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Design and Control Algorithm Research of Active Regenerative Bidirectional DC/DC Converter used in Electric Railway

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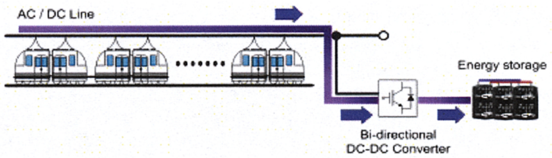
Abstract—The regeneration power which is generated braking period of railway vehicles is increasing voltage of DC-line, and excessive voltage of DC-line is generating several problems. So, it's very important issue to DC traction system about dealing with regenerate power. Regeneration energy storage system is one of the methods to use the regeneration energy efficiently and to improve the problems. In this paper, we proposed the design and efficient control algorithm of the bidirectional DC/DC converter used in electric railway for utilization of regeneration energy. And as realization of prototype model, we verified the efficiency of bidirectional DC/DC converter.

I. INTRODUCTION

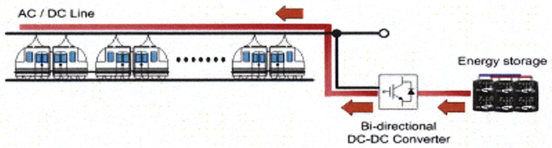
The regeneration energy caused increasing the DC-line voltage because of flow the regeneration energy into the DC-line. And excessive voltage in DC-line is caused many problems to overall system. So, DC-line voltage must be controlled as maintaining regulated value. It is possible to use bidirectional DC/DC converter. The current which flow into the DC-line is the high value current and changing frequently. So, super capacitor is used in system to charged regeneration power. Super-capacitor can store the current which any amount of that. But super-capacitor has the weak point like high cost and rated voltage is so low. So, we proposed the converter algorithm which could operate two modes. First mode is buck converter mode, and second mode is boost converter mode. By the buck-boost operation, bidirectional converter could control the charge and discharge operation. Regeneration energy storage system is able to increase the reliability as controlling the bidirectional DC/DC converter. In this paper, we are proposing a new control algorithm of converter and proved the efficiency of our algorithm through PSIM simulation, and experiment with prototype model.[1-3]

II. THE OPERATION OF BIDIRECTIONAL DC/DC CONVERTER OF REGENERATIVE ENERGY STORAGE SYSTEM

Regenerative energy which is increasing the DC-line voltage controlled by bidirectional DC/DC converter through charge/discharge operation of super-capacitor. Energy flow by generating regenerative energy can be seen in Fig. 1.



(a) Charge modes



(b) Discharge modes

Fig. 1 Schematic power flow diagram of regenerative energy.

Bidirectional DC/DC converter controlled power flow of regenerative energy by variation of DC line voltage. This paper used non-isolation half-bridge type converter to realize the bidirectional DC/DC converter because half-bridge converter has a low inductance value and low capacitance of passive elements and low rated voltage of active elements appropriated in energy storage system in DC traction application. Comparison of converter topologies shows in appendix of last paper. Bidirectional DC/DC converter proposed in regenerative energy storage system using super-capacitor can be seen in Fig. 2.

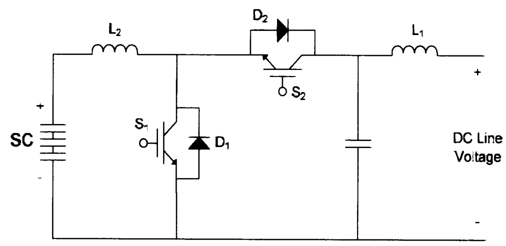


Fig. 2 Non-isolation half-bridge bidirectional DC/DC converter.

Half-bridge DC/DC converter operated as buck converter when charge mode and operated as boost converter when discharge mode.[4-8] Half-bridge DC/DC converter prototype design parameters can be seen in Table 1.

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TABLE 1
DESIGN PARAMETER OF BIDIRECTIONAL DC-DC CONVERTER.

Means	Value
Maximum Discharge Power	4 [kW]
Voltage range of Super-capacitor	50~100[V]
Maximum current of Super-capacitor	50 [A]
Input voltage of Converter (DC Line voltage)	311 [V]
Input current of Converter	10 [A]
Switching Frequency	10 [kHz]

A. Charge mode

Due to the increasing of DC-line voltage bidirectional DC/DC converter operating as buck converter and charging a increasing value in super-capacitor. Switch 2 is operating as active switch element and Switch 1 is operating diode. During the charging mode Switch 2 is operating on/off switching operation frequently as duty ratio DT_S in a T_S cycle. Charge mode operation of bidirectional DC/DC converter can be seen in Fig. 3[4-8]. And output of bidirectional DC/DC converter in charge mode can be seen in Fig. 4 and according to the Fig. 4, balance condition of $Vol \cdot \sec$ shows in equation (1) and duty ratio of bidirectional DC/DC converter when charge mode can be expressed in equation (2).

