Study of Applying Contactless Power Transmission System to Battery Charge

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Abstract -- Contactless power transmission system with the advantages of safety and convenience has been applied to daily supplies. However, general contactless power transmission charger cannot control the current cause there is no charge controller in secondary side and the severe limitation between primary and secondary sides of the battery charger cause difficulty to design. This study provides the charge controller with half-bridge inverter and E-Type core as coupling converter in primary side; A Zeta DC converter is utilized to achieve the outcome of charge with constant voltage and to increase the charging distance between primary and secondary sides. To verify the feasibility of contactless power transmission system, the study completes the contactless charger with the output power of 30W. The result shows that the overall system efficiency is 57.8 % with 150 V/ 0.35A input and 15.2 V/2 A output.

Keywords -- Contactless Power Transmission System, Zeta converter, charge controller

I. INTRODUCTION

The technology advances significantly. In recent years, the research has been concentrating on the applications in relation to our daily life. The demand of many portable electronic products such as notebook, PDA, cell phone, digital camera, MP3, etc. is getting more and more.

The power for portable electronic products is supplied by the secondary battery which is rechargeable. The charge method is classified into metal contact and non-metal contact depending on the ways of power transmission. The charge system of most household appliances mainly applies traditional contact chargers. However, each type of portable electronic products needs to use their specific charger to charge the built-in batteries. Each charger requires a power converter to transform power into DC suitable for charging. Different types of chargers are not compatible with each other, which directly causes a waste of chargers and environmental pollution. In addition, too many chargers cause the inconvenience in identifying them and portability to users.

Contactless power transmission system adopts induction to transmitting power. Electromagnetic induction generates inducted power. Such method doesn’t have contacts between conductors. By considering the safety upon operations, contactless power transmission technology is more advanced than contact power transmission system.

Currently, among the chargers applied to contactless power transmission system, there is no charge controller with DC converter in the secondary sides. In addition, there is stricter limit in the distance between a charger and the primary sides. Based on the above reason, this paper will discuss the application of contactless power transmission to charge controllers. A contactless charger compatible with other chargers is designed so as to achieve charging at constant voltage. Furthermore, the charge distance between a charger and the primary side can be increased. With such design, the electronic products with contactless power transmission will become advantageous in the market.

II. LITERATURE REVIEW

Among the literature proposed so far, the structure consisting of converter, compensated circuit in the primary and secondary sides, inductive transformer and DC converter is most commonly seen. The structure of contactless power transmission system is shown in Fig. 1.

![Fig. 1. Structure of Contactless Power Transmission System](image)

The basic principle of contactless power transmission system is to use electromagnetic induction to implement transformation of electric energy and magnetic energy between two coils. First, alternating current is input at the primary-side coil to generate alternating magnetic field. Then, the secondary-side coil receives the magnetic field to transform it into utilized power and complete the transmission of contactless power.

Currently, overseas studies focused on the technologies and theories relating charge with contactless power transmission have reached a certain level. The topics discussed cover electric energy converter, improvement on converting efficiency, coupling transformer’s relationships with different winding positions, clearances, deviations and coupling inductivity. For example, Choi et al. produced a charger applied to a cell phone by using PCB winding design in 2004. [1] Liu proposed the structure of multiple-layer array to a multi-purpose charging platform. [2] In 2005, Hui used a multi-purpose contactless battery charging...
platform designed with multiple-layer hexagonal spiral PCB coil. [3] In 2007, Kuo et al. suggested to use contactless charging equipment with full-duplex. [4] The above mentioned studies focused on the primary-side control for contactless chargers. Less studies and production have been made on the secondary-side charging control for contactless chargers.

Therefore, the research and production of the charger for this paper are mainly focused on charge control circuit at contactless secondary side.

The efficiency of contactless power transmission system is lowered when the air gap for the primary side and secondary side increases. Consequently, the distance of power transmission is limited. There are two ways to increase the power transmission distance. One is to increase the output at the primary side. However, current efficiency for contactless power transmission system is not high. Therefore, the increase of output at the primary side is just a waste of power. The other way is to adopt the structure proposed by this paper. That is to use boost/buck converter at the secondary side. When the input voltage is higher than that required by a charger under operation, the converter can help to control the output current at a constant current. Contrarily, when the converter voltage is lower than the battery voltage, the boost converter can be used to increase the output voltage to that required by the working battery.

However, such way only focuses on increasing power transmission distance. When the charger at the secondary side is far away from the primary side at a certain distance, it cannot induct voltage and no charge can be done accordingly. [5]

The primary side for contactless power transmission system applies a converter to achieve alternating current for output. The use of half-bridge converter is the commonest which is not only two power switches less than a full-bridge converter but also suitable for the application in lower power supply. As a result, this paper chooses half-bridge converters.

As to the selection of an induction transformer, it is considered to use E-type iron easy to obtain so as to design and implement the coupling transformer required by this paper.

Finally, the secondary-side converter in the contactless power transmission system applies Zeta DC converter as the charging circuit. A micro-computer is used to control the current and voltage to a constant level for charging.

