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Paper

A Power-Assistance System using a Battery and an Electric Double-Layer Capacitor Bank for Light Electric Vehicles

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To improve the performance of light electric vehicles (LEVs), we propose a current sharing control system for series–parallel changeover, whose hybrid energy storage system (HESS) comprises an electric double-layer capacitor (EDLC) bank and a main battery. In the proposed system, the series or parallel connection between the EDLC bank and the main battery is decided depending on the bank voltage for managing the energy stored in the HESS. Moreover, we propose a simple output current control method for the parallel connection of the EDLC bank. This method allows for the ratio of output current in both storage components to be controlled by introducing a share command parameter. Experimental results from field tests demonstrate the parallel operation with adjustable current sharing control. Finally, we discuss the combination of series–parallel operations to provide power assistance for LEVs.

Keywords: light electric vehicles, hybrid energy storage system, electric double-layer capacitor

1. Introduction

In recent years, compact light electric vehicles (LEVs) have attracted attention given their low production, running costs, and ecofriendly characteristics. In fact, the production of LEVs is rapidly increasing in many countries [(1)–(3)]. Simultaneously, the adoption of the electric double-layer capacitor (EDLC), which is a supercapacitor, in the energy storage system of LEVs is increasing with the development of electric vehicles (EV). In (4), (5), and (6), EVs powered only by EDLC were proposed owing to their high power density and long lifetime characteristics at frequent charge/discharge applications. Moreover, hybrid energy storage systems (HESSs) comprising an EDLC bank and a main energy storage unit, which is generally a lead-acid battery, are being developed given the high energy density of the battery, and rapid charge/discharge characteristics of EDLCs [(7)–(13)].

To further improve the performance of LEVs, the regenerative braking energy of the motor can be stored for its subsequent use for locomotion. Hence, the EDLC is convenient for HESSs given its ability to withstand fast and frequent charge and discharge operations and its high responsiveness when compared to conventional batteries. Nevertheless, only nominal 2.5/2.7-V cell voltages are available [(8)(9)], and an EDLC bank obtained from connecting multiple cells in series should be used to meet the main battery voltage. In this case, a bidirectional DC-DC converter is required to control the terminal voltages and power flow of the EDLC bank between the energy storage unit and the inverter DC link. The main strategy of previously proposed methods is to connect the EDLC bank in parallel with the battery to either manage excess energy or quickly mitigate sudden electrical variations.

The capacitance of an EDLC bank decreases proportionally to the number of series-connected cells. Consequently, as few cells as possible should be used to guarantee a high capacitance. In addition, when the EDLC bank exhibits a low-voltage level, the DC-DC converter efficiency reduces by a high boost ratio. In addition, if the stored energy is insufficient, the boost operation cannot be performed. To overcome these problems, we previously developed a series–parallel changeover system to improve LEV performance. The proposed system consists of a main lead-acid battery, an EDLC bank, a bidirectional DC-DC converter, a three-phase inverter, and a brushless DC (BLDC) motor [(14)–(16)]. The system aims to be the power source configuration of the EDLC bank and battery between the series and parallel connections, which depends on the driving conditions such as the road characteristics and stored energy level in the EDLC bank.

In this paper, we propose a control method for output current sharing that establishes a parallel connection between the EDLC bank and battery in the abovementioned changeover system and adjusts their ratio of output current. The EDLC bank voltage determines its output power for saving the energy stored in the battery. In addition, we propose several driving mode, which is a combination of series and parallel connections, to achieve power assistance feature under heavy load condition. Experimental results from a field-driving test verify the proposed control method and validate proposed driving modes.