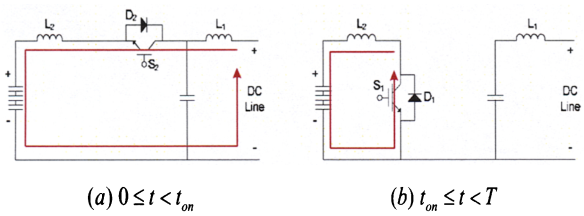

Fig. 3 Charge mode operation of bidirectional DC-DC converter.

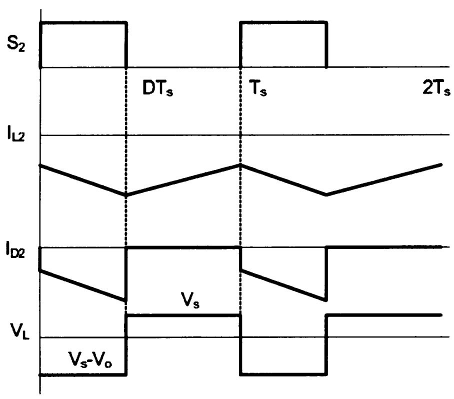

Fig. 4 Output waveform of charge mode.

$$(V_O - V_S)DT_S = V_S(1-D)T_S \tag{1}$$

$$D = \frac{V_S}{V_O} \tag{2}$$

B. Discharge mode

When the DC-line voltage decreased or increasing a retrograde vehicles operation, regenerative energy charged in super-capacitor is supplied into the DC-line through a bidirectional DC/DC converter. This mode was designated as Discharge mode. In this mode, bidirectional DC/DC converter operating as boost converter and Switch 1 is operated as active switch and Switch 2 is operated as diode contrary to the charge mode. During the discharging mode Switch 1 is operating on/off switching operation frequently as duty ratio DT_S in a T_S cycle. Fig. 5 and Fig. 6 can be seen such as discharge mode operation of bidirectional DC/DC converter and output of discharge mode operation.[4-8] Similar to the charge mode discharge mode equation can express according to the Fig. 6, balance condition of $Vol \cdot \sec$ as follows. And duty ratio of bidirectional DC/DC converter when discharge mode can be expressed in equation (3) and (4).

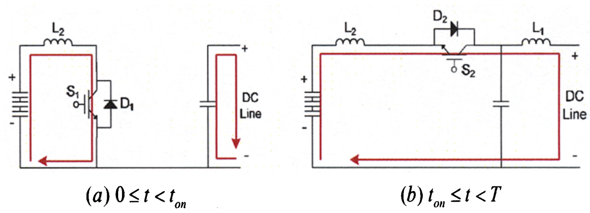

Fig. 5 Discharge mode operation of bidirectional DC-DC converter.

$$V_S \cdot DT_S = (V_O - V_S)\cdot(1-D)T_S \tag{3}$$

$$D = \frac{V_O - V_S}{V_O} \tag{4}$$

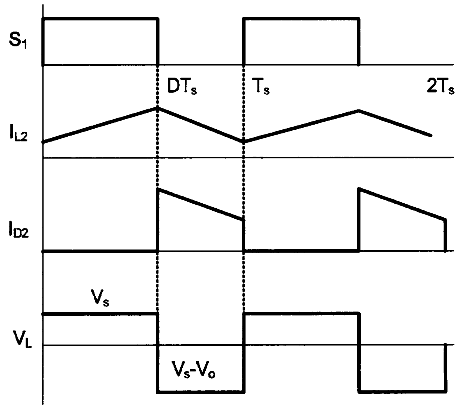

Fig. 6 Output waveform of discharge mode.

