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Regenerative Current Control Method of Bidirectional DC/DC Converter for EV/HEV Application

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Abstract – The control method of the bidirectional DC/DC converter for instantaneous regenerative current control is described in this paper. The general method to control the DC/DC converter is the output voltage control. However, the regenerative current cannot be controlled to be constant with this control method. To improve the performance of the conventional control method, the DC-link voltage of the inverter is controlled within the tolerance range by the instantaneous boost and buck operations of the bidirectional DC/DC converter. By the proposed control method, the battery current can be controlled to be constant regardless of the motor speed variation. The improved performance of the DC/DC converter controlled by the proposed control method is verified by the experiment and simulation of the system with the inverter and IPMSM(Interior Permanent Magnet Synchronous Motor) which is operated by the reduced practical speed profile.

Keywords: Bidirectional DC/DC converter, EV/HEV application, Regenerative current control

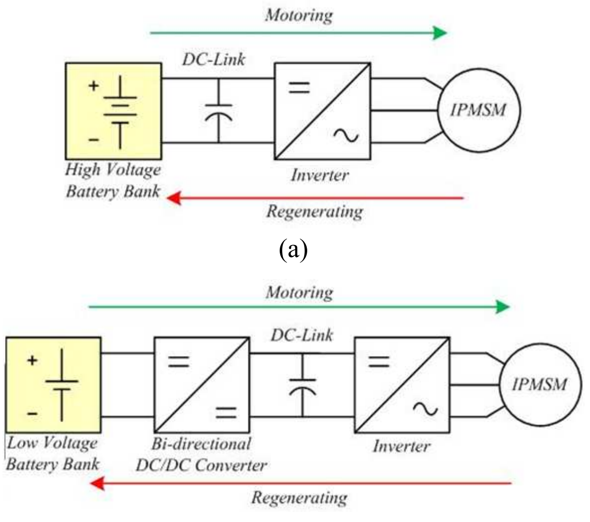
1. Introduction

The most important automotive application of the electrical system is the traction system. This electrical traction system is divided into two categories according to the type of power conversion system [1, 2]. Fig. 1 shows the conceptual diagram of these two power conversion systems. As shown in Fig. 1, the first type uses only the high voltage battery and inverter, and the second type uses comparatively low voltage battery and DC/DC converter which boosts the DC-link voltage and inverter for motor driving.

As in Fig. 1(a), the type which is composed of only battery and inverter has the benefit that efficiency can be increased by minimizing the power devices. However, a high voltage battery is generally composed by a series of connected battery cells of low voltage output. The more the series connected cells are used, the more problems it created such as voltage unbalance of each cells or decrement of life expectancy of the battery. Moreover, the system of Fig. 1(a) has demerit because the output voltage is varied by the output current. It is caused by the internal resistor of battery. This variation of the output voltage limits the inverter output power and control performance.

To overcome these problems, two-stage EV traction system of Fig. 1(b) is proposed in [1]. This system additionally attaches the DC/DC converter controls the bidirectional power flow between the inverter and battery. The system is more complex than the system of Fig. 1(a). However, adjustable boosted voltage makes EV traction system use comparatively small voltage of battery and various traction motors according to EV power capacity. Besides, this system maintains the DC-link voltage of inverter within tolerance range whatever the inverter current is.

Many topologies are developed for the system of Fig. 1(b). Among them, the DC/DC converter of full-bridge type is described in [3, 4], and the converter using transformer is shown in [5-7]. These topologies have



(a)

(b)

Fig. 1. Conceptual diagram of EV traction system (a) One stage inverter EV traction system (b) Two stages (Bi-directional converter and inverter) EV traction system

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merits of ZVZCS switching or high boosted output voltage. However, the needs of comparatively many devices to compose the topology and the increased size of the devices are the critical problems. The general topology of the converter for the traction system is a half-bridge type bidirectional DC/DC converter [1, 2, 8, 10]. The converter for Fig. 1(b) should generate high power for the traction system. However, the inductor and capacitor size is proportional to the capacity of the generated power. Sincespace is limited in the automotive system, the increased size of the inductor and the capacitor for this topology is a burden of two-stage EV traction system.

Moreover, the control for this bidirectional converter is also a complex problem. Half bridge type bidirectional DC/DC converter is alternatively operated as boost and buck mode. Two independent controllers for each mode are inevitable and the gain of boost and buck operation is different [9]. To solve this problem, bidirectional DC/DC converter controls only the DC-link voltage and the inverter takes current control of the battery. Generally, this control method is called regenerative braking control, in which adequate charging current reference is modified to torque reference and it is inserted on inverter controller. [10-13] Among this research, in [10], the battery current is controlled by the look-up table for torque per current which is established by experiment. However, it is tiresome to establish the look-up table, and the actual battery current can be varied by the motor parameter and speed. Moreover, the error between the actual current and the reference current cannot be compensated because the battery current is only controlled by the open loop control, not by the closed loop control. Also, constant current control of bidirectional DC/DC converter is important for battery charging efficiency. The reason is that if the regenerative current is lower than a certain value, it cannot ionize the electrode surface of battery. This current under a certain value cannot charge the battery [17].

