

Design and Implementation of Wireless Charging for Hybrid Energy Storage System on Electric Scooters

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Abstract

This paper presents a design and implementation approach for charging an electric scooter wirelessly. Based on the demands of high performance charging, the presented system contains both battery and super capacitor as a hybrid energy storage system. The super capacitor facilitates filtering and quick charging. This paper proposes an intelligent switching control to manage the energy system and its performance, which can achieve quick and high power charging in a safe requirement. This approach balances the load distribution across the entire energy system and also improves the energy efficiency, which results in a more reliable battery lifetime and safer operation.

Keywords: wireless power transfer, electric scooter, hybrid energy storage system, super capacitor.

1 Introduction

The sale of electric vehicles is increasing due to the rapid evolution of technology. There are many questions surrounding the development of electric vehicles, such as mileage and charge time, which is inconvenient. In order to solve these problems, it is necessary to develop a convenient and rapid charger. This paper proposes a hybrid energy storage system (HESS), which, combined with wireless power transfer (WTP), can solve these problems.

Because of the urgent charging requirement from consumer electronics, WPT has become a popular function, as it has made utilizing electronic devices more convenient. The automotive industry is also attracted by this useful function. Wireless power charging technology can offer some conveniences to gain more freedom in using electric vehicles. Based on this prospect, this study proposes a circuit-designed WPT for electric scooters.

For vehicle applications, the SAE (Society of

Automotive Engineers) [1] surveys laws and safety and published the standard SAE J2954 [2] in 2013. SAE J2954 suggests all the requirements for WPT for all types of electric and plug-in hybrid vehicles. In this study, for seeking high power WTP, a Series-Series type circuit that satisfies SAE J2954 specifications will be employed.

From our previous study [3], the magnetic resonant coupling is a suitable scheme to achieve WPT for electric scooters, where the air gap between the transmitter and receiver can be larger than 15cm. As an energy storage device, a supercapacitor (SC) has many advantages such as high power density, quick charging and long life [4]. Basically, the HESS which combines the SC and battery shows its benefits on electric scooters. That is a solution for the energy system of electric vehicles (EV), and it can provide higher performance when utilizing the advantage of each power bank [5]. Based on the demands for high performance charging, the presented HESS contains both a battery and a SC. Generally, the SC facilitates filtering and quick charging. Consequently, this study focuses on the application of dual sources to

electric scooters.

Through rapid charging, the SC can effectively be charged by high current, and the battery and SC are simultaneously charged with pulse charging. However, this method decreases battery's lifetime in the long-term. The SC can work as a filter, which reduces the impacts on battery pack. During discharging, the driving requirement, and use of a DC/DC converter, dictates output power management [6]. The voltage and current sensors for discharging is used to probe the properties of battery and SC. This study realized the non-isolated DC/DC converter, which employs the SC and battery to implement the charging strategy [7].

In sum, this paper focuses on the HESS, which combines the battery with the SC to be applied in WPT and vehicle application. This paper presents the design of an effective management strategy and implements the intelligent DC/DC converter containing WPT properties. The purpose of this design is to prolong the battery life, decrease charging time and transient load (which is high current), and improve regenerative braking efficiency and performance, which can extend the driving distance.

2 Prototype Electric Scooter with WPT and HESS

Based on the prospect, this study proposes the circuit design and implementation of HESS for electric scooters. Figure 1 shows the power bank for the electric scooter. Additionally, the proposed design can enhance the operation of conventional electric scooters and improve the efficiency.

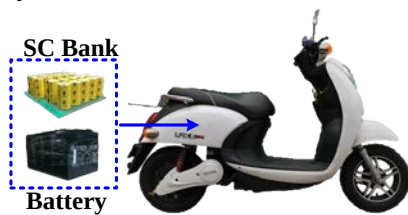


Figure 1: The power sources for the electric scooter.

Figure 2 shows the experimental scooter, whose specification is revealed in Table 1. In this study, the HESS using lead acid batteries and SC is considered for the implementation of our electric scooter. Figure 3 shows the charge scenarios of the proposed system. This system use a DSP to convert the data via the ADC and control the power switch with PWM. It can satisfy the high-speed requesting algorithms of the requirement.

In this paper, a reduced scale power train system are given to show the claimed functions.