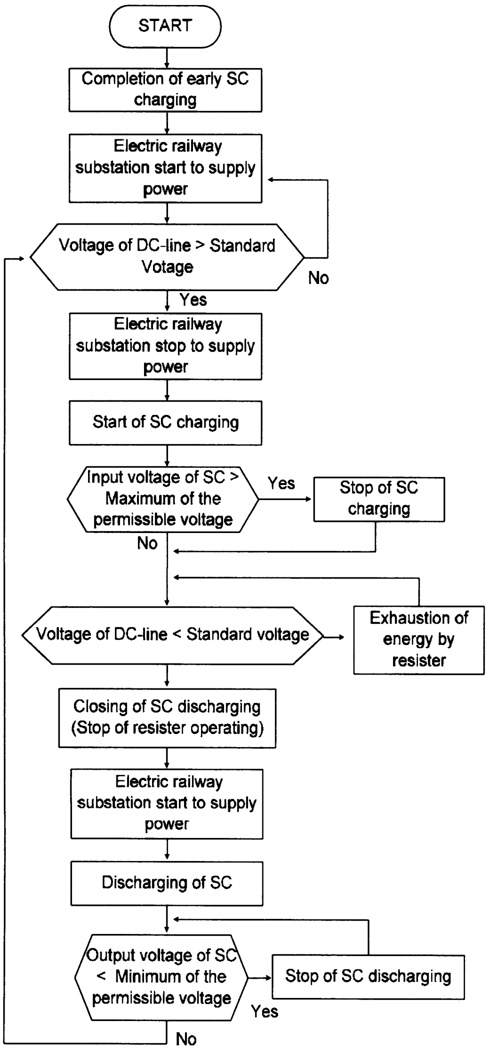

Fig. 7 Control algorithm of regenerative energy storage system.

This paper proposes a control algorithm of bidirectional DC/DC converter which according to the characteristics of super-capacitor. Fig. 7 shows the diagram of control block to control the regenerative energy storage system. In this algorithm, super-capacitor needs initial charging time because the system demanding a large voltage in early stage. And charging operation to the super-capacitor is starting when all vehicles were generating the regenerative energy and when the retrograde vehicles were nonexistence at the moment because that cases caused DC-line voltage rising. If the regenerative energy is generating continuously over the capacity of super-capacitor, regenerative energy which over the capacity of super-capacitor sent into the resistor and dissipated as heat energy.

The prototype model of regenerative energy storage system is shown in Fig.8.

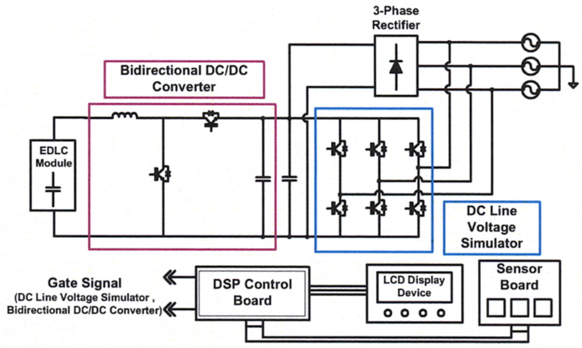

Fig. 8 The prototype model of regenerative energy storage system.

III. SIMULATION RESULTS

The simulation composition of the prototype model and operational standard value Fig. 9 and table 2 as follows.

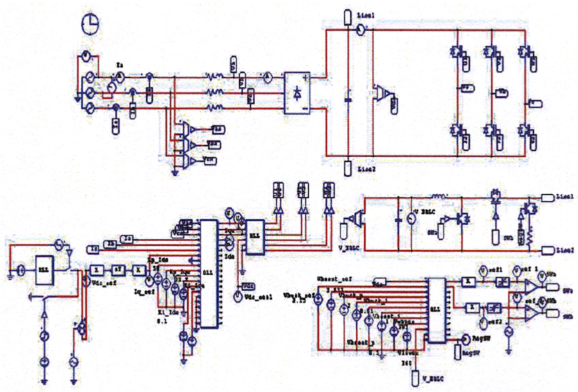

Fig. 9 Scheme of regenerative energy storage system by PSIM.

TABLE 2
CONDITION OF SIMULATION

Condition	Value
Input Voltage	220 [V]
Charge	Over the 370[V]
Discharge	Down the 350[V]
Resistor Operation	DC Line : Over the 370[V] EDLC : Over the 100[V]

Buck mode operations of the bidirectional DC/DC converter that simulated DC-line voltage will rise above 370V it charges in EDLC. And when the DC-line voltage falls below 350V, EDLC energy discharging, it is risen DC-line voltage 350V by bidirectional DC/DC converter boost mode operation. When the voltage of EDLC is charged to 100V completely and the DC-line voltage is over the 370V, charging operation into the EDLC is impossible anymore. Therefore regenerative energy is consumed by the resistor in this case.

