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Development of a Regenerative Braking System Using Super-capacitors for Electric Vehicles

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Abstract

This is the second report on a regenerative braking system using super-capacitors (Electric Double Layer Capacitors) as the energy storage element. A bi-directional controlled current source with the capacitor is connected in parallel with the EV battery, and is controlled so that the whole (or a part of) the braking energy is absorbed into the capacitor and released back to the EV motor upon acceleration. The converter needs the series-parallel switchover circuit for making the best use of the capacitors and for limiting the step-up ratio of the boost converter. The circuit arrangement and its control method are the major topics of this paper. The proposed methods are verified both by computer simulations and tests on the experimental setup.

Keywords

electric vehicle, regenerative braking, bi-directional controlled current source, series-parallel switchover circuit, capacitors

1. INTRODUCTION

From the viewpoint of the energy efficiency and the load-leveling of EV batteries, the development of the high performance regenerative braking systems for electric and hybrid vehicles has recently become an important technical subject of discussion. Capacitors can take in and out the electrical energy rapidly and efficiently. The use of capacitors as energy storage element has become feasible with the recent progress of large capacity super-capacitors.

Some works related to this subject [Takahashi et al., 1999, Ohshima et al., 1998] have been reported so far, but very few papers treat the application of super-capacitors to the regenerative braking system [Kasuga et al., 1998, Takehara et al., 1997]. One of them connects the capacitors directly across the battery terminals, and the other uses a switch circuit to connect the capacitors in series with the battery. Therefore, the system arrangement and its control method as applied to the regenerative braking have not been fully established.

In general, it is desirable not to use any semiconductor switches in series with the main circuit for achieving a high efficiency. We have proposed a regenerative braking system with a bi-directional controlled current source connected in parallel with the EV battery [Nomura, 2001]. The bi-directional controlled current source comprises a DC-DC converter and a capacitor bank, and is controlled so that the whole (or a part of) the braking energy is absorbed into the capacitor and released back to the EV motor upon acceleration.

The converter needs a series-parallel switchover circuit for making the best use of the capacitors and for limiting the step-up ratio of the boost converter. This paper focuses on the circuit arrangement and its control method of the series-parallel switchover circuit for the practical design of this system. The results are verified both by computer simulations and tests on the experimental setup.

2. PROPOSED REGENERATIVE BRAKING SYSTEM

2.1 Energy management by controlled current source

Figure 1 shows the proposed regenerative braking system. Between the battery and the motor is a bi-directional controlled current source, whose input current can flow in either direction and its magnitude is controllable. The DC-DC converter together with the capacitors forms the bi-directional controlled current source. The converter input current i_C is controlled so that it tracks the motor current i_M which flows backward (from motor to battery) when braking, and forward when accelerating.

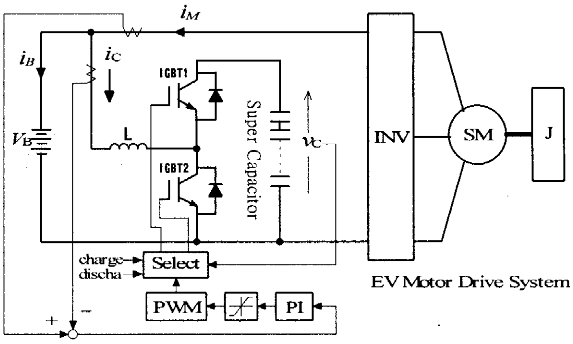

Fig. 1 Proposed regenerative breaking system

These operations can be achieved by detecting both the motor current and the converter current. Comparing i_C with i_M yields an error, which passes through a PI controller. Then the signal is compared with a triangular wave to produce PWM pulses. By applying PWM pulses to IGBT2, the converter operates as a boost converter and takes an input current i_C charging the capacitor. The direction of the input current reverses by gating IGBT1. In this case the converter operates as a buck converter discharging the capacitor. In either case the magnitude of the input current can be PWM controlled. The capacitor voltage must also be detected to stop the converter at its maximum and minimum.

2.2 Simulation

In order to verify the basic performance of Figure 1, a computer simulation using PSIM was performed. The conditions are as follows.

(1) The motor current was modeled by the programmable current source to have a step regenerating and powering current.
(2) Much smaller capacitance was used to reduce the simulation time.
(3) $L=1mH, C=2000uF, V_B=100V, r_B=0.1\ \Omega$.
(4) The transfer function of the PI controller was G(s) = 1+100/s.
(5) The switching frequency of the converter was 20kHz.

The simulation results are shown in Figure 2, from which the following are observed.

(1) During t=0 to 4.5ms, the regenerative current i_M of 50A flows. The converter current i_C keeps track of i_M almost completely charging the capacitor up to about 200V. Hence the battery current i_B is kept zero.
(2) During t>7ms, the motoring current i_M of -50A flows. In this mode i_C changes its direction and follows i_M discharging the capacitor. When the capacitor voltage gets down to 100V, the converter stops and i_M is supplied from the battery.