The constant current control for the battery is proposed in this paper. With this prototype of the two stages EV traction system, motoring and regenerating operation is performed according to the speed profile of practical road drive. From these results, charging energy can be increased with proposed control method.

2. Characteristics of Three Phase Interleaved Bidirectional DC/DC Converter

Bidirectional DC/DC converter is supplied with energy from battery to boost inverter DC-link voltage. This converter should also control regeneration power instantaneously to prevent the increment of DC-link voltage. The bidirectional DC/DC converter in this paper is composed of three parallel connected half-bridge buck-boost converters as shown in Fig. 2. This interleaved converter has merits that the inductance and capacitance of converter, which are determined by tolerance range of current and voltage ripple can be reduced.

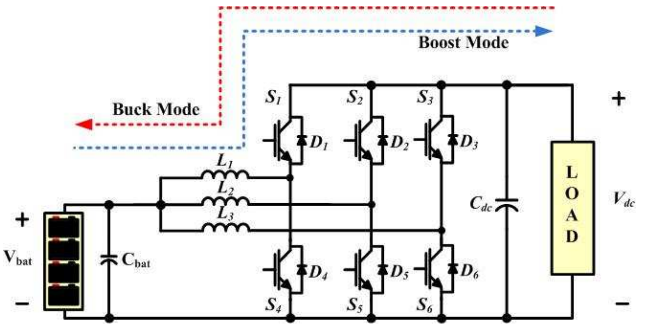


Fig. 2. Circuit of Bi-directional DC/DC converter

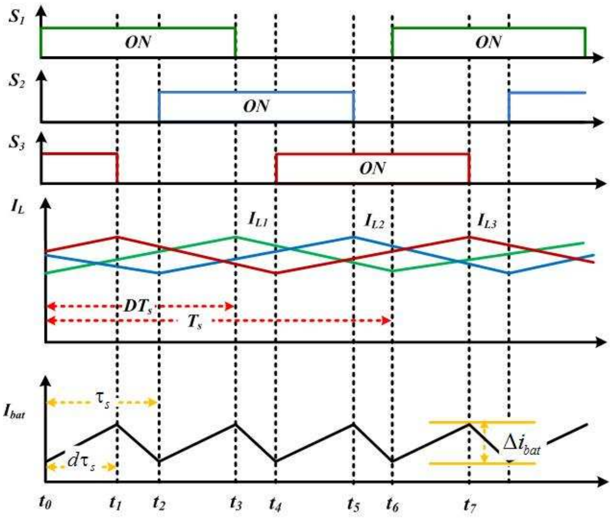


Fig. 3. Switching signal and current waveforms of the three phase interleaved boost converter

Fig. 3 shows the switching signal and current waveforms of three phase interleaved boost converter. The fundamental operation and design method for three phase interleaved converter is described on [1].

3. Control Method of Bidirectional DC/DC Converter

In the general traction system of Fig. 4, the control system is classified by upper controllers and lower controllers. Upper controllers make current, torque and voltage references according to the vehicle circumstance, such as speed, accelerator or temperature and so on. Lower controllers control the devices to follow the references from upper controllers. In the upper controllers, BMS (batterymanagement system) performs the important role to determine the optimized charging current for battery. General control method to follow this optimized current reference, that is, inverter control method by the reverse torque generation is described on [10-13].

