Wireless Super-capacitor Charger for Linear Motion Transportation

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Abstract. This paper proposes a wireless super-capacitor charger for linear motors. The SS compensation method is used in the wireless power transfer (WPT) stage; a four-switch buck-boost converter is applied as the dedicated charging stage for the ultra-capacitor. Current-mode control is designed for the primary side of the WPT charger, which is modulated with phase-shift PWM. On the secondary side, a multi-loop control scheme is developed, which is targeted to regulate three variables, the rectifier output voltage, the inductor current, and the output capacitor current. In order to realize the maximum transfer efficiency of the WPT charger, multi-factor tests are performed to investigate the optimal operation point of the WPT system; finally, the multi-loop control algorithm is implemented in the prototype perform the super-capacitor charging from 0V to the targeted full bus voltage.

1. Introduction

Transportation sector consumes significant amount of energy in each country [1]. For example, the share of total U.S. energy used for transportation went up to 29% in the year of 2017. Typically, the total energy use in transportation is by the passenger and road freight vehicles which consumes fossil fuels such as diesel and gasoline. But this percentage is subjected to decrease due to the increasing concerns on the environmental impact from the burning of the fossil fuels. However, the share parity between electric vehicles and fossil fuel vehicles are not yet to come due to certain definite advantages of the fossil fuel solution. One the other hand, rail vehicles are dominated by electric propulsion due to increasing urbanization in some of the Asian and European countries, as indicated in Fig. 1.

For the choice of transportation mode, the rail mode tends to increase for the coming years in China [2]; not only the high speed rail, the cities with total regional population over 5 million prefer metro or light rail solution for public transportation, which helps promote technologies development around the rail systems.

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Catenary based power supply solution is widely used for the high speed train across the city and regional boarder. In the urban areas where catenary tower and wire are difficult to set up, on board energy storage will be a good solution. The super-capacitor is a good candidate for energy storages in the tram due to the intermittent operation of the tram. For the stop-charge-go operation, wireless power charging is a flexible solution.
References [6-16] proposed WPT applications from low power electronics to heavy industry, where the WPT technologies for roadway powered vehicle are extensively studied and ground breaking achievement has been achieved. In the aforementioned applications, the converter switching frequency is limited below hundreds of kilohertz for loss control purpose. Ferrite structures are widely used in the literature to facilitate energy transfer and to protect against magnetic flux irradiation. Reference [12] studied the alignment issues in inductively coupled CPT application by passively compensating for leakage inductance. Reference [13] eliminated misalignment problems through a carefully designed guide rail structure.

A wireless super-capacitor charger for linear motional transport (TRAM) is proposed in this study. The SS compensation method is used the wireless power transfer (WPT) stage; a four-switch buck-boost converter is applied as the dedicated charging stage for the ultra-capacitor. Current-mode control is designed for the primary side of the WPT charger, which is modulated with phase-shift PWM. On the secondary side, a multi-loop control scheme is developed. In order to realize the maximum transfer efficiency of the WPT charger, multi-factor tests are performed to investigate the optimal operation point of the WPT system; finally, the multi-loop control algorithm is implemented in the prototype perform the super-capacitor charging.

2. Wireless Power Transmission System Structure Design

The on board super-capacitor is used as the energy storage. The wireless power transmitter is placed on each tram stop. When the tram is detected by the position sensors, the transmitter is engaged in power transfer. The proposed WPT system with the super-capacitors load is shown in Fig. 2.

![Diagram of Modern tram system wireless power transmission system](image-url)
3. Modeling and Simulation of Wireless Power Transmission Circuit

The system schematic is shown in Fig. 3. As indicated by the power stage arrangement. The system can be decoupled by the secondary rectifier output capacitor $C_f$. Therefore, for control purpose, two stages can be designed separately. The full bridge inverter is modulated by phase-shift PWM signals, which modulate the output voltage RMS value. By properly modulate the primary side switched, the maximum power transfer can be easily controlled. On the secondary side, the 4-switch buck-boost converter is modulated using duty cycle PWM for Q1, Q4 and Q2, Q3 pair.

The equivalent circuit of the SS resonant can be expressed as in Fig. 4. It is not difficult to find the energy transfer efficiency as shown in Eq. (1); given the operation constraint of the frequency shown in Eq. (2), the current transfer ratio between the input current $I_1$ and output current $I_2$ can be obtained in Eq. (3), where the $\omega_0$ is the angular frequency of the system. One can find that the maximum power transfer efficiency of the wireless coupling network can be found as in Eq. (4)

$$
\eta = \frac{I_2^2R_L}{I_1^2R_L + I_1^2R_2 + I_2^2R_L} = \frac{R_L}{(R_L + R_2)\left(1 + \frac{R_L\left(R_2 + R_L\right)}{\omega_0^2M^2}\right)}
$$

$$
f > \frac{R_L\left(R_L + R_2\right)}{M^2}
$$

$$
\frac{I_1}{I_2} = \frac{R_L + R_2}{\omega_0M}
$$
\[
\eta_{MAX} = \frac{R_L}{R_L + R_2}
\]  

(4)

### 3.1 Primary Side Control Structure

To limit the maximum power processing capacity, the primary RMS current is controlled to be a constant value. The control block diagram is shown in Fig. 5. A conventional PI controller is used. The current is sensed and converted to the mean value using the combination of a current transformer, a rectifier and a low pass RC filter. The current controller \( C_{i1}(s) \) generates the phase-shift angle to drive the power stage.