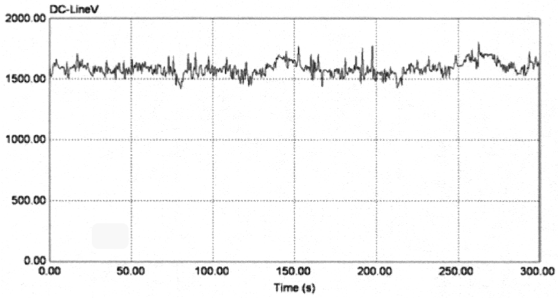

Fig. 10 Variation of DC-line voltage according to the station of Sillim.

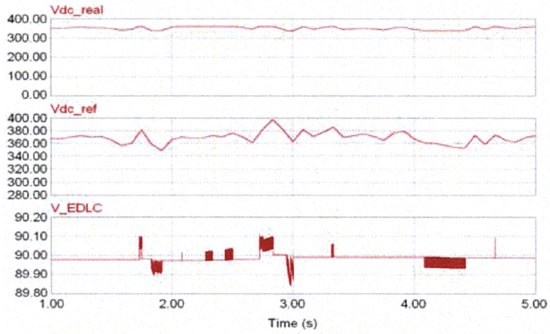

Fig. 11 The graph of simulation result.

Fig. 10 is DC-line voltage data of the Sillim station that was measured. Simulation is simulated by using measured DC-line voltage. Fig. 11 is the wave of simulation result. The first graph is waveform of the DC-line voltage which has become stable. The second waveform is the DC-line voltage that bidirectional DC/DC converter is not applied. The third graph is voltage of EDLC which is charged and discharged.

IV. EXPERIMENT SETUP AND RESULTS

Fig. 12 is the actual composition set of the prototype model. Fig. 13 through 16 shows charging and discharging current and voltage waveform by bidirectional DC/DC converter. The DC-line voltage charged into the EDLC dropped at 100V by the bidirectional DC/DC converter, and it can be seen in Fig. 13. Fig. 14 showed the charging current of EDLC and input current of bidirectional DC/DC converter.

In discharging mode, EDLC voltage is operating with 311V which boosted from 100V by switching operation of boost mode, and it can be seen in Fig. 15.

Fig. 17 is shown the output voltage of the DC-line voltage simulator and Fig. 18 shows the result waveform that stabilized by bidirectional DC/DC converter. As you can see in Fig. 17-18, when the DC-line voltage increasing over 370V, bidirectional DC/DC converter operating as buck converter to charge the voltage into the EDLC, and when the DC-line voltage decreasing down 350V, bidirectional DC/DC converter operating as boost converter to discharge the voltage of EDLC into the DC-line. And through those operations, DC-line voltage keeps up the voltage of 350V.

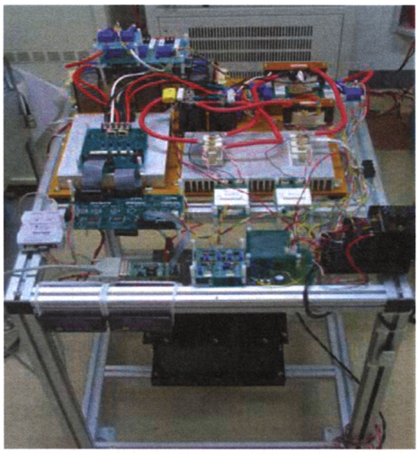

Fig. 12 Proposed prototype model.

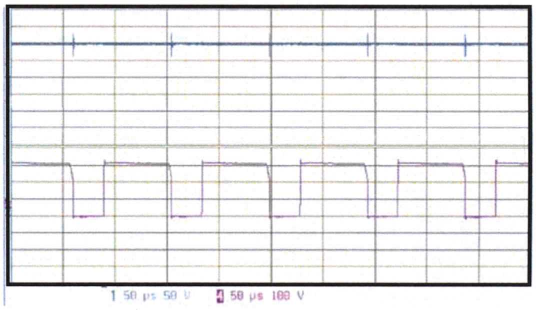

Fig. 13. Charging mode (Buck mode).
Top : Supercapacitor charging voltage, Bottom : Switch voltage.
(50V/div, 100V/div, 50us/div)

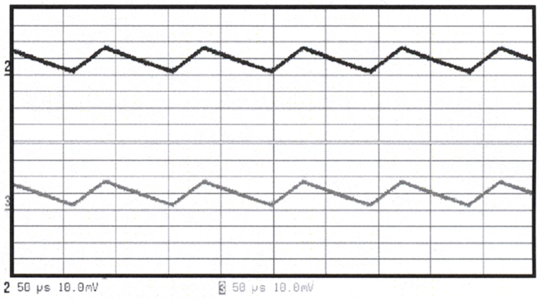

Fig. 14 Charging mode (Buck mode).
Top : Supercapacitor charging current, Bottom : Input current.
(4A/div, 50us/div)