Figure 2: Experimental platform.

Table 1: Specifications of the electric scooter.

Electric scooter	Laike super-mini
Maximum Power	0.8 kW
Battery	1 kWh
Top speed	40 km/h
DC bus voltage	Lead Acid 12V 20Ah *4
SC Bank	27V 40F module *2

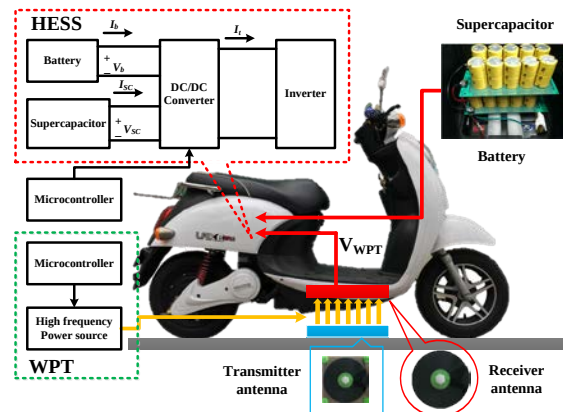


Figure 3: System scheme of the proposed scooter.

The frequency switching device can be devised by common power electronics, such as the MOSFET or IGBT. Based on SAE J2954, the presented system is working around 85 kHz. The system uses the antenna/receiver to transfer the power to the rectifier and then charges the battery wirelessly. In practice, the air gap is set from 10 to 20 cm. The shorter the air gap is, the larger the charging current that can be obtained. Basically, the transmitter coils are underground, and the receiver coils are embedded in the bottom layer of the chassis. This setup does not have a positive/negative pole problem. In addition, it is waterproof, emits no radiation, and the risk of electric shock is low. Based on the magnetic resonant coupling theory, a circuit that satisfies SAE J2954 will be proposed. The proposed design can be applied to any commercial 48V/20Ah electric scooter.

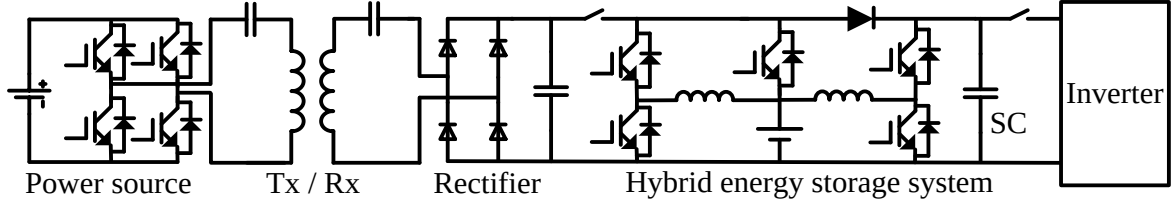


Figure 4: Schematic system of wireless charging for HESS of the proposed scooter.

3 Proposed HESS

As shown in Figure 4, the proposed circuit design of WPT and HESS are revealed. The major functions contain both charging and discharging. In addition, based on the dynamic and static load demands and requirements, the proposed HESS works in six different switching modes. Similar to the study in [8], the super capacitor plays a role to assist the battery system on energy balance and distribution. In this study, the wireless charger is treated as a DC source. With different charging applications, the switches in Figure 4 operate intelligently to achieve a quick and high efficiency operation.

A. Mode of rapid charging

Figure 5 shows the current flow of the rapid charging mode. The WTP charges the SC in full power, and this mode achieves rapid and efficient charging by following the SC storage formula.

$$U = \int_{q_i}^{q_f} \frac{q}{C} dq \quad (1)$$

Herein, U is the energy stored of the SC, C is the capacitance; according to (1), the stored energy in SC can be obtained. Then the charging efficiency η_{SC} of this mode can be gathered using the following equation.

$$\eta_{SC} = \frac{\frac{1}{2}C(V_n^2 - V_f^2)}{\frac{1}{2}CV_n^2} = 1 - \frac{V_f^2}{V_n^2} \quad (2)$$

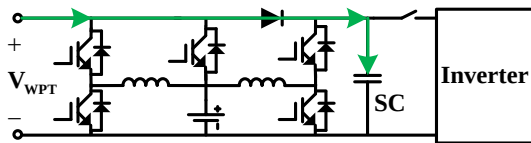


Figure 5: Energy flow of rapid charging mode.

