Effective Charging Method for Ultracapacitors

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Abstract

One of the advantages of ultracapacitors is its high power capability, which is applicable for high rate of charging and discharging operation like motor starting and regenerative braking of an electric vehicle. This paper presents a new charging method for ultracapacitors. Comparing with batteries, ultracapacitor can accept a wide range of charging current and can be fully charged within a few minutes. Common chargers for ultracapacitors are usually equipped with current transducers and closed loop circuitry for current control, which are expensive and complicated. The proposed circuit consists of a minimum number of components. It does not require any current transducer or dedicated voltage/current control circuitry. A simple open-loop control system is applicable for the whole charging stage. It is free of stability problem and protects itself from being overloaded by ultracapacitor with zero initial charge. This paper presents the design and operation of the hardware circuit. Both simulation and experimental results are included.

Keywords

ultracapacitor, charging, charger and infrastructure

1. INTRODUCTION

High energy density batteries, like lithium-ion (Li-ion) and nickel metal hydride (NiMH) battery, and fuel cells have been developed for many years. They are successfully utilized as energy sources for electric vehicles (EVs). However, their power densities are inadequate under certain operation conditions, namely quick acceleration, hill-climbing and regenerative braking. The ultracapacitor is a high power density energy storage device that can deliver high short-term discharging current and acquire burst of charging current. It does not have the drawbacks of batteries like poor temperature coefficient, limited charging and discharging cycle, and critical charging current. It can be used in tandem with batteries for performance improvement of EVs. An ultracapacitor-battery combination system can effectively smooth the power fluctuation caused by periodic acceleration and deceleration. It can also effectively absorb the regenerative energy during braking and provide extra-current for hill climbing. A flat current profile gives rises to a longer cycle life and higher usable ampere-hour capacity of batteries. Hence, premature failure and poor power efficiency can be avoided. Ultracapacitors with capacitances ranged from several hundreds to over a thousand Farads are produced on large scale for transportation applications [S. Pay et. al, 2003], [Y. Kim, 2003].

An ultracapacitor should be charged before it can deliver energy for peak load. Current limiting feature must be incorporated to a charger because an ultracapacitor without initial charge will acquire huge current from the source for a considerable duration. It is undesirable for an ultracapacitor-battery combination system. Even worst, the battery could be damaged if they are directly connected together for charging. Although an ordinary charging circuit with constant-current constant-voltage control is applicable for refueling an ultracapacitor, it involves a complicated closed-loop control circuit and an expensive active current transducer. In this paper, a new and effective charging circuit is developed to tackle the problems. This circuit does not consist of any current transducer. The whole charging process is simply driven by an open-loop control circuit until the ultracapacitor is charged to its threshold voltage.

2. ULTRACAPACITOR

Ultracapacitors are also known as supercapacitors. Two main types of ultracapacitors are pseudocapacitor and double layer capacitor. Their structures are somewhere like a battery, which contains electrolyte with electrodes immersed. The positive and negative electrodes are separated by a separator. The electrodes are made with porous material. There are pores with size in terms of nanometer where ions can travel freely. For the double-layer ultracapacitor, there is no Faradic reaction between the material and the electrolyte. For the pseudocapacitor, Faradic reaction does occur. If an ultracapacitor is charged with constant current, the voltage across the electrodes will rise linearly with time as an idea capacitor.

It can be charged before the breakdown voltage is reached. For batteries, the Nernstain cell potential can be kept theoretically at a certain level unless all the reactants have been consumed during charging or discharging [B.E. Conway et. al, 1997], [A. Burke, 2000]. The major difference in operating an ultracapacitor whereas a battery is that the voltage of a battery is relatively constant but that of an ultracapacitor varies over a wide range.

2.1 Characteristics

The comparison of batteries and ultracapacitors is tabulated in Table 1. Ultracapacitors and batteries possess the advantages of high power density and high energy density, respectively. An ultracapacitor-battery combination system puts the advantages together.

