	5.42
120	240	92	220.8	0.543	130.435	78.26	10.435	6.26
120	240	91	218.4	0.550	131.868	79.12	11.868	7.12
120	240	90	216	0.556	133.333	80.00	13.333	8.00
120	240	89	213.6	0.562	134.832	80.90	14.831	8.90
120	240	88	211.2	0.568	136.364	81.82	16.364	9.82
120	240	87	208.8	0.575	137.931	82.76	17.931	10.76
120	240	86	206.4	0.581	139.535	83.72	19.535	11.72
120	240	85	204	0.588	141.177	84.71	21.177	12.71

According to these data, 13.3kWh of electricity (which worth 8CNY) is wasted during the whole process of charging when energy efficiency is 90%. Taking the number of existing EVs in the globe into consideration, significant amounts of electricity would be wasted if wireless charging with energy efficiency 90% is applied massively, and financial loss is caused along with this. The burden on the national electricity grid would also increase. Therefore, energy efficiency must be improved before wireless charging can be applied massively on EVs.

4. Factors that affect energy efficiency

The coil pairing s in the electric vehicle and the charging base affects the magnetic coupling coefficient, thereby significantly influencing energy efficiency. The vertical distance also impacts the degree of wave attenuation. Generally, closer proximity and improved alignment of the coils directly result in higher efficiency.

For the same type of transmitting coil, the frequency of the alternating current supplied to the coil has a notable impact on energy efficiency, and the optimal frequency varies for different coils. For the same coil, the most suitable alternating current frequency also changes depending on the horizontal misalignment between the transmitting and receiving coils. For example, when using a DDC-type transmitting coil with a horizontal misalignment of 15 mm, an AC frequency of 105 kHz can achieve energy efficiency close to 1, whereas an AC frequency of 80 kHz results in energy efficiency below 0.8 [3].

Additionally, the frequency of the alternating current input to the transmitting coil directly affects energy efficiency. Matching the frequency with the resonant characteristics of the coils optimizes energy transfer and can achieve efficiencies ranging from 50% to 90%. Studies report that a self-resonant frequency around 3.3 MHz yields optimal coil performance, while in a coupled coil configuration, an efficiency of 82.26% was achieved at 130 kHz [4].

Some research indicates that systems operating at 13.56 MHz can achieve 90% efficiency at a distance of 1 meter, and with impedance matching, efficiency improves from 50% to 70% at 2 meters (Beh et al., 2010). This study emphasizes that proper resonance and impedance matching are critical for enhancing efficiency. Simulations demonstrated that adjusting the resonant frequency through an impedance matching (IM) network significantly improves energy efficiency [5].

For electric vehicles, constraints imposed by existing power supply system make it challenging to achieve ideal AC frequencies and coil alignment, thereby limiting energy efficiency. In such cases, optimizing the design of the EV coil becomes a more viable solution. Research has confirmed that the design of the transmitting coil influences energy efficiency [6]. At vertical distances greater than 75 mm, double-D-type transmitting coils exhibit higher maximum energy efficiency compared to circular and DDC-type coils. When horizontal misalignment exceeds 40 mm, DDC-type transmitting coils demonstrate superior maximum energy efficiency over circular and double-D-type coils.

The efficacy of impedance matching between the load and receiver coil thus determines the overall energy efficiency by minimizing reflection losses.

5. Possible methods to improve energy efficiency

The optimization of energy efficiency can be primarily achieved through reducing the distance between coils, employing alternating current at an appropriate frequency, optimizing the design of the transmitting coil, impedance matching, compensation techniques, multi-coil arrangements, and utilizing static charging systems.

To achieve and maintain precise positional alignment between the vehicle and charging base coils, a set of programs or mechanical devices can be installed on both the electric vehicle and the charging base. For example, the charging base can be designed with a movable mechanism: after the vehicle parks and sends a charging request, the internal system of the base senses the coil alignment and automatically adjusts the transmitting coil to an optimal position before initiating charging. Quantitative reports indicate that using a DDC transmitting coil with an AC frequency of 110 kHz, when the air gap is narrowed from 55 mm to 15 mm, the energy efficiency can increase from approximately 0.6 to nearly 1 [7].

Based on the type of transmitting coil it carries and the horizontal misalignment between the coils, the charging base should supply the transmitting coil with an alternating current at an appropriate frequency to achieve the highest energy efficiency.

Optimizing the design of the transmitting coil contributes to improved energy efficiency. Simultaneously, when designing electric vehicles and charging bases, it is essential to thoroughly understand the characteristics of different coil types and select coils that meet practical requirements.

Literature also provides various methods to enhance energy efficiency, such as impedance matching, compensation techniques, and multi-coil arrangements. Among these, impedance matching systems can mitigate issues caused by variations in system load and resonance deviations, while also improving the coupling coefficient. Compensation techniques involve adding equivalent capacitive reactance to the circuit to reduce or even eliminate the highly inductive reactance of the coils. Using multi-coil arrays instead of a single coil can enhance tolerance to positional misalignment, thereby maintaining higher energy efficiency than single-coil systems when misalignment is significant.

For electric vehicles, static charging systems exhibit higher energy transfer efficiency compared to dynamic systems due to fewer variations in distance. Research on dynamic wireless charging indicates that with advanced control and hardware adjustments, highly efficient wireless energy transfer can also be achieved [8]. Frequency retuning and segmented coil activation can improve efficiency by up to 6%, and under precise alignment conditions, segmented coil activation technology has achieved over 90% efficiency in a 25 kW system. Other techniques, such as neural network-based optimization of double-sided orthogonal ferrite coils, have reached peak efficiencies of around 95%. Although material innovations have not quantified specific gains, they have been proven to significantly enhance performance [9]. In static charging systems, the introduction of multiple magnetic bars in the coil layout to regulate magnetic flux distribution—known as magnetic flux shaping technology—can markedly optimize system energy efficiency [10].

6. Conclusion

Given the significant economic potential of wireless electric vehicle (EV) charging systems, this study leverages a systematic literature analysis to identify key factors influencing energy efficiency, including the transmitter-receiver coil misalignment, operating frequency, coil design parameters, and proper impedance matching between the receiver coil and the load.

Specifically, A variety of methods exist for optimizing energy efficiency, including reducing the vertical distance and horizontal misalignment between the two coils, supplying the transmitting coil with an alternating current of appropriate frequency, optimizing the design of the transmitting coil, selecting suitable coils, implementing impedance matching, applying compensation techniques, utilizing multi-coil arrays, and promoting mature static charging systems for electric vehicles.

This study provides insights and feasible solutions to address the energy efficiency challenges of inductive wireless charging for electric vehicles, contributing to the practical application of this technology and offering greater convenience to users.

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