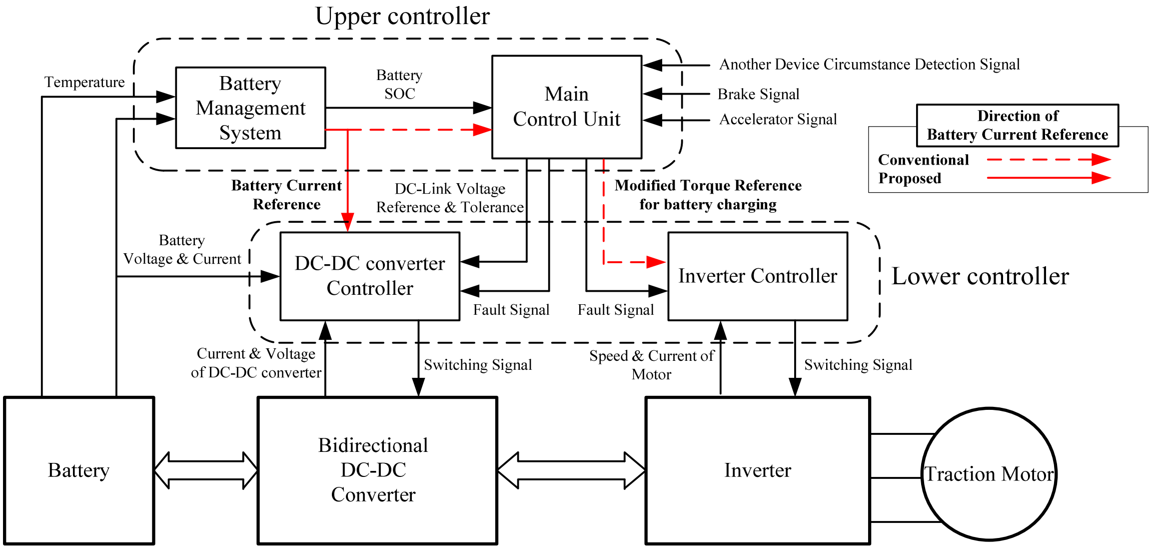


Fig. 4. Signal flow block diagram for traction system

However, with this method, battery current does not constantly controlled due to the variation of motor speed and parameter. One of the most difficult problems in conventional method is that the regenerative energy of the inverter cannot be estimated by DC-link current. As widely known, the actual inverter DC-link current is corrupted by the switching of inverter and back-EMF voltage of traction motor. Extracting the effective component of this current is difficult because the frequency of DC-link current ripple is varied by the motor speed. DC-link current of inverter can be described in (1).

$$\begin{aligned} i_{DC}(t) &= \frac{3V_0 I_0}{V_{dc}}\cos\phi + k_1 \frac{3V_0 I_0}{V_{dc}}\cos(6\omega_r t - \phi) + k_2 i_{SW}(t) \\ &= I_{dc} + \tilde{i}_{DC1}(t) + \tilde{i}_{DC2}(t) \end{aligned} \tag{1}$$

where, V_o and I_o are root-mean-square values of back-EMF voltage and phase current of traction motor respectively,and ϕ is the phase difference between back-EMF and phase current.

In (1), the first component I_{dc} is DC component, which is the effective component of the regenerative energy. The second component $\tilde{i}_{DC1}(t)$ is the 6th harmonic component which is caused by the back-EMF and DC-link voltage. The third component $\tilde{i}_{DC2}(t)$ is theswitching current ripple. Observing the DC-link current, the switching current ripple $\tilde{i}_{DC2}(t)$ can be easily removed by LPF. However, harmonic component $\tilde{i}_{DC1}(t)$ cannot be easily removed because the harmonic frequency is varied by motor speed.

To control the constant regenerative current, the current reference is inserted to DC/DC converter controller in contrast to conventional methods, in which the current reference is inserted toinverter controller as shown in Fig. 4 [10-13]. The regenerative energy can be estimated through the increase of DC-link voltage. The useless components of DC-link current are dissipated by capacitor filtering and the effective energy only increases the DC-link voltage, whatever current flows in (1). The increase of DC-link voltage can be calculated by (2).

$$\begin{aligned} \Delta V_{dc} &= \frac{1}{C}\int i_{DC}(t)dt \\ &\approx \frac{1}{C}\int I_{DC}(t)dt \end{aligned} \tag{2}$$

From (2), relation between DC-link voltage and regenerative energy can be calculated by (3).

$$\Delta V_{dc} = \int \frac{E_{reg}}{C}\frac{1}{V_{dc}}dt \tag{3}$$

where, $E_{reg} = 3V_o I_o \cos\phi$ is the regenerative energy.

When the inverter operates in regenerative mode, the DC-link voltage is increased by ΔV_{dc} of (3). To control this voltage, hysteresis DC-link voltage controller is used in this paper. DC-link voltage is regulated within the bandwidth of certain limitation. Fig. 5 shows the overall control block diagram of bidirectional DC/DC converter for handling the regenerative current reference of Fig. 4. If the DC-link voltage is under the upper limit, the converter should operate as boost mode. In boost mode, $\boldsymbol{k}_2$ signalfrom hysteresis DC-link voltage controller output-activates the boost mode controller. Current control and voltage control for constant DC-link voltage are performed byswitching signal $\boldsymbol{S}_2$. On the other hand, if the DC-link voltage reaches the upper limit, the operation mode of the converter changes into buck mode. In buck mode, $\boldsymbol{k}_1$ signal from hysteresis DC-link voltage controller outputactivates the buck mode controller.Current control for constant

