EVS25
Shenzhen, China, Nov 5-9, 2010

Battery Management Systems for Improving Battery Efficiency in Electric Vehicles

Yow-Chyi Liu

Department of Electrical Engineering, Kao Yuan University
No.1821, Jhongshan Rd., Lujhu Township, Kaohsiung County 821, Taiwan, R.O.C.
E-mail: liuyc@cc.kyu.edu.tw

Abstract

Battery cost and battery capacity are key factors to determine whether or not electric vehicles would be used widely. Having a high energy density, lithium-ion battery can improve the mileage range of electric vehicles, yet the battery cost remains high. Although lead-acid battery has lower energy density than that of lithium-ion batteries, lead-acid battery cost less. Moreover, lithium-ion battery features an excellent discharge characteristic, whereas load current significantly impacts the capacity of lead-acid battery. This paper proposes a novel scheme to improve the efficiency of electric vehicle battery. In addition to connecting lead-acid battery with lithium-ion battery in parallel to the power supply, the proposed method combines their discharge characteristics to optimize the power management in order to improve the efficiency of battery and lower the cost of electric vehicle battery. The experimental result demonstrates that the available capacity can improve 30~50% of the rated capacity of the lead-acid battery.

Keywords: Battery efficiency, lead-acid battery, lithium-ion battery, bi-directional dc-dc converter

1 Introduction

Battery cost and battery capacity are key factors determining whether electric vehicles would be used widely [1]. Batteries are currently more expensive than fuel, and limited mileage severely restricts electric vehicle usage. These problems must be resolved for practical applications. Having a high energy density, lithium-ion battery can improve the mileage range of electric vehicles, yet the battery cost remains high. Therefore, electric vehicle research focuses on lowering battery costs and increasing efficiency simultaneously. Although lead-acid battery has lower energy density than that of lithium-ion battery, lead-acid battery cost less.

As the voltage of a single battery is low, it is therefore necessary to connect the batteries in series to supply power for load voltage demand; whereas connecting the batteries in parallel is able to increase the battery capacity and application flexibility. However, even if we connect the same type of batteries in parallel, it may still generate circulating current due to different internal impedance of the cells. Therefore, there is a need to overcome such circulating current problem [2]. There are literatures indicating the exploration of intermittent current discharge method using parallel-connected lithium-ion batteries to supply power. The research findings have shown the intermittent current discharge method is able to release more capacity than constant current [3-5].

As the available battery capacity is subject to the load current size, the releasable capacity varies under different discharge currents. For instance, while a larger discharge current implies a smaller battery released capacity, a smaller discharge current implies a larger battery released capacity. Such phenomena are especially obvious in lead-acid batteries. Figure 1 shows the relationship of different discharge currents versus discharge times for the SCB 4.5AH/12V lead-acid battery [6]. When the output current is 0.5C, the available capacity of lead-acid battery is 73% of rated capacity. Additionally, a situation in which the output current is 1~2C reduces the available battery capacity to 64~47%.

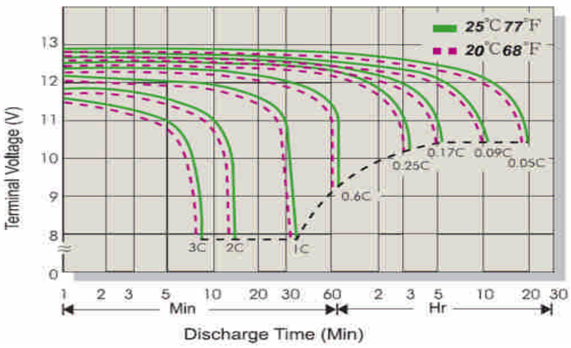


Figure 1: the relationship between different discharge currents and discharge times for the SCB lead-acid battery

