High Efficiency Energy Conversion System for Decreases in Electric Vehicle Battery Terminal Voltage

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The powertrain of electric vehicles in the market has a problem in that its performance degrades because of fluctuations in battery voltage. In order to solve this problem, this paper proposes an energy conversion system to boost a part of the electric vehicle battery voltage. This system consists of the existing electric vehicle powertrain and a bi-directional isolated DC-DC converter called the dual active bridge (DAB). This system is able to compensate for battery voltage drops with high efficiency by using a small capacity DAB converter. In addition, a control method for the DAB converter is proposed. This control method achieves a better response to the transient state than conventional methods. The validity of the proposed system and its control method are confirmed by simulation and experiments. A high efficiency of about 99% is obtained from the experimental system prototype.

Keywords: electric vehicle, dc-dc converter, dual active bridge

NOMENCLATURE

- E Battery voltage.
- \( E_1 \) Primary DC voltage of DAB converter.
- \( E_2 \) Secondary DC voltage of DAB converter.
- \( V_C \) Output voltage of DAB converter.
- \( v_p \) Primary AC voltage of DAB converter.
- \( v_s \) Secondary AC voltage of DAB converter.
- \( i_p \) Primary AC current of DAB converter.
- \( i_s \) Secondary AC current of DAB converter.
- \( i_{out} \) Output current of DAB converter.
- \( I_o \) Input current of the inverter.
- \( L \) AC-link inductance.
- \( C_i \) Input capacitance of DAB converter.
- \( C_o \) Output capacitance of DAB converter.
- \( C_{inv} \) Input capacitance of the inverter.
- \( S_{11} - S_{14} \) Primary switches of DAB converter.
- \( S_{21} - S_{24} \) Secondary switches of DAB converter.
- \( n \) Transformer turn ratio.
- \( T \) Switching period.

1. Introduction

Environmental issues are treated as great concern in recent years. Due to increase in the world population and economic development, the energy consumption continues to increase. Because of that, fossil fuels such as oil may be depleted. In addition, exhaust gas is produced by burning oil. In the exhaust gas, various air pollutants such as nitrogen oxide and carbon dioxide are included. Because air pollutants cause various diseases, reduction measures should be taken as soon as possible. Besides, carbon dioxide is said to be cause of a global warming, emission reduction targets have been set. Therefore, in order to protect the environment, our dependence on oil should be reduced. Above all, the transportation sector is the primary user of oil. In recent years, car sales have continued to increase. Considering the economic development of emerging countries, this demand will continue to grow. Considering all the above, transition from internal combustion engine vehicles to hybrid electric vehicles (HEVs) or electric vehicles (EVs) is required.

Because of that, in the automobile industry, many researches on HEV and EV have been reported in recent years. Especially EVs, which run only on electricity, do not emit any pollutants during driving. In addition, Well-to-Wheel efficiency of EVs is more than twice that of the internal combustion engine vehicles. Therefore, total CO₂ emission values of EVs are less than about 70% compared with that of internal combustion engine vehicles(1). Besides, it is considered that EVs will play an important role in the smart grid technology. As a solution to the environmental issues, the world’s renewable energy production has increased rapidly. When many renewable power plants are connected to the grid, it is said that the power system becomes unstable. Vehicle-to-grid (V2G) is a key technology to solve this problem. It is thought that the battery of the EV has ability to stabilize the power system by controlling charge and discharge intellectually(2)-(4). The battery of EV which is connected to the grid also work as an emergency power source.

EVs have many advantages as mentioned above. However, there are many problems to be solved in order to disseminate them(5). Especially, the extension of the driving range and the improvement of the powertrain performance are major challenges. There are two main ways in order to extend the driving range: one is increase of the charging opportunity and

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the other is increase in the driving range per charge. As the former, for example, contactless power transfer (CPT) technology for EVs have been researched to charge the battery during driving or idling. As the latter, a new powertrain with an ultracapacitor or a chopper have been researched. These studies are also aimed at improving the powertrain performance.

The powertrain of EVs in the market is composed of a battery, an inverter, and a motor. In this system, the input voltage of the inverter depends on the output voltage of the battery. However, the battery has a characteristic that its output voltage drops when the discharge rate is increased or when it is used continuously. In addition, the internal resistance of the battery is increased at low state-of-charge or high output power. Therefore, in this system, the desired output voltage may not be obtained at low state-of-charge or when high output power is required. Besides, at low voltage, the required current to obtain the same amount of power increases compared with normal state. Therefore, the inverter requires large current capacity. Furthermore, in this system, the flux-weakening control is applied at high-speed range. Under the flux-weakening control, the total efficiency decreases because the extra current flows.