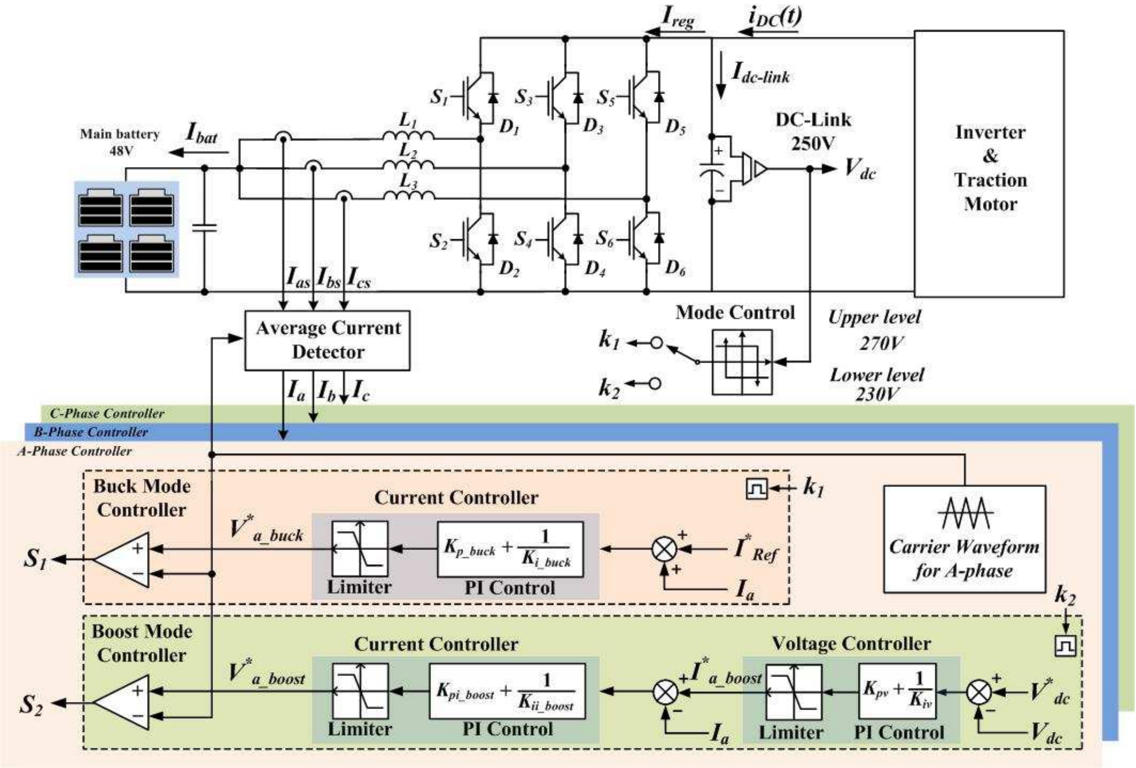


Fig. 5. Overall control block diagram of bi-directional DC/DC converter

battery current to follow the I^*_{Ref} from BMS is performed by switching signal S_1.

Fig. 6 shows the comparison of regenerative operation between conventional method and proposed method. Generally in EV/HEV drive, if the reverse torque is generated from the motor, motor speed is gradually decreasing. Since regeneration energy is the multiplication of torque and speed, the energy is also decreasing according to the motor speed. In conventional method, because the DC-link voltage is controlled to be constant, regenerative current is directly affected by this regeneration energy variation. Regeneration energy of (3) can be differently expressed by (4).

$$E_{reg} = V_{dc}(I_{reg} + I_{dc-link}) = T_e \omega_r \tag{4}$$

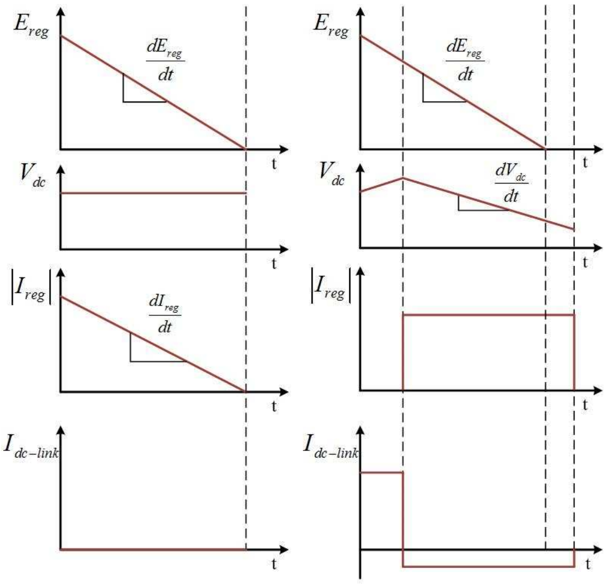
where, T_e is motor torque. ω_r is motor speed. I_{reg} is DC-link current for battery charging ($I_{reg} = DI_{bat}$). $I_{dc-link}$ is DC-link capacitor current in Fig. 6.