2. Energy Storage and Supply System

A bidirectional DC-DC converter is usually required for a system integrating EDLC bank and battery to provide an interface between the bank and the inverter DC link. In this

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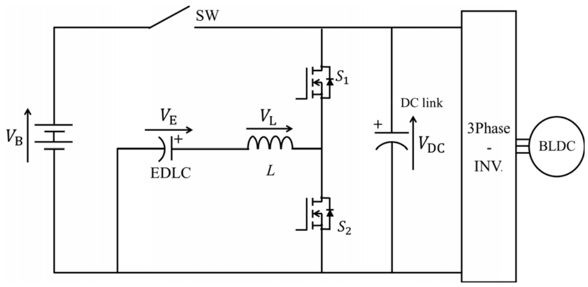

Fig. 1. Energy storage system using bidirectional DC-DC converter

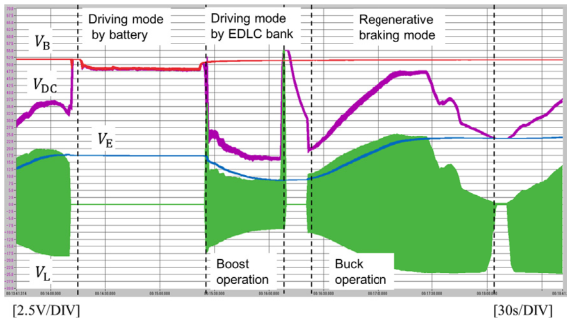

Fig. 2. Measurements of operation using conventional bidirectional DC-DC converter

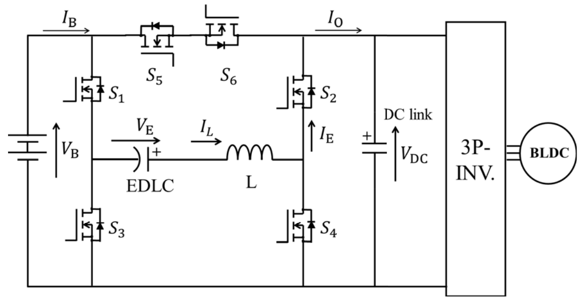

Fig. 3. Proposed series–parallel changeover system

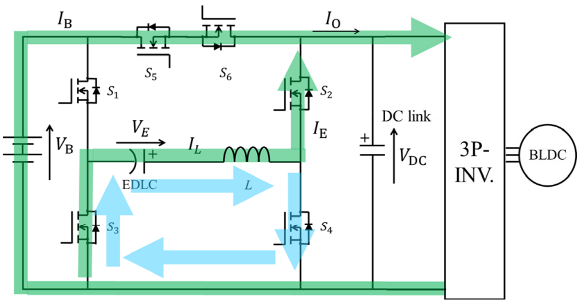

Fig. 4. Current flow during parallel connection of the battery and EDLC bank (Mode 3)

section, we first describe the conventional system using a bidirectional DC-DC converter, followed by the operation of the proposed series–parallel changeover system.

2.1 Conventional Bidirectional DC-DC Converter System Figure 1 shows the basic configuration of a system containing a battery and an EDLC bank connected in parallel to a DC-link bus. The EDLC bank is connected to the DC link by the bidirectional DC-DC converter composed of switches S_1 and S_2, and inductance L. The operation of this system comprises three modes, namely, a driving mode using the battery, regenerative braking with the EDLC bank, and driving mode using the EDLC bank.

Figure 2 shows measurement results of the operation using this energy storage and supply system while driving an LEV. In the driving mode using the battery, switch SW is in the ON state. During regenerative braking with the EDLC bank, SW is in the OFF state, and the bidirectional DC-DC converter operates in buck operation through switch S_1 for the motor to provide energy and charge the EDLC bank. In the driving mode using the EDLC bank, only the bidirectional DC-DC converter operates in boost operation through switch S_2 for the EDLC bank to supply energy to the DC link. However, in boost operation, the controllable voltage range of the EDLC bank is restricted given the low conversion efficiency, which is caused by the high boost voltage ratio and saturation of L by the high inductance current. In Fig. 2, the boost operation be limited under approximately 8 V of EDLC-bank voltage. Consequently, limited ratios between three and four can be obtained for conversion of the EDLC-bank voltage, thus the charged energy that cannot be used given insufficient voltage in boost operation remains in the bank.

2.2 Series–Parallel Changeover System To improve the operating voltage range of the EDLC bank, we proposed a system to connect the battery and EDLC bank in either series or parallel. Specifically, when the bidirectional DC-DC converter cannot be controlled due to a high voltage boost ratio, the proposed system switches the connection between the battery and EDLC bank from parallel to series, such that all the stored energy in the EDLC bank can be supplied to the DC link. The detail operation is described hereafter.