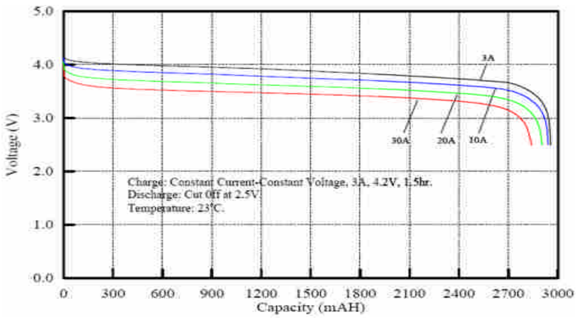


Figure 2: the relationship between different discharge currents and capacities for the Molicel lithium-ion battery

Figure 2 shows the relationship of different discharge currents versus capacities for the Molicel 2.9AH lithium-ion battery [7]. When the output current is 0.5C, the available capacity of lithium-ion battery is 98% of rated capacity; and when the output current is 1~2C, the available battery capacity is 97%. Lithium-ion batteries have excellent discharge characteristics, whereas load current significantly impacts the capacity of lead-acid batteries. This paper focuses mainly on releasing the energy from a lead-acid battery completely.

2 The Proposed Method

2.1 The Configuration of the Parallel Battery

The various discharge currents will result in relatively large differences in the application efficiency of the battery. In most cases of battery applications, when the battery has discharged until the output voltage to drop cut-off voltage, there is still a large amount of energy that has not been released. To use the stored energy of the battery effectively, when the lead-acid battery has released a large amount of output current until the cut-off voltage, we can switch the power supply to the parallel-connected lithium-ion battery and lead-acid batteries. At this point, by controlling the lead-acid battery to release a smaller output current and providing power to load along with the parallel-connected lithium-ion battery, we are able to increase the efficiency of the lead-acid battery.

Figure 3 illustrates the proposed configuration of the parallel power supply system for lead-acid battery with the lithium-ion battery. The battery management center includes estimation of battery capacity, unreleased capacity and load distribution. The voltage and current of the load, as well as the voltage and current of lead-acid battery and lithium-ion battery are measured. Additionally, the lead-acid battery is detected to determine whether its output voltage has reached the cut-off voltage. If it has, a re-use plan of unreleased energy for the lead-acid battery is then conducted. Namely, a smaller output current (1C~0.1C) from this lead-acid battery is discharged until all of the stored energy of the battery has been released. As is estimated, such capacity accounts for 30~50% of the rated power of lead-acid battery.

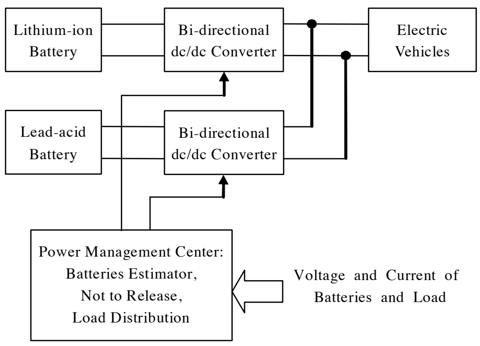


Figure 3: the proposed configuration of the parallel system

The proposed parallel power supply initially allows the lead-acid battery to supply the power. When the lead-acid battery has discharged until to the cut-off voltage, the power supply switches to the parallel-connected lithium-ion battery. At this point, however, the output power from the lead-acid battery must be controlled to release only a smaller amount of the discharged current. Here, as the output power from the lead-acid battery is less than the power demand from the electric vehicle, insufficient power is compensated for by the lithium-ion battery. When the electric vehicle has stopped or reached the destination, the lead-acid battery continuously discharges a small amount of current to lithium-ion battery continuously; at this time, the lithium-ion battery is in the charging state. During the rest period of the electric vehicle, especially when it is waiting for the return trip, the stored energy of the lead-acid battery must be transferred as much as possible to the lithium-ion battery in order to increase the energy of the lithium-ion battery. Doing so increases the efficiency of the lead-acid battery capacity.