Table 1 Comparison of batteries and ultracapacitors

	Ultracapacitors	Batteries
Charging time	Fraction of a second to several minutes	Several hours
Self-discharging	Hours to days	Weeks to several months
Power density	> 1000 W/kg	<500 W/kg
Energy density	< 5 Wh/kg	10 – 100 Wh/kg
Charging /discharging efficiency	85% -98%	70% - 85%
Cycle life	10^6 - 10^8	200 – 1,000

2.2 Modeling

The first-order circuit model of an ultracapacitor is shown in Figure 1. It consists of a series resistance and an inductance, and the leakage current is represented by a resistor in parallel with the capacitor. The series resistance ranges from a few milliohms to several tens milliohms. The inductance depends on the construction and can be ignored for low frequency operation. The leakage resistance can also be ignored for short-term operation. Actually, the leakage current of an ultracapacitor with capacitance over 500 Farads is less than 10mA and its rated current is over a hundred ampere [N. Khan et. al, 2000], [Nesscap, 2003], [Maxwell, 2005].

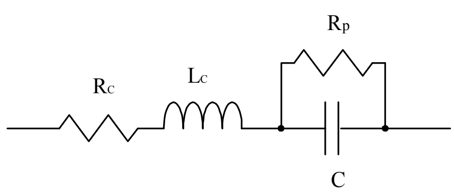

Fig. 1 Equivalent circuit of ultracapacitor

An ultracapacitor can accept a wide of charging current so that precise current control is not necessary. The criterion for terminating charging is the maximum rated voltage of an ultracapacitor. Figure 2 shows the charging profiles of a 680F ultracapacitor with various charging currents. The result reveals that the characteristic of the ultracapacitor is closed to that of an ideal capacitor. The specimen is subjected to constant current charging with charging currents of 1.5A, 2.5A and 3A respectively. The ampere-hour capacity or energy storage capacity of a battery depends on the charging current. For an ultracapacitor, experimental results reveal that the energy storage capacity is nearly constant under different rates of charging.

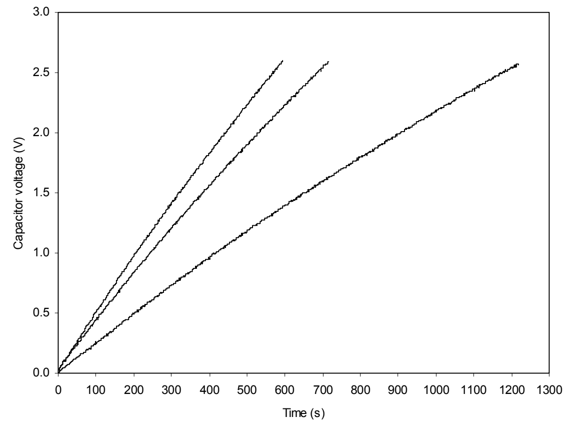

Fig. 2 Charging profile with various charging currents

3. CHARGER FOR ULTRACAPACITORS

Basically, common charging circuits for batteries are applicable for ultracapacitors, but several issues should be taken into consideration. A linear mode power supply is inappropriate since its efficiency is low. Energy loss is very large since the voltage difference between the supply source and the ultracapacitor is great, especially under zero initial charge condition. It reduces the mileage of an EV, and upsets the advantages of an ultracapcitor-battery combination system. A switching mode dc-dc converter with pulse width modulation (PWM) is a good candidate. A battery is usually charged for hours and then the charger can be shut down or even be disconnected from the power source. An ultracapacitor is under repetitive charging with a much shorter time constant. It can be completely discharged within a few minutes or even just a couple of seconds, and then fully charged again within a short period. The charger needs to operate in such a way that it provides a maximum charging current for a short period and then reduces to zero until next charging cycle. This pulsating operation imposes stresses on a PWM charger. Whenever a common PWM converter is started from zero output to maximum, current transient may occur and additional soft-starting circuit is required. Another major difference between the battery charger and the ultracapacitor charger is that the output voltage of the ultracapacitor one swings from zero to its rated value while that of the battery one varies over a narrow range. Actually, the voltage of an ultracapacitor increases slowly during charging, and the charger is virtually short-circuited for a relatively long duration.

3.1 Design considerations

To develop a charger for ultracapacitor, the following points are taken into consideration.

- Low cost.
- Subjected to pulsating operation and output current swings from zero to maximum frequently.
- Able to provide a wide range of output voltage, from zero to the rated voltage of an ultracapacitor.
- Protect the charger from being short-circuited when there is no initial charge in the ultracapacitor.
- Circuit should remain stable over various input and output voltages as well as extreme output currents.
- Flat input current profile.
- Low loss.