Mode 1: Battery Driving

In the driving mode using only the battery, the bidirectional switch consisting of S_5 and S_6 is in the ON state. Hence, the battery is directly connected to the DC link, whose voltage becomes

$$V_{DC} = V_B \quad \cdots\cdots (1)$$

Mode 2: EDLC Bank Driving

This mode can be activated only when the EDLC bank the sufficient stored energy. The converter operates in boost mode through S_4, whereas the battery is disconnected from the DC link. Then, V_{DC} is given by Eq. (2), where D_{S_4} denotes the duty ratio of S_4 in Eq. (3).

$$V_{DC} = \frac{1}{1 - D_{S_4}} V_E \quad \cdots\cdots (2)$$

$$D_{S_4} = \frac{T_{ON}}{T_{ON} + T_{OFF}} \quad \cdots\cdots (3)$$

Mode 3: Parallel Battery and EDLC Bank Driving

In this mode, the parallel connection between the battery and EDLC bank is achieved with S_5 at the ON state and the converter operating in boost mode through S_4, where voltage V_{DC} is expressed by Eq. (4), and the current supplied to the DC link is given by Eq. (5). Figure 4 illustrates the operation during this mode, where the input current to the DC link is supplied by both the battery and EDLC bank, and a diode voltage drop occurs at S_6. In addition, the stored energy in the EDLC bank contributes to save energy of the battery. The current sharing control method during this mode is presented

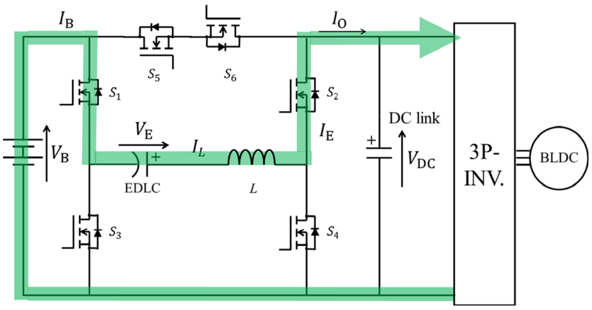

Fig. 5. Current flow during series connection of the battery and EDLC bank (Mode 4)

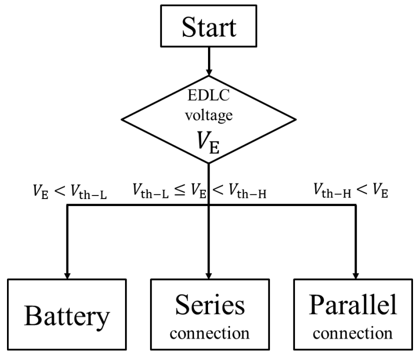

Fig. 6. Diagram of series–parallel changeover control

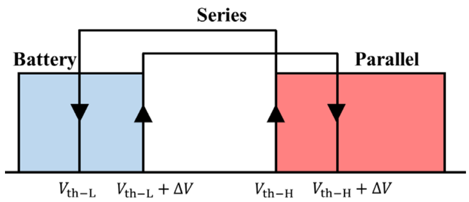

Fig. 7. Change of mode according to voltage of EDLC bank

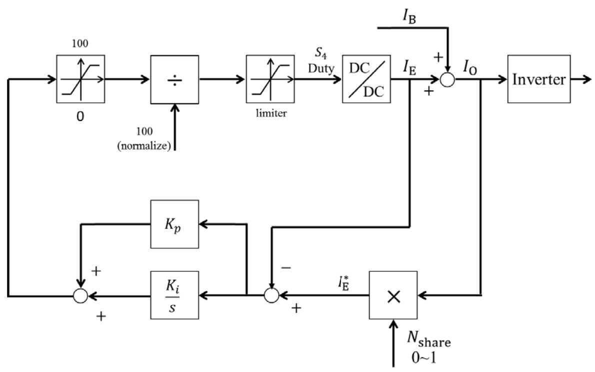

Fig. 8. Diagram of current sharing control

in the next section.

