A Study of increasing regeneration energy using Electric Double Layer Capacitor

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Abstract
This experiment explains about electrical braking equipment using super capacitor. Super capacitors (EDLC) are used to assist output power and save regeneration energy. The experimental equipment is made of battery, BLDC motor and super capacitor (EDLC) for electrical braking simulation. The circuit which can change from serial to parallel for EDLC bank is constituted the experiment equipment. The circuit is designed for regeneration braking that can save the energy from low voltage of generation with BLDC motor. Increasing regeneration energy from braking system is affected by regeneration current and SoC of super capacitor (EDLC). The circuit is suitable for regeneration braking.

Keywords : Regeneration braking; Electrical vehicle; Brush Less Direct Current motor, Electric Double Layer Capacitor

1. Introduction
If we get regeneration energy in kinetic energy of electrical vehicle, it can make high efficiency of energy. Besides, we can get an additional effectiveness that reduces maintenance cost, because it decreases overheat and abrasion of brush of the motor

Recently, study of electrical vehicles is about hybrid system using battery and polymer electrolyte membrane fuel cell. But, driving in city is to repeat of 'stop and start'. In city driving, a EDLC hybrid system is more advantageous than battery hybrid system.

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Generated voltage with BLDC motor is lower than main circuit voltage. The experiment is to make an equipment which can save energy from the low voltage of motor by super capacitor (EDLC). This equipment will save energy of electrical vehicle during city driving.

2. Theoretical background and experiment [3][4]

Main experimental equipment is hybrid system using EDLC and battery. EDLC is the simplified character of "Electric Double Layer Capacitor" which is a super capacitor. A BLDC motor with internal control circuit is used as motor and generator.

2.1 Super capacitor circuit

Super capacitor and battery are chiefly used for hybrid system of fuel cell.[5] Super capacitor is used for assistant power than continuous use.

Fig. 1 shows serial and parallel circuit of capacitors. Electrical character of super capacitors is like general character of a capacitor. Numerical formulas of (1), (2) and (3) are mathematical functions of electrical capacity and saved energy of capacitor.

(Serial): $1/C=1/C_1+1/C_2+⋯+1/C_n[F]$ (1)
(Parallel): $C=C_1+C_2+⋯+C_n [F]$ (2)
(Energy density): $E=(1/2)CV^2 [J]$ (3)

The super capacitor has the characteristic of condenser and battery. So, the energy storage condition expresses by 'SoC (state of charge)'. A numerical formula of (4) is a mathematical function of 'SoC'.

$\text{SoC(\%)} = \left(\frac{V_o}{V_{\text{max}}}\right)^2 \times 100$ (4)

Each capacitor has the same voltage when series connection of capacitors is charged at the same initial SoC state.
Total voltage $V_{AB}$ is equal to the voltage of each bank at the state of parallel connection. Each bank voltage is $V_{ab}$ or $V_{cd}$.
The numerical formula of (5-a) is a mathematical function of one element capacitor's voltage($V_{(1)}$). The numerical formula of (5-b) is a mathematical function of the total voltage as Fig. 1.(a).

$V_{(1)} = (1/3) \times V_{ab} = (1/3) \times V_{AB}$ (5-a)
$V_{AB} = V_{ab} = V_{cd}$ (5-b)

The numerical formulas of (6-a) and (6-b) are mathematical functions of $V_{(1)}$ and $V_{AB}$ after changing from parallel to serial. Total
voltage $V_{AB}$ is the sum of each bank's voltage at serial connection.

$$V_{(1)} = (1/3) \times V_{ab} = (1/6)V_{AB} \quad (6-a)$$

$$V_{AB} = V_{ab} + V_{cd} \quad (6-b)$$

2.2 Electrical braking system

The generator/motor is 500[W] level BLDC motor. BLDC motor’s size is W90*H90*L92 [mm]. It has better efficiency and power than 'DC motor’ or 'induction motor' which has the similar size. But, the rotor is permanent magnet which magnetic flux does not change. It obstructs to make high voltage when the motor is used as generator.

Fig. 2 is the bank by '2.7 Vdc 100F’ EDLC of the NESCAP company which is domestic super capacitor manufacturing company. One bank is made by series connection of 3 super capacitors. It uses the resistance with less error of 1% to remove hazard which is the disparity voltage between the capacitors. The experimental equipment uses 4 banks.

The EDLC bank circuit can change from serial to parallel or vice versa to increase energy recovery. The conversion circuit of the banks is constituted by the 24[V] relay. Fig. 3 is the bank system circuit which is used for electrical brake system. The role of each Relay is shown in the Table 1.

The experimental equipment with fly wheel makes similar situation of braking on real flat ground. Fig. 4 is the external shape of electrical braking circuit.