A. Circuit design with half-bridge resonant converter in series connection

The circuit structure of half-bridge resonant converter in series connection is shown in Fig. 2. This structure includes two capacitors and two switches. In addition, a capacitor Cr in series connection before the primary side of the induction transformer. Such connection aims at generating resonance so as to create the resonant frequency similar to the operating frequency of the switches. It further generates induction, voltage of a capacitor and current wave form close to sinusoidal wave and makes the output become voltage source [6].

![Fig. 2. Half-bridge Resonant Converter in Series Connection](image)

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III. PREPARE YOUR PAPER BEFORE STYLING

The system design of this paper includes three parts: half-bridge resonant converter with contactless power transmission, Zeta DC charging circuit and a micro-computer charge controller.
bridges. Therefore, the design applying IR2110 as gate circuit separating driving circuit can help input the two sets of PWM control signals generated by TL494 to IR2110 and then to generate the driving signals at upper and lower bridge.

Fig. 4. Half-bridge Converter Circuit

Fig. 5 shows the resonant compensated circuit diagram for half-bridge converter. The primary and secondary resonant compensated circuits adopt the structure of the primary-side compensation in series connection and the secondary-side compensation in parallel connection [7].

Fig. 5. SP Resonant Compensated Circuit Diagram.

B. Design of Zeta DC Charge Controller

Zeta converter is a buck/boost converter. It consists of Buck-Boost-Buck pattern. The circuit structure of a Zeta converter is shown in Fig. 6. When the power switch M1 is in conduction, Vr will charge L1 and iL1 will gradually increase until VL1 voltage equals to Vr. At the same time, C1 is charging L2 and iL2 will gradually increase until VL2 voltage equals to Vr. When the power switch M1 is off, the induced L1 will change the direction of magnetic field based on Faraday Principle. Therefore, the voltage pole reverses. Then L1 will discharge the capacitor C1. With the same principle, the induced L2 discharges its load. At the same time, iL1 and iL2 display the decreasing trend until the power switch is conductive again. If the power switch cannot be conductive in time, then iL1 and iL2 will drop to zero and go into the consecutive conduction mode. Based on the principle of circuit operation, all power transmission has to pass through C1 which will bear great charging/discharging current. Therefore, attention should be paid to the selection of a capacitor. [8], [9]

The charge controller described in this paper works under a continuous mode. Under a stable and continuous conduction mode, we can obtain the input/output voltage conversion rate of a Zeta converter from the following formula:

\[
\frac{V_o}{V_i} = \frac{D}{1-D}.
\]  

(2)

D stands for Duty cycle. When the duty cycle is smaller than 0.5, the converter acts as a buck type. Contrarily, the converter acts as a boost type when the duty cycle is bigger than 0.5. First, let’s define ripple current rate of an inductor:

\[
r = \frac{\Delta I}{I_{L,AVG}}. 
\]  

(3)

\(\Delta I\) : stands for the peak-to-peak value of inductor current

\(I_{L,AVG}\) : stands for the average value of inductor current

For achieving \(r=0.4\) under the conditions that Zeta converter operates in continuous mode and under maximum load, the following design is based on the condition of \(r=0.4\) as reference:

1) Selection of \(L_1\) and \(L_2\) Inductors:

\[
L_1 = L_2 = \frac{V_{i,\text{max}} (1 - D_{\text{min}})}{I_o \cdot r \cdot f}. 
\]  

(4)

\(V_{i,\text{max}}\) : maximum input voltage

\(D_{\text{min}}\) : minimum working cycle

\(I_o\) : nominal output current

\(f\) : switching frequency

2) Selection of \(C_1\) Capacitor:

\[
C_1 = \frac{I_o \cdot D_{\text{max}}}{V_r \cdot f}. 
\]  

(5)

\(V_r\) : continuous waves of output voltage

\(D_{\text{max}}\) : maximum working cycle

3) Selection of power switch \(M_1\) and diode \(D_1\):

\[
V_{M1} = V_i + V_o 
\]  

(6)

\[
V_{D1} = V_i + V_o 
\]  

(7)
4) Effective value of current input to capacitor $C_i$:

$$ I_{c_i}^{rms} = \frac{D}{1 - D} I_o \sqrt{D\left(1 + \frac{r^2}{12} - D\right)}. \quad (8) $$

5) Effective value of current output to capacitor $C_o$:

$$ I_{c_o}^{rms} = I_o \sqrt{\frac{r^2}{12}}. \quad (9) $$

Based on system requirements, select suitable element values obtained from formula (2) ~ (9) in order to prepare the charger [8-10].

The charge controller mentioned in this paper consists of 4 parts: Zeta DC charge circuit, single chip PWM control circuit, optical coupling separation circuit and gate driving circuit. The main circuit of the charger supplies power energy after secondary-side rectification and filtering of the contactless transformer. The power passes through Zeta converter to boost/buck voltage for the use of battery charge.