From the equation (4), I_{reg} can be obtained as (5),

$$I_{reg} = \frac{T_e \omega_r}{V_{dc}} \tag{5}$$

As already mentioned, since the DC-link voltage is constantly controlled in conventional method, I_{reg} is decreasing. This reduced current makes the charged current to decrease. If this charging current is under a certain limit, it cannot ionize the battery and just flow through [17]. Because of this current which is not able to charge the battery, regenerative energy cannot be fully used for charging the battery. To increase the effective charging current, DC-link voltage is simultaneously decreased for constant I_{reg} in the proposed control method.

The slope of DC-link voltage in regenerative operation



(a) (b)

Fig. 6. Comparison of regenerative operation between conventional method and proposed method (a) Conventional method (b) Proposed method

is proportional to the motor speed variation, which is obtained by derivative of (4) and (5). In thismanner, the slope of DC-link current for battery charging is obtained by (6).

$$\begin{aligned} \frac{dE_{reg}}{dt} &= T_e \frac{d\omega_r}{dt} \\ \frac{dV_{dc}}{dt} &= \frac{T_e}{I_{reg}} \frac{d\omega_r}{dt} \\ \frac{dI_{reg}}{dt} &= \frac{T_e}{V_{dc}} \frac{d\omega_r}{dt} \end{aligned} \tag{6}$$

As shown in Fig.6, in contrast to conventional method, constant current control can be achieved with proposed method regardless of speed variation.

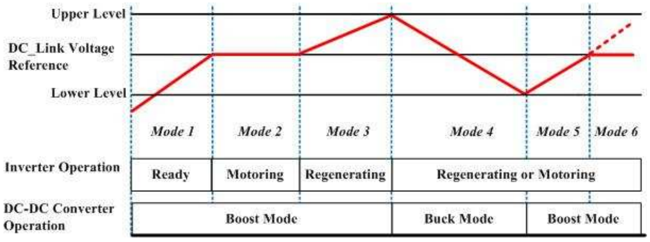


Fig. 7. DC-Link voltage variation range according to the operation mode of inverter and converter

Fig. 7 shows the range of DC-link voltage variation according to the inverter and converter operation with control method of Fig. 5. As already mentioned, the operation mode of the DC/DC converter is changed by the DC-link voltage. Each DC-link voltage variation can be divided into six modes. Mode 1, 2, 3, 5, 6 are boost operation, and Mode 4 is buck operation of DC-DC converter.Mode 1 is preparing operation for suitable DC-link voltage of inverter. If the DC-link voltage reaches the reference, Mode 1 is end and Mode 2 is start.Detailed explanation of these operation modes is explained on Experiment section with inverter operation.

4. Simulation

The simulation of buck mode and boost mode is performed to verify the effectiveness of the proposed bidirectional DC/DC converter. PSIM 6.0 is used as simulation tools and sampling time of simulation is 1 [μ sec]. The specification of the bidirectional DC/DC converter and the test motor is shown in Table 1 and Table 2, respectively. In DC/DC converter, the switching frequency is 10 [kHz], nominal battery voltage is 50.7[V] and DC-link voltage is 250 [V]. From the parameters of Table 2, MTPA control illustrated in [15] and [16] is performed by look-up table for d-q current references.

Table 1. Specification of Bi-directional DC/DC converter

List	Parameter	Unit
Rated power	4	[kW]
Inputvoltage(battery voltage)	50.7	[V]
Inputcurrent(battery current)	80	[A]
Outputvoltage(DC-link voltage)	250	[V]
Outputcurrent(DC-link current)	16	[A]
Switching frequency	10	[kHz]

Table 2. Specification of IPMSM for Traction motor

List	Parameter	Unit
Rated Power	3.7	[kW]
Phase resistor	0.03	[Ω]
Inductance of d-axis(L_d)	0.848	[mH]
Inductance of q-axis(L_q)	1.484	[mH]
Rated Speed	1500	[rpm]
Rated Torque	20	[Nm]
Number of Pole	8	[Pole]