3.2 Circuit

In order to minimize the production cost and complexity of the charger, an expensive current transducer is excluded from the circuit. Nevertheless, the input current limiting function should be retained. The charging circuit is shown as Figure 3, which consists of only five major components. Energy is transferred from the voltage source to the ultracapacitor through an inductor. The circuit operates at fixed frequency and duty cycle. Although the circuit does not consist of any current transducer or closed loop control circuit, the input current is limited because the peak current of the inductor is limited by a fixed turn-on time. The high switching frequency can be easily filtered by using an ordinary electrolytic capacitor placed at the voltage source. Thus, the supply current is flat and free of fluctuation.

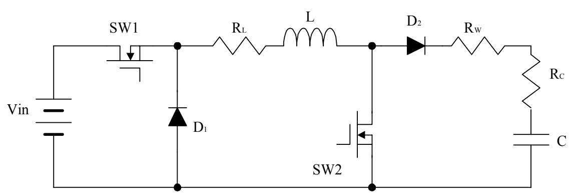

Fig. 3 Circuit diagram of charger

The inductor L is responsible for the transference of energy. The series resistor R_L represents the internal resistance of the inductor. R_W is the total resistance of the wires connected to the ultracapacitor. The ultracapacitor C is represented by a first order model with series resistance R_c. The series inductance and leakage resistance are negligible for the operation of the charger.

3.3 Operation

There are two states of operation per cycle, namely energy absorption and energy transference stage. During the first state, the inductor absorbs energy from the supply source. Then, it delivers the energy to the ultracapacitor at the second state and the ultracapacitor can acquire constant amount of energy per switching cycle. The two MOSFETs, namely *SW1* and *SW2*, are switched on simultaneously in the first state. The input current is a function of the inductance and the turn-on time of the synchronous switches. The wire resistance R_W is less than 0.5Ω to minimize the conduction loss. The turn-off time and switching frequency is determined by the ratio of the inductance L and total series resistances of R_L, R_W and R_C. However, the total resistance of R_L and R_W is greater the equivalent series resistance of the ultracapacitor, and the influences of different characteristics of the ultracapacitors provided by various manufacturers are negligible. In order to minimize the circuit size and to have a better utilization of the ferrite core, the circuit operates in the discontinuous mode. Since no residue dc current flows through the inductor for each switching cycle, magnetic saturation can be avoided. During the on-period, the inductor is charged as if a boost or flyback converter. In the second state, the two switches are turned off, and the freewheeling diodes, D_1 and D_2, conduct. The inductor is in series with the series resistors and the ultracapacitor. Unlike common low loss RLC-series circuit, the inductor current cannot be described by the equations for an underdamped system because the capacitance is much greater than the series resistances and the inductance.

3.4 Derivation

When the synchronous switches, SW_1 and SW_2, are turned on, the inductor current can be expressed by:

$$V_{in} = L\frac{di_{on}}{dt} + R_L i_{on} + 2V_{SW} \qquad (1)$$

where V_{SW} is the voltage drop across a synchronous switch. The values of V_{SW} and R_L are small, and the voltage drops are negligible in this stage.

$$V_{in} = L\frac{di_{on}}{dt} \qquad (2)$$

If the turn-on time is short, (2) can be approximated by a linear equation. Thus, the peak inductor current during T_{on} is given by:

$$I_{peak} = V_{in} \frac{T_{on}}{L} \tag{3}$$

During the energy transference state, the synchronous switches, SW_1 and SW_2, are turned off. The inductor current can be expressed by:

$$L \frac{di_{off}}{dt} + (R_L + R_W + R_C) i_{off} + \frac{1}{C} \int i_{off}\, dt + V_{C0} = -2V_d \tag{4}$$

where V_{CO} is the previous voltage of the ultracapacitor, and V_d is the voltage drop of each diode. As an extreme condition, V_{CO} is zero when the ultracapacitor is completely discharged.