$$V_{DC} = (V_B - V_{D\text{-}S_6}) \| \frac{V_E}{1 - D_{S_4}} \quad \cdots\cdots (4)$$

$$I_O = I_B + I_E \quad \cdots\cdots (5)$$

Mode 4: Series Battery and EDLC Bank Driving

In the driving mode using the series connection between the battery and EDLC bank, only S_1 is at the ON state. The battery and EDLC bank contribute to V_{DC} with their respective voltages V_B and V_E, as expressed in Eq. (6), where V_{D-S_2} is the diode forward voltage drop at S_2. In addition, the series connection makes the same current flow through all the elements indicated in Fig. 5. Likewise, the output voltage of the inverter, which is the terminal voltage for the BLDC motor, increases according to the EDLC bank voltage. Hence, after S_1 turns on, the speed and torque of the BLDC motor increase instantaneously, and thus this mode has a power assistance feature.

$$V_{DC} = V_B + V_E - V_{D\text{-}S_2} \quad \cdots\cdots (6)$$

Mode 5: Regenerative Braking for EDLC Bank

In this mode, only S_3 is at the ON state, and the bidirectional DC-DC converter operates in buck mode through S_2. Consequently, the braking energy flows into the EDLC bank, and V_E is given by Eq. (7), where D_{S_2} is the duty ratio of S_2.

$$V_E = D_{S_2} V_{DC} \quad \cdots\cdots (7)$$

Mode 6: Regenerative Braking for Battery

In this mode, only S_6 is at the ON state, and thus the braking energy flows into the battery for charging.

3. Control Method

This section first explains the strategy for choosing the type of connection, either series or parallel. Next, we propose a simple current sharing control method for the parallel connection. This method allows to control the ratio of output current between the battery and EDLC bank using a feedback controller for the output current of the EDLC bank.

3.1 Selection of Connection Type In the proposed changeover system, we monitor the EDLC bank voltage, and the operation mode is decided accordingly as illustrated in Figs. 6 and 7. Threshold voltageV_{th-H} determines the changeover between series and parallel connection, whereas threshold voltage V_{th-L} determines the changeover from series connection to battery mode. Specifically, when EDLC bank voltage V_E is higher than V_{th-H}, the proposed system applies the parallel driving mode. The output current of the DC-DC converter is supplied from both the battery and EDLC bank, which can share the output current of the battery. During this mode, the current sharing control is required to regulate the output current.

Next, when V_E is lower than V_{th-H}, S_1 turns on, thus series connecting the EDLC bank and battery. Then, the series mode changes to the battery mode when V_E is lower than V_{th-L}, whose value is the smallest voltage level. Moreover, for each change mode interval, we set hysteresis band ±ΔV for the corresponding thresholds to avoid undefined connection mode and jittering. Mode shifting from parallel to series can be automatic, but the reverse shifting from series to parallel directly does not occur because the EDLC bank voltage does not increase any driving conditions in series mode.

3.2 Current Sharing Control During parallel driving mode, we employ the proposed output current sharing control method, which is depicted in Fig. 8, to regulate the battery and EDLC bank output currents. In the method, one current is automatically determined by controlling the other one. The input current to the DC link, I_O, is the sum of the output currents from the EDLC bank I_E and battery I_B. The

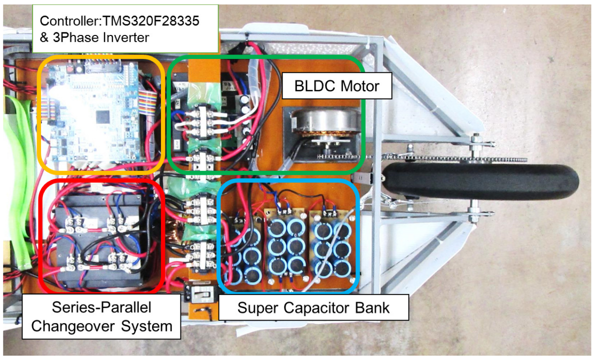

Fig. 9. Implemented driving system for LEV using the proposed method

Table 1. Experimental LEV specifications

Motor	BLDC motor (1 kW continuous, 2 kW peak output, 3 phases, 16 poles)
Battery	48 V, 7.5 Ah (4 series-connected 12 V, 7.5 Ah batteries)
EDLC bank	77.8 F, 22.5 V (9 series-connected 2.5 V, 350 F cells)
DC-link capacitor	5000 µF, 150 V
Inductance L	40 mH
Switching frequency	10 kHz
V_{th-H}	14 V
V_{th-L}	1 V