B. Mode of equalizing charging

Figure 6 shows the equalizing charging scenario. The WTP charges both on battery and SC. During this mode, the efficiency changes

because the resistance, which is nonlinear, is battery and SC in parallel. The current passively distributes to the battery and SC. This mode can use the switch to charge the battery with pulse-charging control, but pulse-charging typically deteriorates the battery's lifetime. The proposed system has a filter based on SC transiently protects the battery from pulse-charging. The efficiency of the charging is determined by the following equations.

$$I_{WPT}(t) = I_b(t) + I_{SC}(t) \quad (3)$$

$$\frac{V_{WPT}(t) - V_b(t)}{I_b(t)} = R_b(t) \quad (4)$$

$$\frac{V_{WPT}(t) - V_{SC}(t)}{I_{SC}(t)} = R_{SC}(t) \quad (5)$$

$$R_{load}(t) = (R_b(t) \parallel R_{SC}(t)) \quad (6)$$

$$\eta_{SC} = \frac{(\omega L_m)^2 Z_L}{(R_{rx} + R_{load}(t)) \left[R_{tx} Z_L + R_{rx} R_{tx} + (\omega L_m)^2 \right]} \quad (7)$$

Herein, I_{WPT} is the wireless transfer power. I_b and I_{SC} are distributed by each resistance. V_{WPT} is the voltage of the open-circuit. V_{SC} and V_b are the voltage of the SC and battery. $R_b(t)$ and $R_{SC}(t)$ are the transient resistance. η_{SC} is the efficiency of charging which is applied in HESS by WPT. ω is the angular frequency of the WPT operation. L_m is the mutual inductance coupled with the receiving antenna and transmitting antenna. R_{tx} and R_{rx} are resistance of the antenna. Z_L is the complex impedance of HESS.

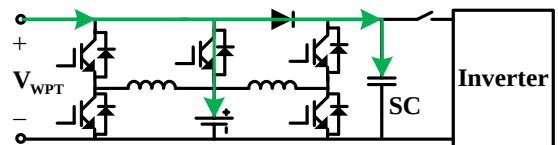


Figure 6: Energy flow of normal charging mode.

C. Mode of detecting charging

Figure 7 illustrates the slow charging mode. In this stage, the energy storages are expected to be saturated. The voltage, $(V_{WPT} - V_{SC})$ decreases so that I_{SC} decreases too. Thus, we design the new cycle of charging. During the cycle, which is divided into two parts, the first part starts up the buck converter to charge at a constant voltage, and the second part is charged with the boost converter by the battery. This method can relieve electrochemical reaction of the battery and improve the overall efficiency of charging.

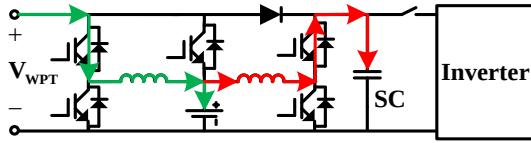


Figure 7: Energy flow of slow charging mode.

For discharging, three scenarios are considered. Usually, the electric scooter needs higher current for traction propulsion. In this stage, the SC can compensate this energy demand smoothly and reduce risks of heavy load discharging from batteries. It is known that regular heavy discharging deteriorates the lifetime of batteries.

D. Mode of starting or accelerating

Figure 8 shows the operation starting or accelerating. This mode needs to examine the SC voltage and the ratio of output power can be adjusted by a control algorithm. The strategy applies the boost converter to achieve it. This mode can protect the battery from the output of high current, thus extending the battery life.

$$P_t = P_b + P_{SC} = P_{motor} = \tau\omega + P_{loss} \quad (8)$$

$$D_{SC} = \frac{P_{SC}}{P_b + P_{SC}}, 1 - D_{SC} = D_b \quad (9)$$

Herein P_t is the total of output. P_b and P_{SC} are battery power and SC power, respectively. D_{SC} and D_b stand for duty ratio of battery and SC.