Through this simulation, it has been shown that the control is quite stable and fast in both breaking and accelerating modes.

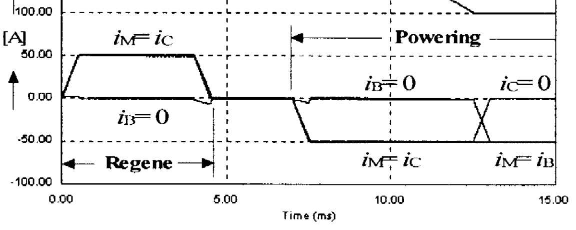

Fig. 2 Simulation results

3. SERIES-PARALLEL SWITCHOVER OF CAPACITORS

3.1 Capacitor

Figure 3 shows the super capacitor bank used for the experiment. Ten 14V, 80F capacitors are connected in series to have a 140V, 8F capacitor bank which weighs 55kg. Using series connected capacitors might cause the voltage unbalance on each unit capacitor. Figure 4 shows the capacitor voltage on each capacitor when the capacitor bank was charged with a constant current of 10A. Without any voltage balancing means, the voltage unbalance was negligible.

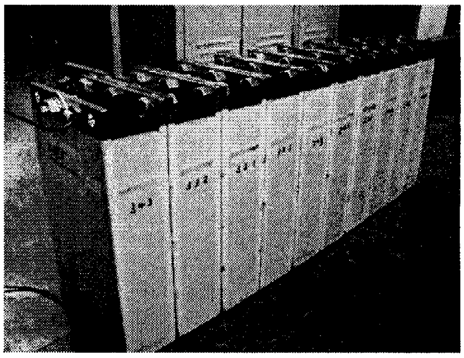

Fig. 3 Super capacitor bank: 140V, 8F

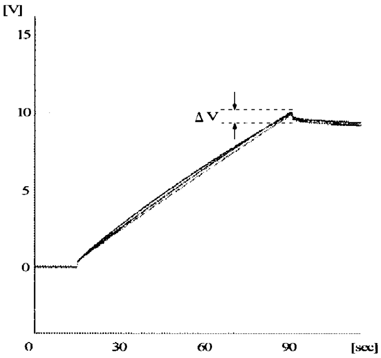

Fig. 4 Voltage balance of series connected capacitors

3.2 Series-parallel switchover circuit

The converter circuit for the controlled current source operates as the boost converter when it charges the capacitor. Therefore, the capacitor voltage rating must be higher than the battery voltage. The higher the voltage rating is, the larger the stored energy can be, at the expense of more capacitors and more series connections. Also, the step up ratio of the boost converter has its practical limit, usually 2 to 3. For these difficulties the series-parallel switchover circuit [Sugimoto et al, 1998] shown in Fig.5 is effective, because it makes it possible to use the capacitor more effectively limiting the step up ratio of the converter within 2.

Figure 5 shows the bi-directional chopper circuit with the series-parallel switchover circuit. By detecting one of the capacitor voltages, SW1, SW2 and SW3 are switched over as follows.

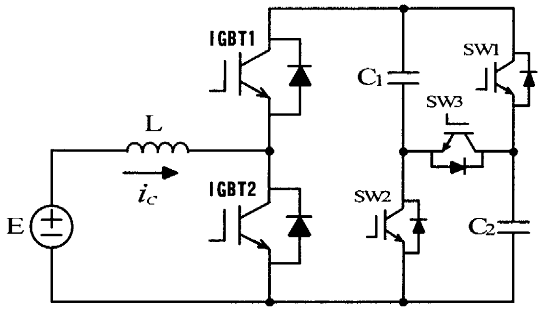

Fig. 5 Converter circuit with series-parallel switchover circuit

1. Charging (IGBT2 in operation)
(1) With all the switches SW1-SW3 off, the capacitors C_1 and C_2 are charged in series until the voltage on each capacitor reaches E.
(2) At the voltage E, SW1 and SW2 are turned on having a parallel charging path.
(3) The gate signal of IGBT2 is blocked to stop charging when the capacitor voltage reaches 2E.

2. Discharging (IGBT1 in operation)
(1) With all the switches off, discharge from 2E to E is performed through the parallel path.
(2) When the capacitor voltage drops down to E, SW3 is turned on having a series discharging path.
(3) The gate signal of IGBT1 is blocked to stop discharging when the capacitor voltage reaches E/2.

It is seen that the sequential switchover mentioned above limits the step up ratio of the boost converter within twice, which is favorable for a stable and efficient operation of the converter. Another merit of this circuit is that the capacitor utilization factor becomes as high as 93.8% because of a wide capacitor voltage range (E/2 to 2E). The energy storage capacity can be expanded by 25% as compared with the one without the switchover circuit.