<table>
<thead>
<tr>
<th>Relay n</th>
<th>Using</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay1</td>
<td>for Bank changing</td>
</tr>
<tr>
<td>Relay2</td>
<td>for Bank changing</td>
</tr>
<tr>
<td>Relay3</td>
<td>for Bank changing</td>
</tr>
<tr>
<td>Relay4</td>
<td>Circuit breaker of Bank</td>
</tr>
<tr>
<td>Relay5</td>
<td>Relay for Dynamic braking</td>
</tr>
<tr>
<td>Relay6</td>
<td>Relay for Dynamic braking</td>
</tr>
<tr>
<td>Relay7</td>
<td>Circuit breaker</td>
</tr>
</tbody>
</table>

Fig. 2. EDLC bank module (2 parts)
Fig. 3. Electrical braking circuit
(V1: Circuit voltage V2: Module voltage A1: Current)

3. Result

Fig. 5 shows open circuit voltage which is measured at each 100rpm increase. The voltage of generation with BLDC motor at 1500rpm is about 12.5[V]. So, if the main voltage of circuit is maintained at 24[V], it can not get regeneration energy of the motor.

When regeneration braking system is applied with cutting off circuit’s main voltage, regeneration energy can be saved if EDLC bank’s voltage is lower than generated voltage by motor.

3.1 Driving BLDC motor without change of EDLC bank’s circuit

Battery voltage (main voltage: “Circuit voltage”) and super capacitor voltage (EDLC: “Module voltage”) voltage and regeneration current (“Current”) and speed change (“Rpm”) of motor are measured. Fig. 6 shows change of data by time in hybrid state of battery and super capacitor.

Table 2 is switching time table of relays. Relays 1, 2, 3 and 4 are turned off not to change EDLC bank’s circuit. At 200[s], relay 7 cuts off the main power of battery to measure regeneration energy. The fly wheel
turns motor by inertial force. The motor stopped completely at 237 [s].

Fig. 5. Open circuit voltage of BLDC motor

Regeneration current did not happen between 200[s] and 237[s]. This result shows that the battery and super capacitor did not acquire regeneration energy. Because bank’s voltage was about 24 [V], it is impossible to get regeneration energy by generation voltage of motor.

Fig. 6. Driving BLDC motor with battery and EDLC (Not change the EDLC module, @24.5[V])

3. 2 Driving BLDC motor with change of EDLC bank’s circuit.

This experiment is to get regeneration energy by switching condenser bank’s circuit during braking power is applied. Fig.7 shows V1 (Circuit voltage) and super capacitor voltage (EDLC : Module voltage) and regeneration current (Current) and speed change (rpm) of motor by time.

Table 3 is switching time table of relays. Relays 1, 2 and 3 are turned on between 145 and 187[s] for switching bank’s circuit. Relay 7 cuts off battery power to measure regeneration energy. During 145~187 [s], banks are kept in parallel to know whether module voltage is the same with main voltage by conversion of bank’s circuit. During 187~196[s], the banks are connected in series again to know whether whole module voltage is risen up. Finally main power of battery is connected to the circuit system.
Regeneration current appeared as triangle wave form which continues about 5[s]. Because the module voltage is about 4.26[V] in parallel connection which is low enough to save regeneration energy. Circuit voltage and module voltage become the same because regeneration energy current flows into the modules to make the module voltage high. At last the whole voltage rises up to about 24[V] when the banks are connected in series again at 187[s].

<table>
<thead>
<tr>
<th>Relay</th>
<th>0~145(s)</th>
<th>145~187(s)</th>
<th>187~196(s)</th>
<th>196~215(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relay 1</td>
<td>×</td>
<td>o</td>
<td>×</td>
<td>×</td>
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<tr>
<td>Relay 2</td>
<td>×</td>
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<td>Relay 4</td>
<td>×</td>
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<td>Relay 6</td>
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<tr>
<td>Relay 7</td>
<td>×</td>
<td>o</td>
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</table>

(○: Relay on, ×: turn off)

3.3 Regeneration energy

Saved regeneration energy in super capacitors is calculated by equation (8) with measured voltage change.

\[
E = \frac{1}{2} \times \left( \frac{100}{3} \right) \left( V_2^2 - V_1^2 \right) \times 4\text{[J]} \quad (7)
\]

Fig. 8 shows quantity of regeneration energy by SoC state. Fig. 9 shows peak current time and current flow time as a function of EDLC module voltage. Fig. 9 shows that more energy is saved when SoC is lower because of more difference between generated voltage and module voltage. But, charging is not good at the module voltage of 1.5[V] - (Cell voltage : 0.5 [V], SoC : 3. 43% ). The reason is EMF (electromotive force) effect by sudden change of electric current. Therefore, optimum module voltage to save the most regeneration energy is 3.0 [V] as shown in Fig. 8.

Fig. 8. Regeneration energy according to SoC as a function of motor rpm
4. Conclusion

1. Regeneration energy can be saved by changing the bank's circuit from serial to parallel even though the generation voltage of motor is low.
2. Saved energy in the super capacitors can be used to motor as hybrid system with battery when the bank's circuit is changed from parallel to serial.
3. Saving of regeneration energy is affected by SoC of super capacitor (EDLC).

Acknowledgements

This work was supported by the Brain Korea 21 Project in 2004.

Reference

[4] Dong Kuk Song, An Implementation of Regeneration Braking Controller using DSP for Electric Motor Car, Pusan National University, p1, 1999

Fig. 9. Peak current and current flow time as a function EDLC module voltage(SoC) - (@1500rpm)