Optimization of structure and control strategy for EV wireless charging systems

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Abstract. Low efficiency is the key factor restricting the development of EV wireless charging systems in recent years. In order to improve the efficiency, the main circuit of the system is simplified by removing the DC/DC circuit and replacing full bridge inverter with half bridge inverter. And the output power control strategy is optimized by changing the duty cycle of PWM that controls the inverter. Besides, the peaks are reduced by changing the frequency of the system, and the output power can also be controlled by changing frequency. The performance of two most common magnetic couplers is compared and a direction of how to select couplers is given. The methods are all verified by simulations and experiments. By optimizing of the circuit and control strategy, the efficiency and the safety of the system are all improved.

1. Introduction
As for EV charging, wired charging is the most common at present. But compared to wireless charging, wired charging has a lot of weaknesses and deficiencies. For example, aged charging cable will endanger personal safety, and wired charging cannot realize charging automation and intelligence. But wireless charging works through a magnetic field between two coupling coils, and without direct electrical connection, which can be controlled intelligently and automatically, and electric shock can also be effectively avoided [1-3].

Although wireless charging has many advantages, the emerging technology is immature and there are also many problems to be solved. One of the biggest problems is the low efficiency. To increase the efficiency, many researchers have done some relevant works. Series resonant capacitive circuit and ZCS (Zero current switching, ZCS) have been designed to minimize converter switching losses [4]. Zhao \textit{et al} [5] developed a method called phase-shift control to alleviate change of efficiency when input power changes. Zeng \textit{et al} [6] and Zhang \textit{et al} [7] optimized the magnetic core structures by FEM simulation and experiments, reducing the weight of the magnetic couplers as well as improving the efficiency, and Zeng \textit{et al} [6] proposed a method of optimizing the core structure. The copper losses are analysed in [8] in order to reduce the losses in the coupler. A converter based on SiC-topology is introduced in [9], but its efficiency is a little bit low (85%). Deng \textit{et al} [10] took a novel topology of a phase-controlled inverter and put it in a wireless charging system.

The low efficiency of the wireless charging system is mainly caused by the complexity of the circuit and low coupling coefficient. Thus, this paper will improve the efficiency by simplifying the
circuit and optimizing the control strategy, which can reduce the number of devices and the impact of switching tube. Besides, choosing the best magnetic coupler by FEM simulation to achieve bigger coupling coefficient is also important.

2. Circuit simplification

2.1. The classic circuit design

Figure 1 shows a most common control circuit of transmitting coil, which mainly includes four parts: Rectifier bridge, PFC (Power Factor Corrector, PFC), buck-circuit and full bridge inverter.

![Figure 1. A classic circuit design of transmitting terminal of a wireless charging system.](image)

The function of Buck-circuit is to control the output power of the wireless charging device by changing the duty cycle of the PWM waves. As shown in figure 1, the inverter is also controlled by the PWM, So if it is feasible to control the output power by controlling the duty cycle of the PWM that controls the inverter circuit, then the Buck-circuit can be discarded and the circuit is simplified.

Besides, as for inverter circuit, both full bridge inverter and half-bridge inverter can be used in charging system. It is necessary to explore their distinctions and try to use the half-bridge circuit mainly to reduce power consumption and devices used.

2.2. The simplified circuit and simulation

At first, the feasibility of removing DC/DC is researched by simulation. The toolbox called Simulink in MATLAB is used. Figure 2 shows the circuit without DC/DC, and figure 3 shows the connection type of capacitance and inductance. Figure 4 shows one of the simulation models in Simulink. With the same input and load, the efficiency curves and output power of the two circuits are shown in figure 5.
Figure 4. The simulation model without DC/DC in Simulink.

Figure 5. Changes in output power and efficiency when duty cycle of the inverter is changed.

The load in simulation is 48 V, 24 Ah lithium battery. The DC voltage is 311 V, which is equal to the output voltage of single-phase (220 V) rectifier. The frequency of PWM that controls inverter is 85 kHz. As shown in figure 5, when the duty cycle varies between 0.1 and 0.5, the output power varies from 150 W to 800 W, which means, it is practicable removing the DC/DC. Besides, the efficiency is measured at t = 0.04 s, and the comparison of efficiency in figure 5 illustrates that removing DC/DC can improving the transmission efficiency.

From figure 4 and figure 5, the max output power is achieved when duty cycle is 0.5. Thus, if the max output power is not enough for the load, a Boost circuit is still needed to increase the output power.

Figure 6 shows the voltage and current waves of L1 when duty cycle is 0.2 and 0.5, respectively. With DC/DC, the duty cycle of the inverter circuit is always equal to 0.5 and the voltage and current waves are shown in figure 6(b). But if the duty cycle is changed to 0.2, the waves will be distorted (shown in figure 6(a)). So it is necessary to test it in experiment and make sure that the peak does no harm to the system.
Figure 6. Voltage and current of L1 when duty cycle is different.

(a) Duty cycle=0.2

(b) Duty cycle=0.5

Figure 7. Circuit with half bridge inverter.

Figure 8. Performance comparison of circuit with full bridge inverter and half bridge inverter.