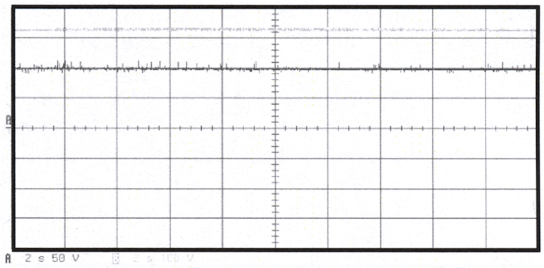

Fig. 15 Discharging mode (Boost mode).
Top : Output voltage , Bottom : Supercapacitor discharging voltage.
(Top: 100V/div, Bottom: 50V/div, 2s/div)

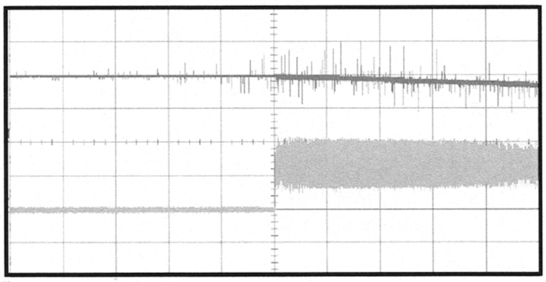

Fig. 16 Discharging mode (Boost mode).
Top : Supercapacitor discharging voltage, Bottom : discharging current.
(4A/div, 50us/div)

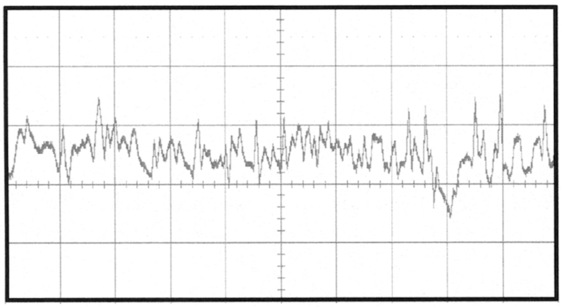

Fig. 17 Output voltage of the DC-line voltage simulator.
(30V/div, 10s/div)

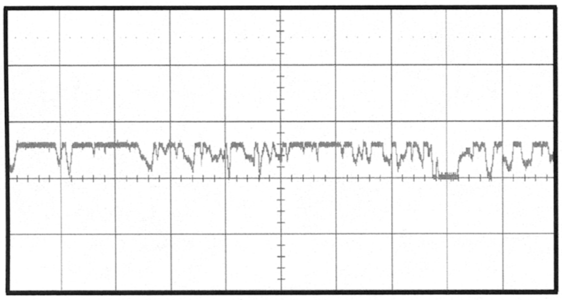

Fig. 18 The DC-line voltage that the bidirectional DC/DC converter is applied. (30V/div, 10s/div)

V. CONCLUSION

There is the method which using storage system for efficiently usage of regenerative energy that generated by DC traction.

In this paper, we propose the half bridge type bidirectional DC/DC converter. And efficient control algorithm and design method of bidirectional DC/DC converter which applied for regenerative energy storage system used in DC traction system are proposed also, for improvement of the efficiency of whole system.

Through the simulation and experimental results, it can be confirmed that regenerative energy use safely, and DC-line is stable. Consequently, it is expected that proposed converter topology and control algorithm will improve the efficiently usage of regenerative energy in real regenerative energy storage system.

APPENDIX

TABLE A1
VOLTAGE AND CURRENT COMPARISON AMONG THE BIDIRECTIONAL DC-DC CONVERTER TYPE

	Half-bridge	Cuk	Sepic
Switch V_{peak}	V_o	$V_{in}+V_o$	$V_{in}+V_o$
Diode V_{peak}	V_o	$V_{in}+V_o$	$V_{in}+V_o$
Capacit V_C	•	$V_{in}+V_o$	V_{in}
or Switch I_{peak}	$H.B < Cuk = Sepic$	$H.B < Cuk = Sepic$	$H.B < Cuk = Sepic$

TABLE A2
ACTIVE ELEMENTS COPACITY COMPARISON AMONG THE BIDIRECTIONAL DC-DC CONVERTER TYPE

	Half-bridge	Cuk	Sepic
L_1	*Small*	*Large*	*Large*
L_2	•	$Cuk = Sepic$	$Cuk = Sepic$
C_1	*Large*	*Small*	*Large*
C_2	•	$Cuk = Sepic$	$Cuk = Sepic$

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