In order to solve these problems, a DC-DC converter is often inserted serially between the battery and the inverter in order to change the input voltage of the inverter even if the battery voltage drops. However, in this solution, the total efficiency may be worse because conduction losses in the DC-DC converter always occur. In the previous method, although the efficiency of the inverter and motor is improved by inserting the chopper and lowering the battery voltage, the overall efficiency gets worse depending on the operating conditions. Even if the total efficiency is better, the large-capacity DC-DC converter is heavy. As a result, the cruising range may be shorter. In general, it is difficult to achieve both high efficiency and high power density. Hybrid energy storage system (HESS) using an ultracapacitor is effective in extending the battery life. In order to change the inverter input voltage, HESS using both the dc-dc converter and the ultracapacitor has also been researched. In most of these HESS, the large-capacity DC-DC converter is required. HESS using the relatively small-capacity DC-DC converter was proposed. However, the boost operation can not be realized with high output in this configuration.

In this paper, in order to solve the above problems, a voltage boosting system called High Efficient Energy Conversion System (HEECS) is considered. A similar topology has been researched. However, with the previous method, it is difficult to achieve high efficiency and small size when the converter output power becomes large because of its converter topology. In this system, Dual Active Bridge DC-DC converter (DAB converter) is used as a buck converter. Due to its circuit topology, the DAB converter has attracted attention in the automotive and the aerospace industry. In most of these applications, the DAB converter is used to transfer energy between the different voltage sources. However, the DAB converter is utilized as a part of powertrain in HEECS. This system allows input power to the DAB converter only when the voltage boosting is required. When the boost is not needed, the DAB converter does not operated. Therefore, the conduction loss of the DAB converter almost does not occur. In this system, DAB converter is assumed to be used frequently in the transient state. This is because the switches between powering and regeneration and between on and off state are performed frequently by the load fluctuation. In general, DAB converter is controlled with a phase-shift control. However, the transient response is not good in the phase-shift control. Hence, this paper proposes a control method for DAB converter called hysteresis control. Hysteresis control which has the better transient response is suitable for the control of the DAB converter in this system.

The rest of this paper is organized as follows. Section 2 describes HEECS. Section 3 introduces the theory of DAB converter. Section 4 describes the principle of hysteresis control. Section 5 performs simulation and confirms the effectiveness of the proposed control method. Section 6 performs experiments to verify the operation and evaluate the efficiency. Section 7 concludes this paper.

### 2. High Efficient Energy Conversion System

#### 2.1 Basic Circuit Configuration

The basic circuit configuration of HEECS is shown in Fig. 1. $R_{out}$ simulates an inverter. This circuit has a configuration in which the DAB converter is inserted between a battery and an inverter of an existing powertrain. Inserting the DAB converter in this way makes it possible to boost a part of the battery voltage. HEECS has the following advantages.

- The efficiency during non-boosting is high because the current is not passing through the DAB converter.
- The efficiency during boosting is high because only a part of the total power goes through the DAB converter.
- Relatively small capacity DAB converter can be used because only a part of total power is input to the DAB converter.

#### 2.2 Theory of Operation

The operating modes are shown in Fig. 2 and Fig. 3. This system has two operation modes; one is non-boosting mode (Fig. 2), and the other is boosting mode (Fig. 3).

The DAB converter is turned off at low or middle output power. As a result, the input voltage of the inverter is equal to the output voltage of the battery. When the DAB converter is off, only the secondary switches of DAB converter are on. The efficiency seems to decrease due to the conduction loss of switches. However, in this system, the secondary side voltage of the DAB converter is low. Therefore, MOSFETs can be used as the secondary switches. Since the MOSFET has very low on-resistance, the efficiency almost does not decrease.

The DAB converter is turned on at high output power. As a result, the input voltage of inverter is the sum of the output voltage of battery $E$ and the output voltage of DAB converter.
The efficiency of the DAB converter is calculated as follows.

\[
\eta_{total} = \frac{N}{N + 1} \eta_{direct} + \frac{1}{N + 1} \eta_{dab}
\]

(1)

Where \( \eta_{direct} \) means the efficiency of the power which is supplied to the load directory and it is close to 100%. \( \eta_{dab} \) means the efficiency of the DAB converter. Therefore, even if \( \eta_{dab} \) is low, \( \eta_{total} \) does not decrease so much.

