CHARGE EQUALIZING SYSTEM FOR TWO UNITS OF A SERIALLY CONNECTED LEAD-ACID BATTERY STRING USING A BUCK-BOOST CONVERTER TOPOLOGY

Charnyut Karnjanapiboon,1, Kamon Jirasereamornkut,2,* and Veerapol Monyakul3

1Department of Electrical Engineering, Faculty of Engineering, Rajamangala University of Technology Lanna Nan 55000, Thailand
2Department of Electronic and Telecommunication Engineering, Faculty of Engineering, King Mongkut’s University of Technology Thonburi 10140, Thailand
3Biochemical Engineering and Pilot Plant Research and Development Unit (BEC), National Science and Technology Development Agency (NSTDA) 12120, Thailand
*e-mail chanyut@rmutl.ac.th

Abstract

This article presents a charge equalizing system for two units of a serially connected lead-acid battery string using buck-boost converter topology. Serially connected two unit lead-acid battery strings are popular as a main power source in modern electric vehicles. The main problem of serially connecting a lead-acid battery string is the unbalanced energy levels in the battery units. To manage the problem, a charge equalizing system is introduced. A converter is part of the system. The operation of the converter can be buck and boost mode. In the buck mode the converter steps down the output voltage to be equal or lower than the input voltage. Conversely in the boost mode the converter steps up the output voltage to be equal or greater than the input voltage. Both of these modes allow the converter to drain excessive energy from batteries or supply additional current to batteries to manage the unbalanced energy level problem. Computer CAD simulation results consolidate the proposed technique.

Keywords: charge equalizing system, buck-boost converter, lead-acid battery

Introduction

Nowadays many modern electrical vehicles use serially connected lead-acid battery strings as a power source. The electric vehicle market is growing rapidly to meet the demand of customers. As a result, the demand of lead-acid battery strings for this electric vehicle is also growing hand-in-hand. The main maintenance expense of this electric vehicle is the cost to replace the lead-acid battery strings every two years at the end of the service life time of the batteries. Some electric vehicles require a serially connected battery string with two or more battery units to provide a large enough power source. There are many reasons that shorten the service life time of a lead-acid battery string. One is an unbalance energy problem between serially connected battery units. A charge equalization system is one of the solution methods for the unbalance problem. A charge equalization system acts as an electrical bridge that allows energy to transfer forward and backward between battery units for balancing their energy level. Balancing the energy level of a serially connected battery string keeps service life time to its maximum capability.
Literature Review and Proposed Technique

Previous research (Uno et al. 2011; Uno et al. 2011) proposed a charge equalization system using a power electronic converter with a single switch. It had problems because it was complicated to adjust and balance the current between batteries in the string. To overcome this obstacle, this paper proposes a charge equalizing system for two serially connected lead-acid battery strings using a buck-boost converter topology. The mode of operation of the proposed converter can be buck mode and boost mode. The buck mode is a mode where the converter steps down the output voltage to be equal or lower than the input voltage. The boost mode is a mode where the converter steps up the output voltage to be equal or greater than the input voltage. The proposed changes in the equalizing system topology are shown in Figure 1.

For a serially connected battery string with a two battery unit, the charge equalization system consisted of four main switches, two inductors and one capacitor. Switches $Q_1$, $Q_2$ and $L_1$ were the component parts of the buck/boost converter’s first charge equalization module. Switches $Q_3$, $Q_4$ and $L_2$ were the component parts of the buck/boost converter’s second charge equalization module. These two charge equalization modules were tied together with one DC-linked capacitor $C$.

Principle of Operation of the Proposed Technique

The principle of operation of the proposed technique could be derived in eight operating modes, as shown in figure 2.

mode 1: Switches, $Q_1$ was turned on, $Q_2$, $Q_3$ and $Q_4$ were turned off. Energy from DC-linked capacitor flowed to charging battery $B_1$ and some energy was stored in inductor $L_1$.

mode 2: Switches, $Q_2$ was turned on, $Q_1$, $Q_3$ and $Q_4$ were turned off. Energy from inductor $L_1$ continues flowed to charging battery $B_1$ until energy from inductor $L_1$ dropped to zero.

mode 3: Switches, $Q_2$ was turned on, $Q_1$, $Q_3$ and $Q_4$ were turned off. Energy from battery $B_1$ flowed to storage at inductor $L_1$.

mode 4: Switches, $Q_1$ was turned on, $Q_2$, $Q_3$ and $Q_4$ were turned off. Energy from inductor $L_1$ flowed to storage at capacitor $C$.

mode 5: Switches, $Q_3$ was turned on, $Q_1$, $Q_2$ and $Q_4$ were turned off. Energy from the DC-linked capacitor flowed to charging batteries $B_1$ and $B_2$, some energy was stored in inductor $L_2$. 