The inductor current of this stage can be expressed as:

$$i_{off}(t) = I_{peak} \left(\frac{ae^{at} - be^{bt}}{a-b} \right) - \frac{(2V_d + V_{C0})}{L} \left(\frac{e^{at} - e^{bt}}{a-b} \right) \tag{5}$$

where

$$a = -\frac{R}{2L} - \frac{1}{2} \sqrt{\left(\frac{R_L + R_W + R_c}{L} \right)^2 - \frac{4}{LC}}$$

$$b = -\frac{R}{2L} + \frac{1}{2} \sqrt{\left(\frac{R_L + R_W + R_c}{L} \right)^2 - \frac{4}{LC}}$$

When there is no initial charge stored in the ultracapacitor, V_{C0} is zero. To ensure the circuit operated at boundary condition, the inductor current i_{off} should reduce to zero at the end of energy transference stage. Substituting $V_{C0} = 0$ and (2) into (5), we have

$$V_{in} T_{on} \left(ae^{at} - be^{bt} \right) = 2 \cdot V_d \left(e^{at} - e^{bt} \right) \tag{6}$$

The above equations have been input to Matlab and the optimum turn-on time T_{on} can be obtained. All the magnetic energy stored in the inductor will be transferred toward the ultracapacitor. However, the energy loss is large if the ultracapacitor voltage is very low because most power is dissipated on the series resistance and diodes.

4. CIRCUIT DEVELOPMENT

A charger is designed for charging a 680F ultracapacitor with a 12V DC input supply. The switching frequency is 40kHz. It is targeted to fully charge the ultracapacitor to its rated voltage of 2.5V in around 15 minutes.

4.1 Simulation

In order to examine the switching characteristics of the circuit and reduce the effort on hardware development, the above equations have been input to a Matlab program for simulation. The result is shown in Figure 4. The upper waveform of the gate pulse is simply for the easy of illustration, which does not take part in the calculation. The switching period is 25μs. An optimal turn-on time is found to be 3μs while the inductance of the circuit is 6 H. The inductor current rises to a peak value of 6A during the energy absorption stage. Then the current decays to zero, and energy is transferred to the ultracapacitor.

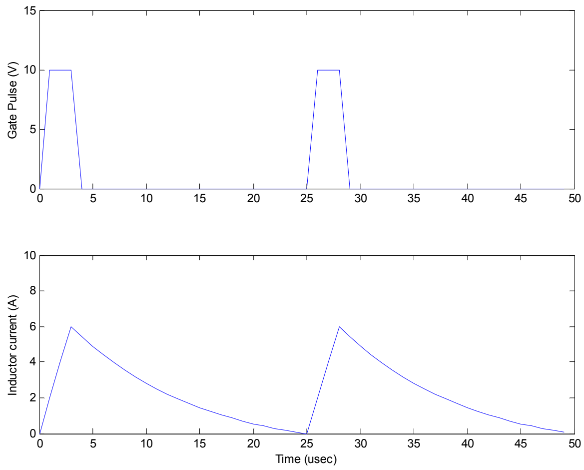

Fig. 4 Simulation waveform of inductor current (lower) and gate pulse (upper)

4.2 Hardware experiment

A hardware circuit has been developed for verification. From (6), energy loss mainly depends on the voltage drop across the diodes, so Schottky diodes are chosen for the circuit. SW_1 and SW_2 are MOSFETs that are driven by gate pulses generated from the same signal source with a driver IR2114.

The current waveforms of the inductor and ultracapacitor are shown in Figure 5 and Figure 6, respectively. The voltage waveforms of diode D_1 and MOSFET SW_1 are shown in Figure 7. The inductor current rises to a peak value of around 5.8A that is closed to the result of simulation as shown in Figure 4. Due to the presence of stray inductance, the charging current of the ultracapacitor cannot increase to the peak value of inductor current immediately after the turn-off of MOSFETs, but the influence is negligible and inductor current decays to zero before the next cycle begins. Ripples can be found on the decayed current waveform of the ultracapacitor, and the influence is not noticeable. The whole charging profile is recorded with a data log-