3. DAB Converter

The schematic of the DAB converter is shown in Fig. 4. The DAB converter which is kind of an isolated DC-DC converter consists of two full bridge voltage source inverters, a high frequency transformer, and an inductor. Due to the symmetry of this circuit structure, the DAB converter provides bidirectional power transfer. The DAB converter has following advantages.

– The primary bridge and the secondary bridge are isolated by the transformer.
– The size is compact due to the small number of components.
– The efficiency is high because of zero voltage switching.\(^{(19)(20)}\)

The DAB converter behaves differently depending on the amount and form of the AC voltage \( v_p, v_s \). Recently, several modulation methods have been proposed to extend ZVS range \(^{(16)(22)(24)}\). However, at the moment, the DAB converter in this system may be controlled with square wave AC voltage simply. The slope of the AC current \( i_p \) is calculated by (2) using parameters shown in Fig. 4.

\[
\frac{di_p}{dt} = \frac{v_p - v_s/n}{L}
\]

(2)

The theoretical waveforms are shown in Fig. 5. When \( v_p \) is equal to \( v_s/n \), the slope of \( i_p \) becomes 0 from (1). As a result, the waveforms as shown in Fig. 5(a) are obtained. On the other hand, when \( v_s \) is very small or 0, the slope of \( i_p \) depends only on \( v_p \). As a result, the waveforms as shown in Fig. 5(b) are obtained. In HEECS, the initial output voltage of the DAB converter is 0 because HEECS operates with non-boosting mode until the DAB converter starts its operation. Thus the waveforms like Fig. 5(b) appear immediately after the start of the DAB converter. After the output voltage rises, the waveforms become like Fig. 5(a).

4. Hysteresis Control

The DAB converter is often controlled with the phase-shift control\(^{(18)(20)}\). In the phase-shift control, the current \( i_p \) is controlled indirectly by controlling the phase shift \( \phi \). Inductor current \( i_p \) is expressed as a function of time \( t \) as follows.

– mode 1 \((0 \leq t \leq t_\phi)\)

\[
i_p(t) = i_p(0) + \frac{E_1 + E_2/n}{L} t
\]

(3)

– mode 2 \((t_\phi < t \leq T/2)\)

\[
i_p(t) = i_p(t_\phi) + \frac{E_1 - E_2/n}{L} (t - t_\phi)
\]

(4)

From (3) and (4), the output power \( P \) is given as

\[
P = \frac{1}{T} \int_0^T V_1(t)i_1(t)dt = \frac{2}{T} \int_0^{\phi} V_1(t)i_1(t)dt
\]

\[= \frac{E_1E_2}{L} t_\phi \left( 1 - \frac{2t_\phi}{T} \right)
\]

(5)

However, because of this indirect control, various problems such as overcurrent in the inductor occur in the transient state. Therefore, this control method is not suitable for DAB converter of HEECS which will be used in the transient state frequently. In order to solve this problem, a control method which is suitable for HEECS is proposed in this section. In this paper, this control method is called hysteresis control. In hysteresis control, the current in the secondary side of the DAB converter \( i_s \) is directly controlled. Thereby, response to the transient state can be improved.

The control principle is described with reference to Fig. 6 and Fig. 7. Figure 6 and Fig. 7 are examples of the powering. Figure 6 can be devided into two parts: a primary side...
Fig. 6. Hysteresis control block

Fig. 7. Control principle

Fig. 8. Controlled $i_s$ ($E_1 = E_2/n$)

Fig. 9. Controlled $i_s$

In this simulation, the effectiveness of the proposed control method is verified. Both the phase-shift control and hysteresis control is used to control the DAB converter for comparison. The simulation is mainly performed at the transient state.

5. Simulation

In this simulation, the effectiveness of the proposed control method is verified. Both the phase-shift control and hysteresis control is used to control the DAB converter for comparison. The simulation is mainly performed at the transient state.

5.1 Simulation of the DAB Converter

The simulation circuit and simulation parameters are shown in Fig. 10 and Table 1. The simulation parameters are set based on the parameters of experimental system, different from the parameters of the actual EV.