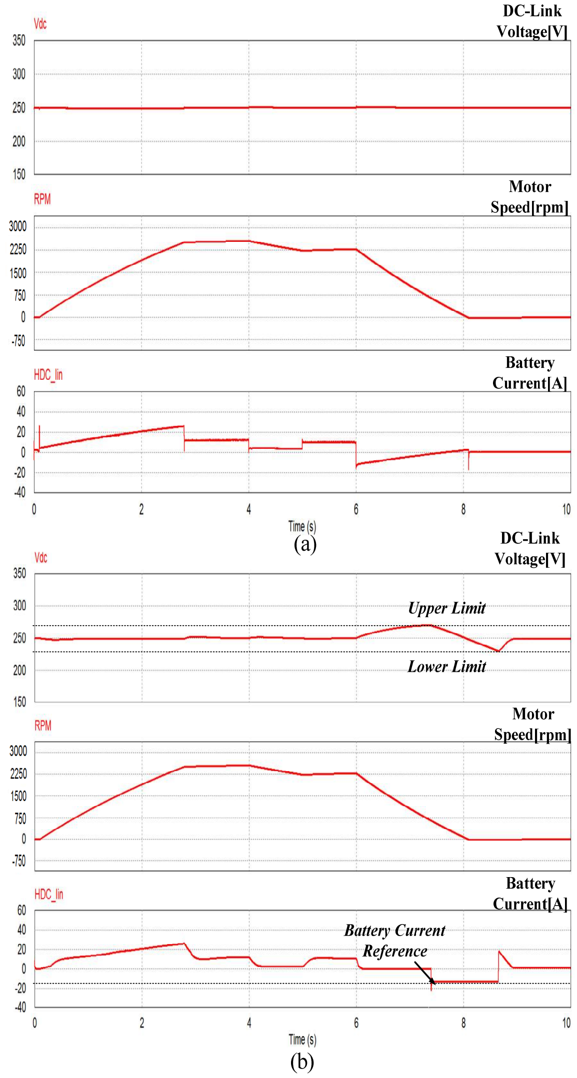
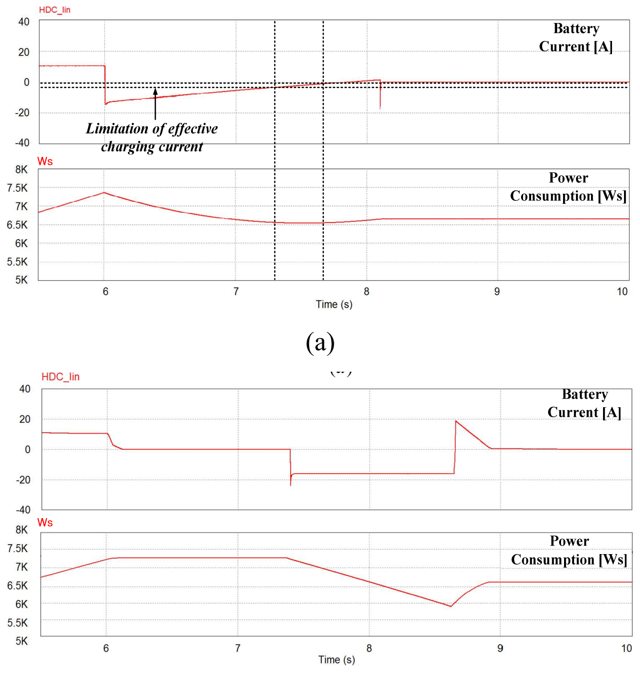


Fig. 8. Comparison results between the conventional method and proposed method (a) Conventional method (b) Proposed method



(a)

(b)

Fig. 9. Magnified current and power consumption at regenerative operation (a) Conventional method (b) Proposed method

Fig. 8 shows the results of comparison between the proposed method and the conventional method. From Fig. 8(a), although the DC-link voltage is controlled properly, the high peak of battery current is occurred. Moreover, the regenerative current is reduced according to the decrement of motor speed. On the other hands, with proposed method, although DC-link voltage has some ripples, battery current is controlled constantly and follows the current reference until the DC-link voltage reaches the lower limit.

If the regenerative current is lower than a certain value, it cannot ionize the electrode surface of battery. This current under a certain value cannot charge the battery [17]. This minimum regenerative current is generally determined as 0.025C of battery. ('C' means polarization coefficient of battery: C-rate) [18]. If 1C of the battery is rated current of DC/DC converter which is illustrated on Table 1, the minimum regenerative current can be determined as 2 [A].

5. Experiment

Fig. 10 and 11 show the experimental setup of the EV/HEV in the operation of reduced scale. Overall system is composed of three phase bidirectional interleaved converter and voltagesource inverter with 3.7 [kW] IPMSM (Interior Permanent Magnet Synchronous Motor) of Table 2 and battery bank. Specification of battery back is described on Table 3.