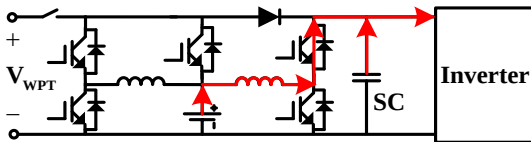


Figure 8: Energy flow of acceleration mode.

E. Mode of constant speed

Figure 9 shows the mode of driving at a constant speed. It operates with the boost converter after starting or accelerating is

completed. In this mode, D_b will increase and charge SC to keep the voltage in a suitable range for acceleration.

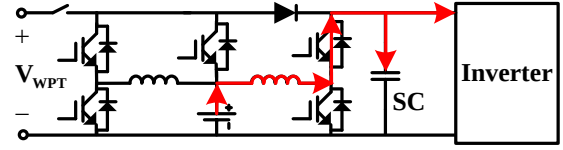


Figure 9: Energy flow of constant speed operation.

F. Mode of low speed / light load

Figure 10 shows the mode of driving at low speed with a light load. It is applied to the scenario of urban traffic condition. In this condition, the power of the requirement is low, and the battery can directly power the load.

All in all, Figure 11 summarizes the proposed system in a flowchart.

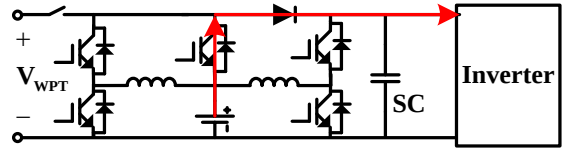


Figure 10: Energy flow of light load operation.

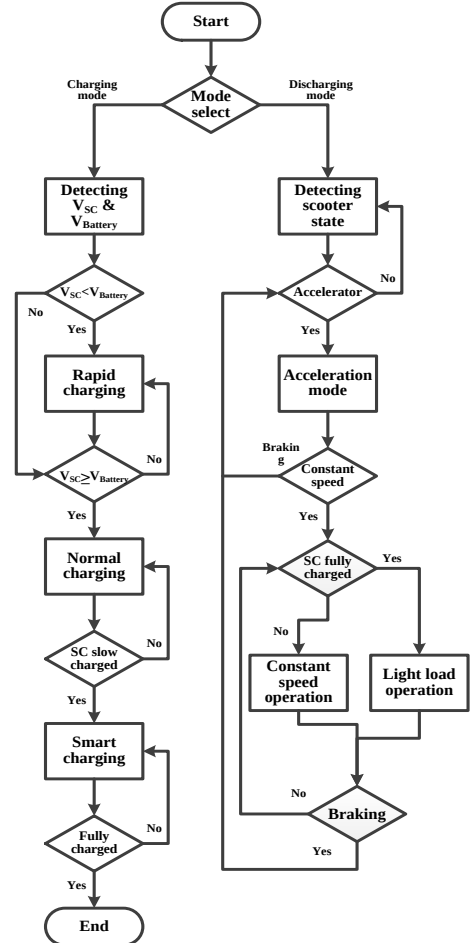


Figure 11: Flowchart of HESS.

4 Experimental Results

Figure 12 shows the antenna in the experiment. The radius of it is 25 cm, which can be equipped under the chassis of the scooter. Figure 13 shows the air gap between antennas. The distance is larger than 15 cm. Figure 14 shows the prototype of the HESS. The experiments is realized in a reduced scale power system before setting the HESS with converter prototype to the electric scooter.



Figure 12: Size of antenna.

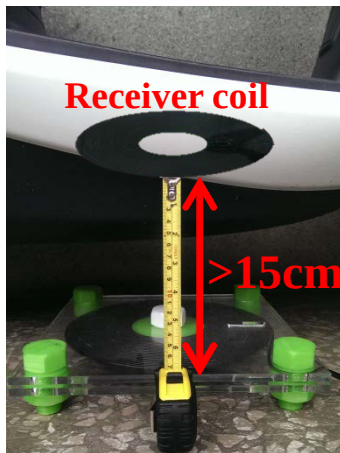


Figure 13: Air gap between transmitter and receiver.