4. EXPERIMENT

4.1 Circuit configuration

In order to confirm the energy management process of the proposed system, a basic experiment using a DC motor has been performed. Figure 6 shows the experimental circuit.

A 100V, 2.2kW, 1,800rpm DC motor having an inertia load runs at a high speed with SW1 on and SW2 off. To generate a breaking current, the field current is increased by closing SW2. At the same time the converter starts to take the regenerative current into the capacitors. SW1 must be turned off in order not to restart the motor. The capacitors start to discharge when SW1 is closed to run the motor. All the starting current should be fed from the converter first, then from the battery.

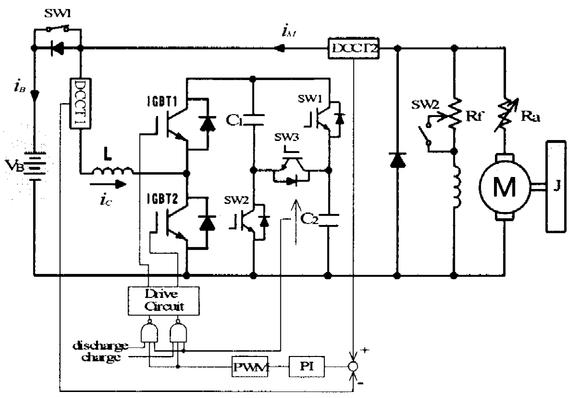

Fig. 6 Experimental circuit with a DC motor

In this experiment, ten 350V, 6,000uF electrolytic capacitors are connected in parallel for C_1 and C_2 in place of the super capacitors. The maximum energy storage is 7,350J.

4.2 Experimental results

Figure 7 is the test results for regenerating operation. The capacitor voltage v_C, the motor current i_M, the converter current i_C and the battery current i_B were recorded to time. It is seen from this figure that a peak motor current of about 20A flows and all of the current is taken into the converter circuit resulting in no battery current. The capacitor voltage rises from the initial 50V (E/2) to about 160V at the end. The series to parallel switchover of capacitors occurs when the capacitor voltage passes through 100V.

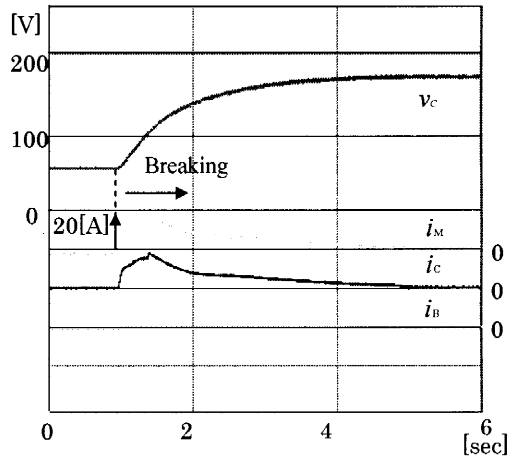

Fig.7 Test results for regenerative braking

Figure 8 is the test results for accelerating operation. It is seen that all the starting current is fed from the converter at first discharging the capacitor then the battery current takes over. The capacitor voltage drops down from 200V to 50V rapidly since the stored energy is too small in this experiment.

Through this experiment it has been shown that the control circuit works quite stable for both braking and accelerating modes confirming the basic energy management process of the system.

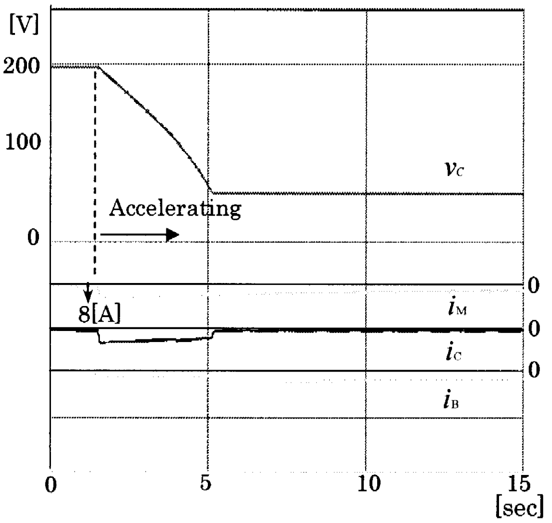

Fig. 8 Test results for accelerating

5. CONCLUSION

For obtaining a better energy efficiency of regenerative braking, a power management system employing a controlled current source using super capacitors has been considered. The basic idea of energy processing method has been explained with a special emphasis on the series-parallel switchover circuit. The experiments using a DC motor confirmed that the system operation was stable and that the series-parallel switchover was effective for expanding the energy storage range of the capacitors. The practical design of this system and test on the actual EV are left for future studies.

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