Table 3. Specification of battery bank

List	Parameter	Unit
Rated Capacity	80	[Ah]
Nominal Voltage	12.1	[V]
Type of battery	Lead-acid	
Composition	4 series-connected	

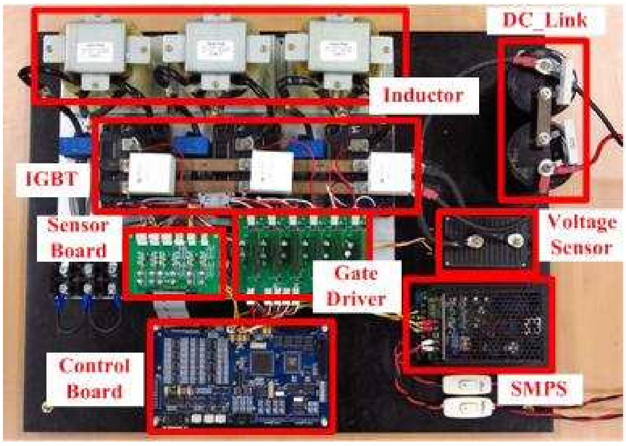


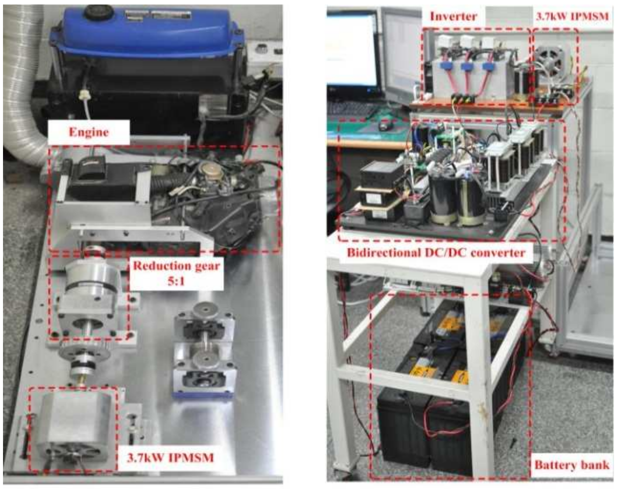
Fig. 10. Prototype of bidirectional three phase interleaved DC/DC converter

To simulate the inertia of practical EV/HEV, mechanical engine of scooter is coupled to IPMSM. Although this inertia load of engine does not provide enough inertia of EV/HEV practically, the regenerative load pattern is almost the same as the practical operation at the reduced scale experiment.

To simulate the practical vehicle in the acceleration and deceleration, reduced driving cycle of ECE(united nations Economic Commission for Europe specification)-15 [19] is adapted. The reduced time scale is 1:10. Fig. 12(a) and 12(b) show the experimental results of ECE standard.

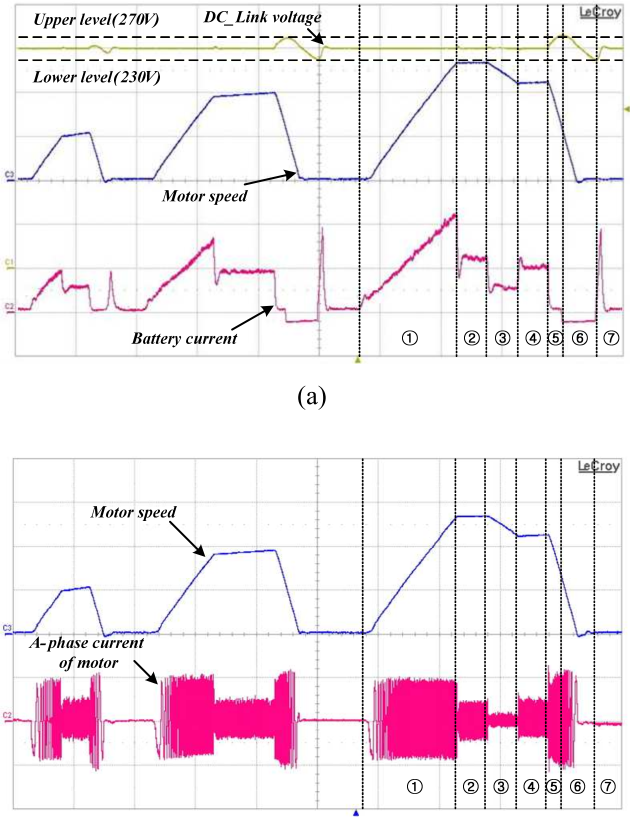
Period ① of Fig. 12(a) is acceleration operation. In this period, the battery current is increasing according to the motor speed. The DC-link voltage is sustained by the boost mode of DC/DC converter which has the controller of output voltage.