Then the full bridge inverter is replaced by a half bridge inverter, as shown in figure 7. Then, with the same input and load the simulation results are obtained and the curves about output power and
efficiency are shown in figure 8.

From the comparison shown in figure 8, the efficiency of circuit with half bridge inverter is higher. However, its output power is just about half of the full bridge circuit. Thus, half bridge circuit can be used in low-power situations.

3. Optimization of control strategy

As shown in figure 3, usually compensation capacitor is resonant with inductor in order to achieve maximum transmission power [11]. Thus, in SS (series-series connection) topology, the relationship

$$\omega L = \frac{1}{\omega C} \quad (1)$$

is workable. Then, the frequency $f$ is

$$f = \frac{1}{2\pi} \frac{1}{\sqrt{LC}} \quad (2)$$

And the output active power

$$P_{out} = I_s^2 R_L = \left( \frac{\omega MI_s}{R_s + R_L} \right)^2 R_L \quad (3)$$

In EV wireless charging system, the output power is generally controlled by adjusting the duty cycle of the PWM. But the relative position of transmitting and receiving coils is varied as the position of EV is not stationary. Thus, when the position of car is changed, and the receiving coil is off-center, mutual inductance $M$ will be decreased and equation (1) will be no longer valid. At this time, if improving the output power by adjusting the duty cycle of PWM, peaks will be enlarged on the output voltage waveform of inverter (shown in figure 9), and efficiency will be reduced. As shown in figure 9, the “Over” means overshoot. Then a new way to adjust the output power is come up with, which is frequency adjustment.

![Figure 9](image_url)

Figure 9. The enlarged peaks on inverter’s output voltage.

3.1 Frequency adjustment to alleviate the peak

In EV wireless charging systems, when the receiving coil with no misalignment, the transmission power and efficiency will be maximum, and the impact will be minimal. This is because that inductance and capacitance resonate exactly at this time. But as the receiving coil with misalignment, mutual inductance $M$ will be decreased and equivalent inductance will be reduced. So, the circuit is capacitive and there is no stream current when MOSFETs switch, which leads to larger peaks.

Solutions to the problem are to re-calculate the resonant frequency using equation (2) and change it by MPU. But we always don’t know the change value of inductance, so higher frequency is set to
alleviate the peaks as the circuit is inductive. And then change the frequency closer to the resonant frequency step by step.

The method described above is realized by MPU called STM32F103ZET6 in experiment, which realizes the peaks reduction and efficiency improvement.

![Figure 10](image1.png)

**Figure 10.** The peaks comparison when the circuit is capacitive and inductive. (a) The output voltage and current of inverter when the circuit is capacitive; (b) The output voltage and current of inverter when the circuit is inductive.

As shown in figure 10, peaks in inductive circuit are smaller than in capacitive circuit. Thus, frequency adjustment is necessary to insure the safety of the circuit.

### 3.2. Frequency adjustment to adjust the output power

From equation (3) the output power is influenced by frequency. So, if the output power can be adjusted by changing frequency, there will be another reason to remove DC/DC. In order to let the circuit work in inductive condition, the frequency must be higher than resonant frequency. The experiment results are shown in figure 11.

From figure 11, the method changing frequency to adjust the output power is workable. As the output power changes, the efficiency decreases slightly, which conforms with reality. So, frequency adjustment has little influence on efficiency, which means the output power can be adjusted by changing the frequency, and the method can relieve the peaks.

![Figure 11](image2.png)

**Figure 11.** Changes in output power and efficiency as the frequency changes.

### 4. Optimization of magnetic coupler

There are so many different kinds of magnetic couplers in EV wireless charging systems. An ideal coupler is hoped to have high coupling coefficient and light weight, as well as good performance when
misalignment occurs. At present the most commonly used are the circular magnetic coupler and DD coils. In this section, the performance of circular coils and DD coils is compared.

Supposing k represents the coupling coefficient, the coupling coefficients of circular coils and DD coils with different misalignments are shown in figure 13, which is analysed by FEM simulations.

![Figure 12. The most commonly used couplers. (a) circular magnetic coupler; (b) DD coils.](image)

![Figure 13. The performance of circular coil and DD coil.](image)

From figure 13, when the receiving coil has no misalignment, the coupling coefficient is almost the same. But when misalignment is increased, the coupling coefficient of circular coils is falling faster than DD coils. Thus, the DD coils are much better applying in EV wireless charging systems.

5. Conclusion
In order to improve the efficiency of EV wireless charging system, DC/DC converter of the main circuit is removed and the output power control is realized by adjusting duty cycle of PWM that controls the inverter. Feasibility of this method is verified by simulation by a toolbox called Simulink. Besides, the full bridge inverter is replaced by half bridge inverter, but the limitation of the change is that circuit with half bridge inverter has a lower output power. With the two methods above, the frequency has been improved a lot.

To alleviate the peaks and insure safety as well as improve the efficiency, frequency adjustment is comp up with and by changing the working frequency of the system, the peaks are smaller and output power control can also be realized, which is verified by experiments.

At last, the two most common couplers are compared by FEM simulation. The conclusion is that the performance of DD coupler is much better than circular coupler, and DD coils are more suitable for EV wireless charging systems.
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