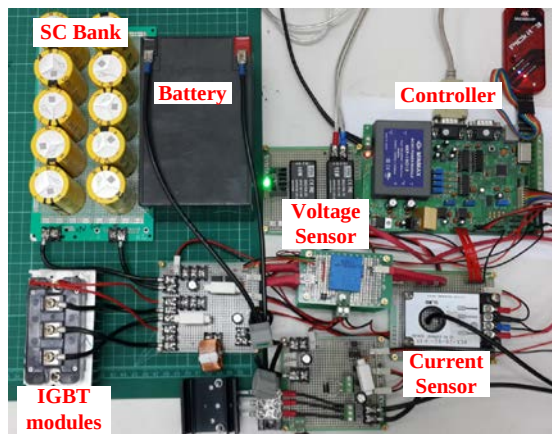


Figure 14: Prototype of the experimental circuit

Figure 15 shows that the SC can be charged by WPT. In this mode, a rapid and effective charging of up to 5.77A in the initial moments can be observed. Figure 16 shows change of voltage and current of SC. During the difference of voltage is equalizing, the change of resistance is not obviously changed. Because of that, the current is dropping while the voltage is increasing. If the difference of voltage which is between the battery and SC is tremendous, such as Figure 17, the voltage is dropped by the high-current output. This phenomenon which the battery is forced to output high-current to the SC is related to the internal resistance and the maximum power of the battery. In Figure 17, SC is charged by I_{WPT} is 3.55A and $I_{Battery}$ is 19.86A. Basically, this condition is harmful to the lifetime of the battery.

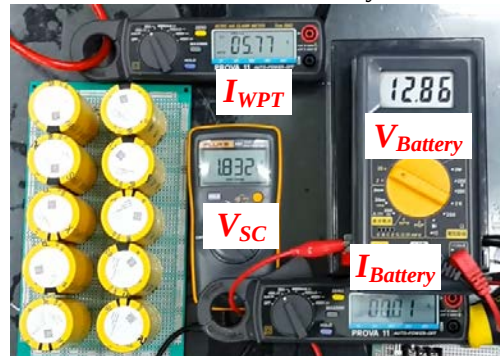


Figure 15: The initial data of rapid charging.

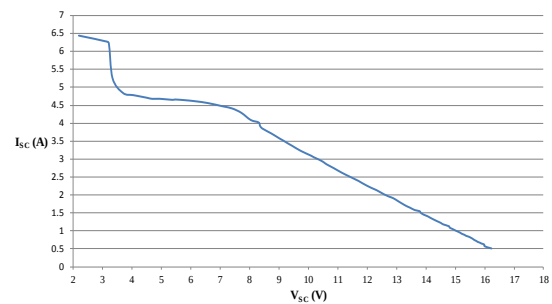


Figure 16: I-V of SC.

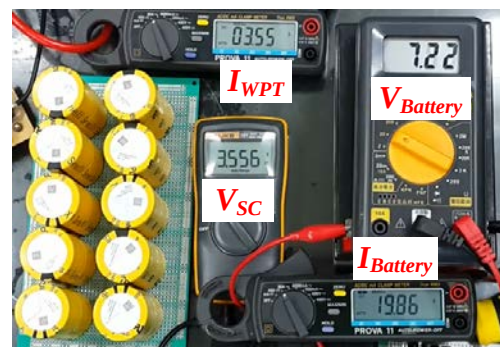


Figure 17: The current of battery without HESS.

To avoid the battery from high-current output which is caused by the difference of voltage

between battery and SC, mode of equalizing charging is operated when the difference is small. WPT can charge the battery and SC, such as Figure 18. It shows that the operation of HESS can protect the battery from the overloading. The current of this mode is distributed by the ratio of the resistance between the battery and the SC when the voltage of them are equalizing.

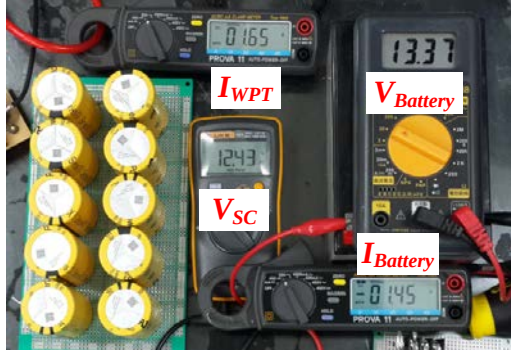


Figure 18: The data of equalizing charging

During the mode of equalizing charging, the difference of the voltage between SC and battery is very small. The battery is charged by the constant voltage with the buck-down converter in this moment. SC is timely charged by the boost-up converter. This condition can increase the capacity of the total storage. Additionally, it can act as a buffer between the charging and discharging of the electrochemical reaction. Under this condition, battery can keep in the healthy operation with this strategy.