The simulation results are shown in Figs. 11–13. In this simulation, capacitors on the secondary side of the DAB converter are charged, $v_{C2} = 16.5\, [V]$ and $v_{C0} = 33\, [V]$. Figure 11 shows the current $i_s$ immediately after the start of operation with the phase-shift control. Figure 12 shows the current $i_s$ immediately after the start of operation with hysteresis control.

In Fig. 11, compared to the steady state, approximately twice overcurrent is flowing immediately after the start. In the phase-shift control, although the initial value of $i_s$ is zero, phase difference as same as the steady state is used. As a result, this overcurrent occurs. By contrast, overcurrent is prevented by using the hysteresis control as shown in Fig. 12.
Fig. 12. \( i_{\text{c}} \) immediately after the start of operation (hysteresis control)

Fig. 13. Simulation results of the switching

Fig. 14. Simulation circuit

Figure 13 shows the waveform of the DAB converter with hysteresis control at the switching from the powering to the regeneration. Output current \( i_{\text{out}} \) is vibrating because the load is a voltage source. The switching from the powering to the regeneration is performed by sign inversion of the current command value \( I_{\text{outref}} \). In the response to switching signal in 0.005 s, the switching from the powering to the regeneration is performed instantaneously. In the phase-shift control, instantaneous switching can not be achieved because the switching period is fixed and only the phase difference is controlled. In addition, approximately twice over current is flowing immediately after the switching.

5.2 Simulation of the Whole System The simulation circuit is shown in Fig. 14. In this simulation, operations of the whole system at the start are focused on. The DAB converter starts its operation with initial input voltage \( E_1 = 200 \text{[V]} \), initial output voltage of the DAB converter \( V_{\text{Co}} = 0 \text{[V]} \), and initial output current \( I_0 = 10 \text{[A]} \).

First, change in \( i_{\text{c}} \) and the rise time of \( V_{\text{Co}} \) due to the

Fig. 15. Operation waveforms not applying peak current suppression

Fig. 16. Operation waveforms applying peak current suppression

Table 2. Control parameters

<table>
<thead>
<tr>
<th>Gain</th>
<th>( K_v )</th>
<th>( \tau ) [s]</th>
<th>Limit of output</th>
</tr>
</thead>
<tbody>
<tr>
<td>( i_{\text{hysteresis}} )</td>
<td>0.01</td>
<td>0.001</td>
<td>( \pm 20 \text{[A]} )</td>
</tr>
<tr>
<td>( \text{phase-shift} )</td>
<td>0.02</td>
<td>0.0015</td>
<td>( \pm 90 \text{[deg]} )</td>
</tr>
</tbody>
</table>

difference of the peak current suppression method are confirmed. The simulation results are shown in Figs. 15–16. Compared with Fig. 15 and Fig. 16, though current is limited in Fig. 16, there is almost no difference in the rise time.

Next, the comparison of the output voltage response due to the control methods is performed. The voltage control block and control parameters are shown in Fig. 17 and Table 2. The voltage controller is the simple PI controller. The output
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Fig. 18. The rise time of $v_{Co}$

Fig. 19. Conceptual diagram of the whole setup

Fig. 20. DAB converter

Fig. 21. Experimental result shown in Fig. 20. Each parameter is the same as that used in the simulation.

6.2 Experimental Results at the Start In this experiment, the DAB converter starts its operation under the same conditions in the simulation of the whole system. The experimental results are shown in Fig. 21 and Fig. 22. Figure 21 shows the output voltage of DAB converter $v_{Co}$ and Fig. 22 shows the inductor current $i_L$ immediately after the start of operation. From Fig. 22, compared with the simulation result under the same condition (Fig. 18(b)), their ways of rising of the output voltage are similar.

However, the rise time of the output voltage is longer than that of simulation. This may be due to differences in the controller and difference between the real components (switches, transformer, inductor, etc.) and the ideal components. In addition, the rise time becomes longer under the larger output current in Fig. 21. This is because our voltage source has a current limit of 25 A. Actually, the voltage response depends on the current limit of the DAB converter and the control method.

6. Experiment

In this experiment, hysteresis control is implemented, then verifying operations at the start and the steady state are performed in HEECS.