The period ② and ④ are the constant speed operation periods. During these periods, the current amplitude is varied by the motor speed. The difference between period ① and ② is in the torque current. In period ①, battery current is not only for the sustaining motor speed but also for the torque generation. However, in period ② and ④, the generated torque is almost zero and the current is only for sustaining motor speed. This torque, which is generally called friction torque, is proportional to the motor speed, and it is caused by gear box and pen belt of experimental setup. In period of ③, generated torque is almost zero and reverse torque is not applied. In this mode, motor speed is decreased by the friction torque. In period ⑤, reverse torque is applied to motor, and reduces the motor speed rapidly.



(a) (b)

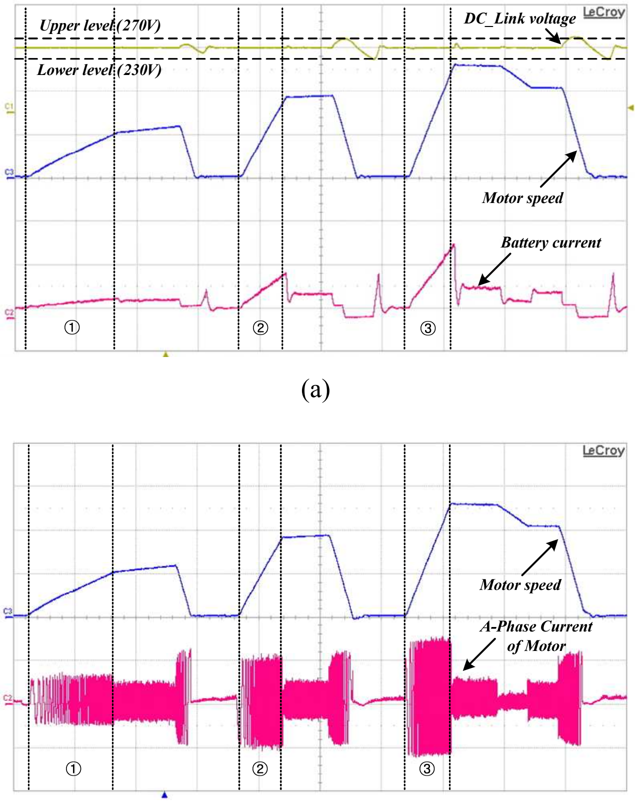
Fig. 11. Overall experimental setup (a) Test motor and engine (b) composition of power conversion devices



(a)

(b)

Fig. 12. Experiment of speed profile using ECE standard cycle (2[s/div.]) (a) DC-Link voltage and battery current (DC-Link voltage : 50[V/div.], battery current: 10[A/div.], motor speed : 1000 [rpm/div.]) (b) Motor phase current(5[A/div.])



(a)

(b)

Fig. 13. Experiment of speed profile using ECE cycle with different accelerations (2[s/div.]) (a) DC-Link voltage and battery current(DC-Link voltage : 50 [V/div.], battery cur- rent:4[A/div.], motor speed : 1000[rpm/div.]) (b) Motor phase current(5[A/div.])

Because of this reverse torque, motor speed decreases gradually with constant deceleration rate. Deceleration rate is proportional to the inertia of the motor, and this affects the duration of regenerative mode of inverter. This regenerative energy increases the DC-link voltage. If the voltage reaches the upper limit(270[V]), period ⑤ is ended and DC/DC converter operates as buck mode. In period ⑥, this regenerative energy from motor is accumulated on battery by buck mode of DC/DC converter.

Although the regenerative operation of inverter is ended when the motor speed reaches zero, DC/DC converter still operates as buck mode until the DC-link voltage reaches lower limit. When the regenerative operation of the inverter is ended and buck mode of DC/DC converter is still operated, DC-link voltage decreases rapidly to the lower limit(230[V]).

Fig. 13 shows the experimental results of different acceleration rate. As shown in these figures, the current is proportional to generated motor torque. In acceleration periods of ①, ② and ③, as gradient of the speed is increased, the current of battery and inverter is increased proportionally to the gradient of speed. From these results, the designed DC/DC converter is operated properly in spite of the various torque current of the inverter.

6. Conclusion

The control method of bidirectional DC/DC converter for EV/HEV application is described in this paper. To control the battery charging current to be constant, each operation mode of three-phase bidirectional interleaved DC/DC converter is selected according to the DC-link voltage variation. In contrast to conventional method, battery charging current is not affected by the motor speed with proposed control method.

To verify the proposed control method, prototype inverter and three-phase interleaved DC/DC converter is experimented by down scaled ECE cycle. From the experimental results, DC-link voltage and battery charging current are well regulated with the proposed method. Consequently, this constantly regulated battery current can be increased charging efficiency in contrast to conventional control method.

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