![Fig. 5. Primary side constant current control block diagram](image)

### 3.2 Secondary Side Power Adjustment Control Structure

A secondary dc-dc charger is to provide dedicated and real time management to the super-capacitor bank due to its terminal voltage and current is undergoing swing. For example, when the super-capacitor is fully discharged, its terminal voltage is zero while the charging current has to be controlled in upper limit value to guarantee quick restoration of the charges. As the charging process proceed, the super-capacitor terminal voltage rises and the charging rate shall be tuned down gradually to minimum when entering the trickle charging phase.

The secondary side control block diagram is shown in Fig. 6. The rectifier output voltage is set as the outer loop reference as the previous study indicated the secondary side DC voltage contributed to the power transfer. The internal variable generated by the voltage controller \( C_{vin}(s) \) is used as the inductor current limit value for the inner current loop.

![Fig. 6. Secondary side power adjustment control block diagram](image)

Small signal analysis is used to calculate the secondary side power adjustment control transfer function.
3.3 Wireless Power Transmission System Simulation

The simulation of this system is built in MATLAB/SIMULINK. During the super capacitor group charging process, the primary voltage is set at the same value. The inductor current decreases with the rising output voltage of the DC/DC circuit. The output voltage is controlled by the PI controller and the output value becomes smaller. When it reaches less than the setting current, the duty cycle output is switched until the output voltage stabilizes at 25V and the average inductor current is zero.

\[
G_{\text{wind}}(s) = \frac{G_{\text{wind}}(s)}{G_{\text{red}}(s)} = \frac{\bar{u}_{m}(s)}{\bar{d}(s)} = \frac{\bar{u}_{e}(s)}{\bar{d}(s)}
\]

\[
= \frac{I_L \cdot L \cdot s - U_{\text{in}}}{D - D^2} \cdot \frac{LCS^2 + \frac{L}{R} s^2 + (1 - D)^2}{U_{\text{in}} - L \cdot I_L \cdot s}
\]

Fig. 7. MATLAB/SIMULINK simulation main circuit

Fig. 8. Super-capacitor charging voltage and current waveform
4. Experimental Results and Analysis of Wireless Power Transmission

The system is prototyped as a 60VDC input and 27VDC super-capacitor module load system. The test bed of the WPT charger system is shown in Fig. 9.

4.1 Transmission Performance Experiments

First set of experiments: the transmission distance between the primary and the secondary windings is 4cm, and the electronic load voltage is controlled at 35VDC. The system power transmission efficiency is analyzed by controlling the primary current from 1.2A to 2.6A respectively.

The results show that the input and output power of the system increase as the primary current increases. As the primary current increases, the transmission efficiency of the system also increases.

The second set of experiments: the primary side constant current is 1.4A and other parameters remain. The system power and efficiency are analyzed by changing electronic load from 6VDC to 48VDC.
The results shown in Fig. 11 illustrate that when the primary circuit operates in a resonant state and the DC/DC output voltage is 40V, the power and transmission efficiency of the primary and secondary circuits reach a maximum value of 87%.

4.2 Primary Constant Current and Secondary Constant Current Performance Experiments

In the third set of experiments: the primary current is controlled at 1.4A, the inductor current of the DC/DC converter is controlled to be 2.5A, and the output voltage of the power regulating circuit changing from 5VDC to 100VDC.

The output voltage of the DC/DC converter circuit has a great influence on the transmission power and efficiency of the whole system.

4.3 Primary Constant Current and Secondary Constant Current Constant Voltage Performance Experiments

The fourth set of experiments: the primary current is 1.4A, the input voltage of the DC/DC converter circuit is researched and analyzed by controlling the voltage of the output electronic load of the DC/DC converter circuit from 10VDC to 100VDC under a constant supply of 40V.
As the output voltage of the DC/DC converter rises, the inductor current decreases. When the primary current is constant, the voltage at the DC/DC input terminal is kept constant.

According to the series experiments, the inductor current of the power regulation circuit is uncontrollable, the current loop is used as inner loop to realize the current protection control. In the super capacitor WPT system, the output voltage loop is added to protect the super capacitor from overshoot voltage damage.

4.4 Super-capacitor Charging Process Experiments

With the increasing of the super-capacitor voltage, the inductor current gradually decreases. When the super-capacitor voltage rises to the setting voltage 24V, the circuit is turned off and the charging process is completed.

5. Conclusion

The paper proposed wireless super-capacitor charger for trams. Optimal operation points and super-cap protection are the main focus of this research. The multi-loop control scheme is developed, which can regulate three variables, the rectifier output voltage, the inductor current, and the output capacitor current effectively and realize the maximum efficiency charge.
References