6.1 Experimental System The DSP and FPGA are used as a controller. The conceptual diagram of the whole setup is shown in Fig. 19. Two power loads are used as a voltage source (primary side) and a current source (secondary side). The controller is mainly composed of a DSP board, a FPGA board, and some A/D converters. DSP performs PI control using the measured voltages and currents. FPGA performs hysteresis control using the current command value received from DSP. DAB converter used in this experiment is voltage $v_{Co}$ follows the reference value $V_{Coref}$. It is difficult to do pure comparison because the optimal control block and control gain of the two control methods are different. For relatively pure comparison, the voltage response simulations are performed by using same PI control block. PI gain is set to the values with no voltage overshoot respectively. The simulation results are shown in Fig. 18. From Fig. 18, the voltage response is improved with hysteresis control. The voltage response becomes worse only when the output current approaches the current limit of the DAB converter.
From Fig. 22, the inductor current can be suppressed to $I_{\text{L,pmax}}$. From these experimental result, this proposed system can compensate the input voltage of the inverter while preventing overcurrent flowing through the inductor.

6.3 Experimental Results at the Steady State

The experimental result when the DAB converter is turned off (non-boosting mode) is shown in Table 3. Looking at the total efficiency, a high efficiency of 99.86% was obtained. Total resistance can be calculated at about 18 mΩ.

In the experiment, only the operation at the start and the steady state was performed. However, in the actual EVs, the loads (an inverter and a motor) fluctuate frequently. Then the switches between powering and regeneration and between on and off state are performed frequently. Accordingly, this system has to be able to operate in such situations. In conclusion, though more efforts are required to apply this system to the actual EVs, this system which is light weight, compact size and high efficiency may contribute to the realization of the EV with high performance.

Table 3. Powering with the non-boosting mode

<table>
<thead>
<tr>
<th>Reference voltage [V]</th>
<th>33</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage [V]</td>
<td>200.10</td>
<td>200.10</td>
<td>200.10</td>
</tr>
<tr>
<td>Output voltage [V]</td>
<td>199.86</td>
<td>199.86</td>
<td>199.86</td>
</tr>
<tr>
<td>Output power [kW]</td>
<td>2.998</td>
<td>2.998</td>
<td>2.998</td>
</tr>
<tr>
<td>Total efficiency [%]</td>
<td>99.15</td>
<td>99.15</td>
<td>99.15</td>
</tr>
</tbody>
</table>

Table 4. Powering with the boosting mode

<table>
<thead>
<tr>
<th>Reference voltage [V]</th>
<th>33</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage [V]</td>
<td>200.10</td>
<td>200.10</td>
<td>200.10</td>
</tr>
<tr>
<td>Output voltage [V]</td>
<td>231.98</td>
<td>240.07</td>
<td>240.21</td>
</tr>
<tr>
<td>Output current [A]</td>
<td>17.182</td>
<td>17.393</td>
<td>16.650</td>
</tr>
<tr>
<td>Input power [kW]</td>
<td>4.039</td>
<td>4.036</td>
<td>4.042</td>
</tr>
<tr>
<td>Output power [kW]</td>
<td>4.003</td>
<td>4.002</td>
<td>4.000</td>
</tr>
<tr>
<td>Total efficiency [%]</td>
<td>99.11</td>
<td>99.14</td>
<td>98.96</td>
</tr>
</tbody>
</table>

Table 5. Regeneration with the boosting mode

<table>
<thead>
<tr>
<th>Reference voltage [V]</th>
<th>33</th>
<th>30</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage [V]</td>
<td>200.57</td>
<td>200.61</td>
<td>200.71</td>
</tr>
<tr>
<td>Output voltage [V]</td>
<td>233.94</td>
<td>238.98</td>
<td>241.06</td>
</tr>
<tr>
<td>Input power [kW]</td>
<td>-2.999</td>
<td>-3.000</td>
<td>-3.000</td>
</tr>
<tr>
<td>Output power [kW]</td>
<td>-3.023</td>
<td>-3.024</td>
<td>-3.031</td>
</tr>
<tr>
<td>Total efficiency [%]</td>
<td>99.21</td>
<td>99.20</td>
<td>99.15</td>
</tr>
</tbody>
</table>

7. Conclusion

In this paper, an high efficient energy conversion system for the compensation of the battery voltage decrease of EVs was considered. In addition, in order to improve the response to the transient state, hysteresis control which directly controls the inductor current of the DAB converter was proposed. In the simulation, effectiveness of the proposed control method was confirmed. The proposed control method was implemented using DSP and FPGA, and the system prototype was build. The DAB converter was controlled properly by using the proposed control method. Furthermore, very high efficiency about 99% was obtained in the boosting mode and close to 100% was obtained in the non-boosting mode.

References
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