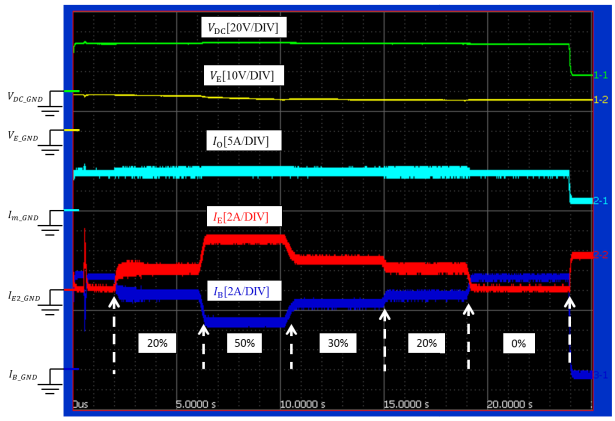

Fig. 10. Voltage and current during current sharing

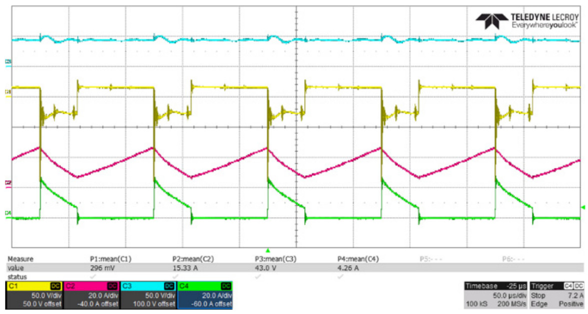

Fig. 11. Voltage and current during current sharing at a 50% ratio. (C1: V_L, C2:V_{DC}, C3: I_L, C4: I_E, 50 μs/div)

current sharing reference, N_{share}, is introduced to determine the ratio between I_E and I_B. Thus, the output current reference I_E^* of the EDLC bank is set to $N_{share}I_O$. Likewise, I_E is regulated to I_E^* using a PI controller, and the duty ratio of S_4 is controlled accordingly. Output current I_E can be controlled considering the range limit of the inverter DC-link voltage.

4. Experimental Results and Discussion

In our laboratory, we develop single-seater LEVs for Eco-run marathon competitions [14][15]. We implemented the proposed current control method on the LEV driving system. Figure 9 shows the implemented driving system is shown, and Table 1 lists the LEV electrical specifications. The main lead-acid battery has 48 V_{DC} from four series-connected 12 V batteries. The EDLC bank has capacitance of 77.8 F and terminal voltage of 22.5 V, which are obtained from eighteen 350 F, 2.5 V cells arranged with 9 in series and 2 in parallel connection. A DSP controller (TMS320F28335, Texas Instruments, Inc.) implements the proposed method. The driving motor is a 2 kW three-phase BLDC motor controlled by a three-phase inverter. The bank operation modes for driving or parallel operation can be selected according to the driving conditions in the range from 14 V, which is corresponds to threshold V_{th-H} 22 V, which is the maximum terminal voltage of the EDLC bank. When the voltage of the EDLC bank is below 14 V during parallel operation, the series connection is established. When the voltage of the bank is below 1 V, the operation mode automatically changes to battery mode.

First, we verified the current sharing control during the parallel driving mode. The EDLC bank was charged up to a voltage above V_{th-H}, and we continuously varied sharing ratio N_{share} from 0% to a high value. Figure 10 shows the results from this experiment under BLDC motor speed approximately constant at 800 rpm.