The driving circuit for the upper-arm power switch of the Zeta DC converter has a different ground level from that of Zeta converter. For ensuring that the power switch can operate normally, it is necessary to use optical coupling isolation circuit to isolate the system ground. Though the power activated for turning the power switch is little, the influence of the capacitor at the gate source end on the power switch will be greater peak current upon on and off of the power switch. The optical coupling isolating circuit and gate driving circuit diagram is shown in Fig. 7.

Zeta charge controller circuit diagram is shown in Fig. 8. The Zeta charger circuit prepared by this paper reaches a constant current and constant voltage through micro-computer controller so as to make charge control and boost/buck voltage control. When the charge controller approaches to the primary-side charge base, the micro-computer picks up Zeta input voltage to determine if it will start charging. Upon starting charging, the micro-computer determines the constant charge current by referring to the charge current. In the meantime, the micro-computer also picks up the battery voltage to determine if it is overcharging. If it reaches the critical charge voltage, it will become the mode of charge at a constant voltage. Finally, the battery is fully charged under the constant voltage if the charge current is detected below 0.01C. The indicator lights up to inform a user that the battery is fully charged. The micro-computer charge controller is shown in Fig. 9. The flow chart of micro-computer charge control design is shown in Fig. 10. [11]

IV. SYSTEM TEST AND RESULT

There are two parts in the test of contactless charge controller. One is half-bridge resonant converter, and the
other is Zeta DC converter. The design specifications are listed in TABLE I.

### TABLE I

**DESIGN SPECIFICATIONS OF CONTACTLESS CHARGE CONTROLLER**

<table>
<thead>
<tr>
<th>Component</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loosely Coupling Transformer</strong></td>
<td></td>
</tr>
<tr>
<td>Coupling coefficient</td>
<td>( k = 0.68 )</td>
</tr>
<tr>
<td>Operation frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Primary side self-inductance</td>
<td>( L_p = 1 ) mH</td>
</tr>
<tr>
<td>Secondary side self-inductance</td>
<td>( L_s = 13 ) uH</td>
</tr>
<tr>
<td>Primary side leakage inductance</td>
<td>( L_{lk} = 575 ) uH</td>
</tr>
<tr>
<td>Resonant frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>Primary side compensated capacity</td>
<td>( C_s = 47 ) nF</td>
</tr>
<tr>
<td>Secondary side compensated capacity</td>
<td>( C_p = 0.3 ) uF</td>
</tr>
</tbody>
</table>

| **Zeta Converter**               |                        |
| Switching frequency              | \( f = 31.25 \) kHz    |
| Inductance L1                    | 300 \( \mu \) H        |
| Inductance L2                    | 300 \( \mu \) H        |
| Capacitor C1                     | 10 \( \mu \) F         |
| Input capacitor Ci               | 220 \( \mu \) F        |
| Output capacitor Co              | 330 \( \mu \) F        |
| Output current                   | 2 A                    |
| Output voltage                   | 15 V                   |
| Duty cycle                       | 13 %                   |

The input voltage of the half-bridge resonant converter of this system is DC 150 V and its current is 0.35 A. Fig. 11 shows the input voltage and current waveforms of half-bridge resonant current converter with the voltage at 75.3 V and the electric current at 1.243 A. The Fig. 12 demonstrates the voltage and current waveforms of the secondary-side resonant tank in parallel connection of the induction transformer. The measured voltage is 69.62 V, and the electric current is 13.54 A; therefore the efficiency of half-bridge resonant converter is 75 %. The input voltage and waveforms of Zeta charge controller is shown in Fig. 13. The input voltage is 63.47 V and the input electric current is 627 mA. The voltage and current waveforms of Zeta charge converter is shown in Fig. 14. Its output voltage is 15.19 V and the output electric current is 2.13 A. Therefore, the efficiency of Zeta charge controller is 81.23 % and the whole efficiency of contactless charge controller is 61.57 %. The efficiency of the contactless charge controller at each level is shown in TABLE II.

### TABLE II

**Efficiency of charge controller with contactless power transmission system at different levels**

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Overall Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half-Bridge Converter</td>
<td>75 %</td>
<td>61.57 %</td>
</tr>
<tr>
<td>Zeta Converter</td>
<td>81.23 %</td>
<td></td>
</tr>
<tr>
<td>Charging System</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 15 and Fig. 16 show the voltage and current waveforms upon induction and power switch when Zeta converter is charging. The comparisons of various conditions of contactless charge controller by air gap are shown in Table III. The system input voltage is controlled at DC150V. The comparisons of the test of the charge gap show that even though the air gap is bigger this system can still reach a charging condition at constant voltage. The picture of a contactless charge controller prepared by this paper is shown in Fig. 17.
V. CONCLUSIONS

The contactless charge controller in this paper is prepared based on contactless power transmission and a Zeta DC converter with charge controller. The following conclusions have been obtained through theoretical analysis and test results: contactless charger adding a controller at secondary-side charger will reach a constant current and constant voltage for charging. Such structure prolongs the battery life. Finally, the charge controller with nominal output power at 30W is substantially completed so as to verify the feasibility of contactless charge controller proposed by this paper.

REFERENCES