Figure 1 Proposed change in the equalizing system topology

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mode 6: Switches, $Q_4$ was turned on, $Q_1$, $Q_2$ and $Q_3$ were turned off. Energy from inductor $L_2$ flowed to charging batteries $B_1$ and $B_2$ until the energy from inductor $L_2$ dropped to zero.

mode 7: Switches $Q_4$ was turn on, $Q_1$, $Q_2$ and $Q_3$ were turn off. Energy from battery $B_1$ and $B_2$ flowed to storage at inductor $L_2$.

mode 8: Switches, $Q_3$ was turn on, $Q_1$, $Q_2$ and $Q_4$ were turn off. Energy from inductor $L_2$ flowed to storage at capacitor $C$.

Figure 2 Principle of operation of the proposed technique
Simulation Results

For setting up the computer CAD simulations, the pre-defined variables of the proposed charge equalization technique are shown in Table 1.

<table>
<thead>
<tr>
<th>Input variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Battery</td>
<td>2 Units</td>
</tr>
<tr>
<td>Battery Voltage</td>
<td>12 V</td>
</tr>
<tr>
<td>MOSFET</td>
<td>IRFZ44</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Inductor Value $L_1$ and $L_2$</td>
<td>100 µH</td>
</tr>
<tr>
<td>Capacitor Value $C$</td>
<td>1,000 µF</td>
</tr>
</tbody>
</table>

The computer CAD simulation results $I_{L1}$, $I_{L2}$ and $V_C$ are shown in Figure 3. The operation of the proposed technique in modes 1, 2, 5 and 6 was to transfer energy from capacitor $C$ to batteries $B_n$. In contrast, the operation of this technique in modes 3, 4, 7 and 8 was to transfer energy from batteries $B_n$ to capacitor $C$. The slew rate of inductor current can be calculated from:

$$\Delta i_L = \frac{V_L \Delta t}{L}$$  \hspace{1cm} (1)

Where
- $\Delta i_L$ is a small change of inductor current
- $V_L$ is the voltage drop across inductor
- $\Delta t$ is a small change of time
- $L$ is the inductance

The maximum $\Delta i_L$ occurs at $\Delta t = DT$ \hspace{1cm} (2)

Where
- $D$ is a duty cycle of the power switch
- $T$ is the switching period that can be calculated from $T=1/f$
- $f$ is the switching frequency
From the simulation results, the average current in modes 1 and 2 was greater than the average current in modes 3 and 4 because the inductor voltage of modes 1 and 2 was equal to the sum of the two battery voltages $V_{B1}$ and $V_{B2}$. In contrast, the inductor voltage of modes 3 and 4 was equal to the sum of only one battery voltage $V_{B1}$. This problem of an unequal current waveform can be solved by compensating with a switching duty cycle command for each power switch, thereby decreasing the duty cycle for modes 1 and 7, and increasing the duty cycle for modes 3 and 5. This compensation of the duty cycle command made the average inductor current to be equal. To perform intelligent control of all system operation, the duty control signal could be generated from a small microcomputer such as microcontroller dsPIC30F4011. In addition, the advantages of using a microcontroller were their ease of use, simple circuit configuration and reprogrammable firmware.

**Figure 3** The computer CAD simulation results of proposed charge equalization technique.
Discussion and Conclusion

This proposed charge equalizing system for two units serially connected lead-acid battery string using buck-boost converter topology is a selective choice for balancing an unbalance energy problem for extends battery service life time. The main advantage of this proposed circuit is not required auxiliary power supply to support high side gate driving signal leading to simple circuit configuration. However, this article proposes only a computer CAD simulation. It is better to verify this simulation results by setting up an experimental prototype charge equalization system.

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References