From top to bottom, the graphs in the figure show DC-link voltage V_{DC}, EDLC bank terminal voltage V_E, inverter input current I_O, EDLC output current I_E, and battery output current I_B. In this experiment, the inverter supplies approximately 600 W to the BLDC motor with an input current close to 13 A. The results confirm that the EDLC bank constantly shares current at the intended value N_{share}. Even for step variations of N_{share}, no sudden variations in the DC-link voltage and current occur, and the BLDC motor rotates at an almost constant speed. The output current of the battery varies according to the share ratio for compensating the EDLC bank current, with both currents being equal at a 50% sharing ratio. In addition, the EDLC bank does not supply current at 0% sharing ratio, when operation in single battery mode occurs. Figure 11 shows the voltage and current curves under ratio N_{share} of 50%, from where the boost operation can be verified. These results confirm that the appropriate operation of the proposed current sharing control allows specifying any sharing ratio during driving through the parallel connection between the EDLC bank and battery.

Figure 12 shows waveforms of the system operation at sharing ratio of 40% with irregular variations of the load on the motor. When the load of the BLDC motor varies, the inverter, EDLC bank, and battery currents, as well as the speed of the motor vary accordingly.

In contrast, V_{DC} exhibits an almost constant value. In addition, the average inverter input current is 6.79 A, the average EDLC bank current is 2.52 A, and the average battery current

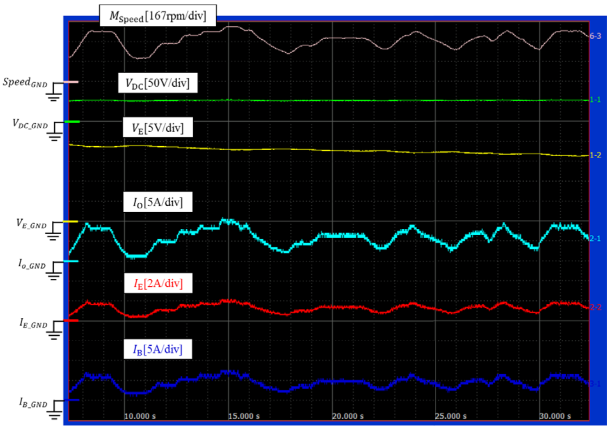

Fig. 12. System behavior under varying load

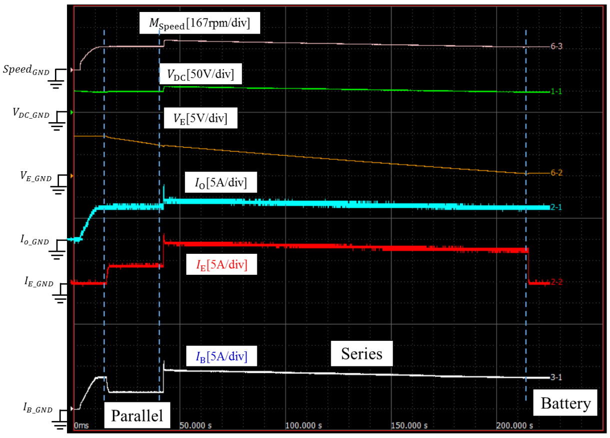

Fig. 13. System behavior during mode switching

is 4.39 A, thus verifying that the EDLC bank shares about 40% of the load current. These results suggest that the proposed control method stably follows load fluctuations when the LEV drives over rough surfaces.

Figure 13 shows the proposed system switching from single battery to parallel and then to series mode. When the energy source changes from the battery to the parallel connection of the battery and EDLC bank, the input current to the inverter increases, and both V_{DC} and the motor speed increase slightly, whereas V_E gradually decreases as the EDLC bank discharges in the parallel mode. Next, the system changes from parallel to series mode when the EDLC bank voltage reaches 14 V. At this point, V_{DC} rapidly increases from 48 V to approximately 62 V along with an increase in the input current and BLDC motor speed, as the available EDLC bank voltage is added to the battery voltage. Finally, when the EDLC voltage decreases below 1 V, the system switches to single battery mode. These results confirm the application of the power assistance mode when the LEV either enters a steep slope or passes over an obstacle. Ratio N_{share} can reach up to 70% during a short period, and then the system switches to a series mode to boost the output power. Moreover, almost all the stored energy in the EDLC bank can be supplied to the motor. Figure 14 shows waveforms of the system when it switches from parallel to series mode. Although a sudden inrush current is generated during switching, it can be limited by properly selecting threshold V_{th-L}, inductance L, and the