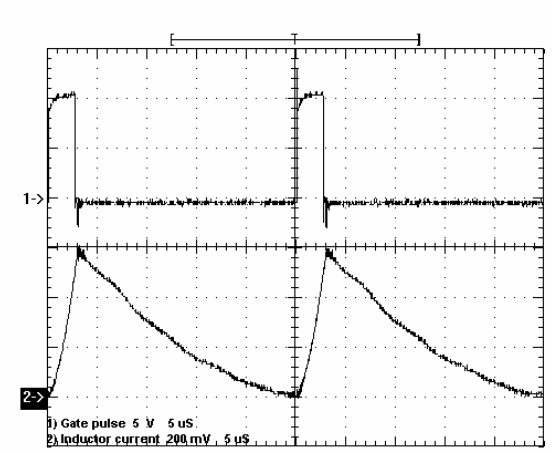

Fig. 5 Waveform of gate pulse and inductor current

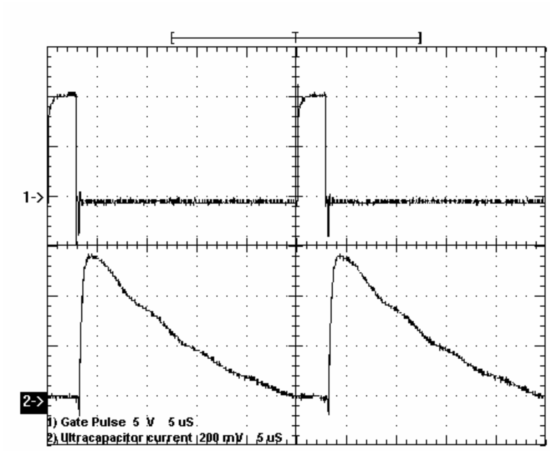

Fig. 6 Waveform of gate pulse and ultracapacitor current

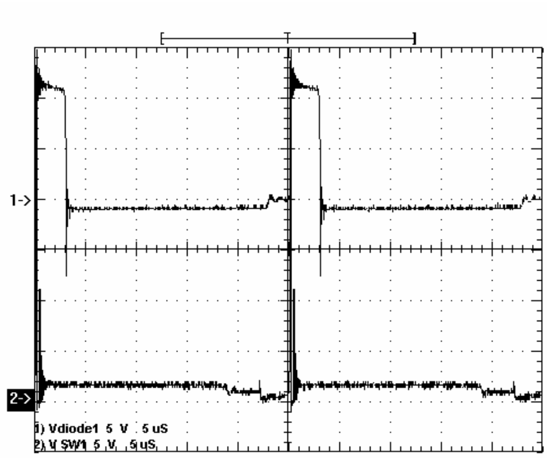

Fig. 7 Voltage waveform of diode, D_1, (upper) and MOSFET, SW_1 (lower)

ger with a sampling rate of 1 second, which is shown in Figure 8. The ultracapacitor is fully charged to its rated value in 15 minutes.

As a practical consideration, a voltage comparator is employed for charging termination. Once the voltage

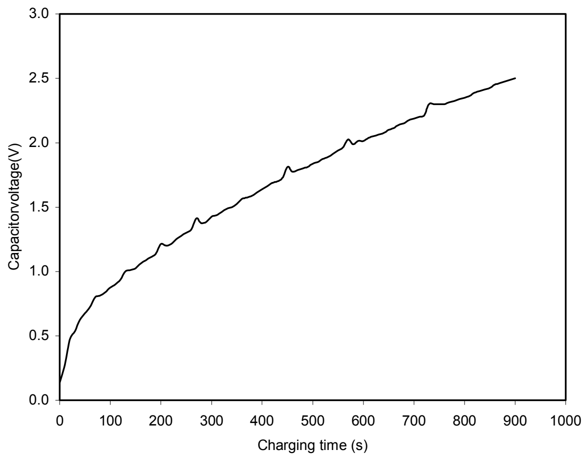

Fig. 8 Voltage profile of the ultracapacitor during charging

of the ultracapacitor reaches its rated value, the comparator will inhibit the IR2114, hence stopping the generation of the gate pulse.

5. CONCLUSION

The ultracapacitor plays an important role in the EV industry. A new charging circuit with minimum component count has been developed, which highly reduce the production cost as well as circuit failure rate. Based on the equations, optimal inductance and pulse width can be determined. The simulation result and experimental results are consistent. The charger can fully charges up a 680F ultracapacitor in 15 minutes. The circuit does not consist of complicated closed loop control and is free of stability problem. It favours the application of ultracapacitor-battery combination system for EVs.

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