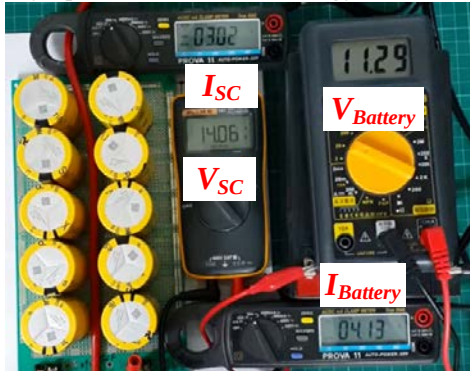


Figure 19: The data of smart charging.

When the load of the requirement is tremendous, the controller adjust the power of the battery. The experiment prove the control of the power to attain the acceleration by the adjustable duty cycle. Figure 20 shows the voltage of SC can be operated in the range of inverter. It limit the output current by controlling the duty cycle. Because the power density is medium, it bears the tremendous and transient change but the change of the voltage is very obvious. Therefore, the ratio of power which is

outputted by the battery increase to achieve the requirement of the constant speed.

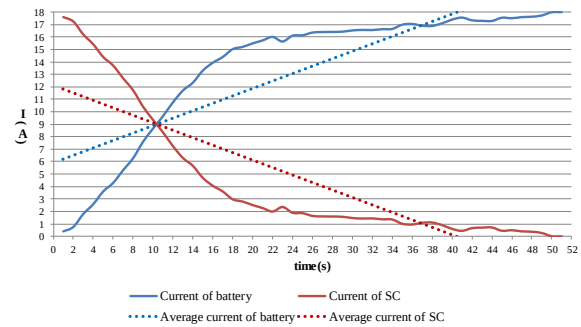


Figure 20: Current of battery and SC.

When the load is declined, the controller can determine the range of operating voltage and adjust the ratio of duty cycle to do the slight boost. This strategy can shorten the time of charging the SC. When the difference of voltage is small, the system will switch the mode to naturally equalize the voltage and avoid the unnecessary waste of energy. Figure 21 shows that battery is operated in the mode of constant speed. In this condition, it can be find that the operating voltage of inverter is important. Because of it, the difference is not suitable and the battery outputs the high-current for equalizing the voltage. It results in a deterioration of the lifetime to the battery. During driving with light load, the battery directly output to the load. In this condition, the SC can be acted as a low pass filter.

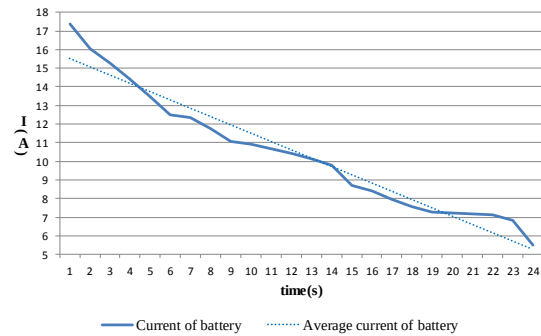


Figure 21: The current SC charged by battery.

The experimental results show that the proposed HESS is feasible, and the control strategy is verified to be useful. It can be quickly, safely, and effectively to charge by the adjustable strategy with WPT. This strategy also can improve the total efficiency from the result of the discharging experiments.

5 Conclusion

In this paper, the HESS has been proposed. This proposed approach can be applied to wireless

charging of electric scooters. The intelligent controller was presented to achieve a quick, smart, and efficient management. The operating fundamentals of the circuit which is proposed were fully explained the modes of operating. This approach has been confirmed that the load can be distributed by the proposed operation. It also improved the efficiency of the energy which results in a safe and reliable control of the battery and operation.

The experiments were built on the scaled-down specification in order to verify the proposed strategy of the WTP and HESS. For further investigation, issues are suggested as follows. The research on improving the WTP up to the level of kilowatt, increasing the specification of HESS, and designing the suitable inverter are also curial topics.

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