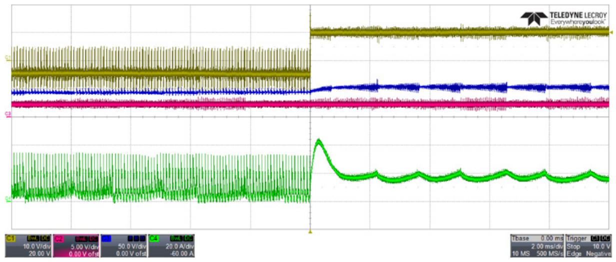

Fig. 14. System waveforms during changeover from parallel to series mode (C1: gate signal of S_1, C2: M_{Speed}, C3: V_{DC}, C4: I_O, 2 ms/div)

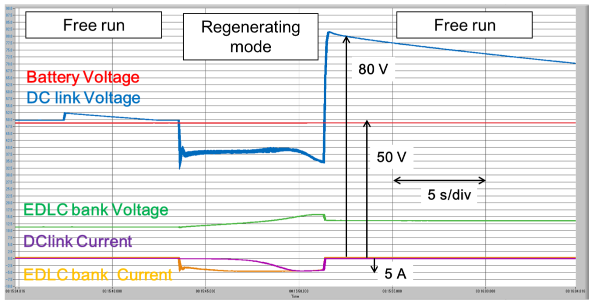

Fig. 15. Waveforms during regenerative braking mode

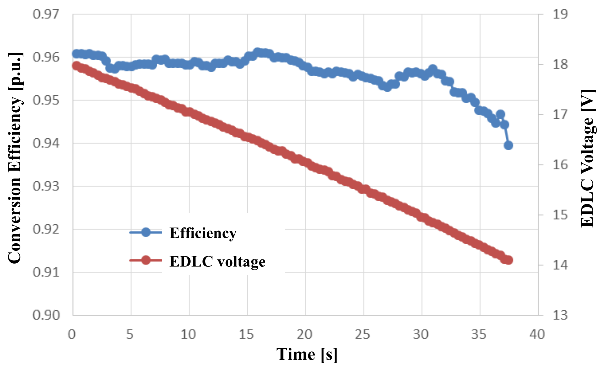

Fig. 16. Conversion efficiency during parallel mode for N_{share} of 30%

switching of S_2.

Figure 15 shows waveforms during regenerative braking for the EDLC bank. In this mode, the battery is disconnected by S_5 and S_6. When the LEV undergoes a regenerative operation, the voltage of the DC link increases, and the proposed system operates under buck operation by the duty of S_2 and activation of S_3. Given the power generated from the BLDC motor, there appears a negative current flow into the EDLC bank. The free-run periods in Fig. 15 indicate that all MOSFETs are in the OFF state and the LEV runs by inertia.

The conversion efficiency of the proposed system reaches 96% during battery mode. Given that switches S_5 and S_6 are at the ON state simultaneously during this mode, the power loss is only related to the conduction of these two MOSFETs. The conversion efficiency under the series mode is 88% in average for EDLC-bank voltage from 14 V to 1 V. Figure 14 shows the efficiency during parallel mode, where the maximum efficiency of 96% is reached when the EDLC bank has a high voltage level, and as the voltage decreases and the boost ratio increases over time, the conversion efficiency decreases. The abovementioned efficiency values correspond only to the proposed series–parallel changeover system, and we did not consider the efficiency of the inverter and BLDC motor.

5. Conclusions

In this paper, we propose the series–parallel changeover system with a current sharing control method to manage the power contribution of the EDLC bank in an LEV. The EDLC bank can be connected in series or parallel to the main battery depending on the terminal voltage level of the former. By controlling the EDLC-bank output current, the current of the battery can be adjusted as necessary. When the LEV momentarily requires high power, the proposed control method applies a high current-sharing ratio and series connection for the EDLC bank for delivering power to the BLDC motor. In addition, the EDLC bank can be connected in parallel and share the battery output for energy saving during normal driving conditions. According to the field test results, the proposed method exhibits not only power assistance capabilities but also offers power saving of the battery energy. Therefore, we expect that this method will lead to improved performance of LEVs.

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