2.2 Bi-directional dc-dc Converter

To ensure the discharge action of batteries is coming from the same group of dc converters, a bi-directional dc-dc converter shown in Figure 4 is employed. The difference between a bi-directional converter and a general power converter is there is no fixed output and input terminal in its circuit operation but it needs to follow the power flow direction to define its output and input positions. The application scope of a bi-directional converter includes the electric vehicle, fuel cell system or renewable energy conversion system, etc [8-12].

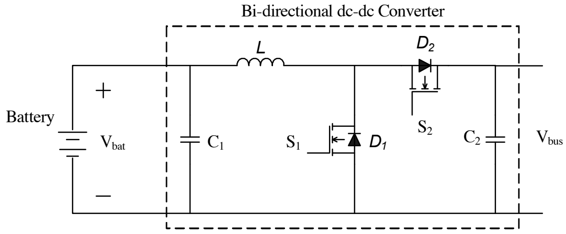


Figure 4: a bi-directional dc-dc converter

In an electric vehicle system, for example, we can use the regenerated brake energy to perform battery charging through a bi-directional converter. When the electric vehicle is running under the motor status, we can switch the operation state of the bi-directional converter to the battery discharging state to provide the electric vehicle with the power it needs. As the bi-directional dc-dc converter is changed from a buck converter, changing the diode of the buck converter into an active power switch enables it to convert into the bi-directional mode.

The operation mode using the battery management center to control the bi-directional dc-dc converter can be divided into two operation modes. The first type is the buck mode where the energy is delivered from the high-voltage side V_{bus} to the low-voltage side of the battery. Here, the bi-directional converter serves as a charger. The second type is the boost mode where the output voltage from the lead-acid battery is raised to a required voltage for the load, and the energy is delivered from the low-voltage side of the battery to the high-voltage side V_{bus} to supply power to the load.

2.3 Analysis of Voltage-mode Control and Current-mode Control

When bi-directional dc-dc converter operates in boost mode, the energy saved in the battery can be provided for load at high voltage side. In order to adjust high voltage side V_{bus} by controlling the discharge current of the battery. Take voltage loop as outer loop in order to adjust the output voltage to achieve voltage regulation effect as well as take current loop as inner loop to speed up transient response, to improve system stability and to provide over-current protection.

The discharge current command of battery, I_{bat}* could be derived from voltage regulation controller G_v via the errors between voltage command V_{bus}* and actual value V_{bus}. I_{bat}* can be specified as Equation (1).

$$I_{bat}* = G_v \times (V_{bus}* - V_{bus}) \tag{1}$$

$$G_v = k_P + \frac{k_i}{s} \tag{2}$$

Equation (2) shows the voltage regulation controller G_v, in which k_p and k_i is for the proportion of voltage regulation controller and integral control gain, respectively.

If ignoring internal resistance of inductor L and consumption and voltage drop of power semiconductor switch and introducing current prediction method for current control to calculate the switch duty ratio via current error value, forcing actual discharge current I_{bat} close to discharge current command I_{bat}* under a switching time period. The conversion rate of inductor current for current prediction method is as Equation (3).

$$\frac{d}{dt} I_{bat} \approx \frac{1}{T_S} \times e_i \tag{3}$$

where e_i represents current error ($e_i = I_{bat}* - I_{bat}$), T_s represents the switching time period.

Equation (4) shows the voltage of inductor L.

$$L\frac{d}{dt}I_{bat} = V_{bat} - (1-d_{S1})\times V_{bus} \quad (4)$$

Applying equation (3) to equation (4) will derive duty ratio of power semiconductor switch S_1, as shown in equation (5).

$$d_{S1} = 1 - \frac{1}{V_{bus}}\times\left(V_{bat} - \frac{L}{T_S}\times e_i\right) \quad (5)$$

is connected to a load as the voltage of the output terminal is 24V. The lead-acid battery is in commercial standards. The output voltage of each lead-acid battery is 12V and rises to 24V through the bi-directional dc-dc converter, and then connects with the lithium-ion battery in parallel for operation. Figure 6 shows the physical diagram of lead-acid battery and lithium-ion battery in parallel.

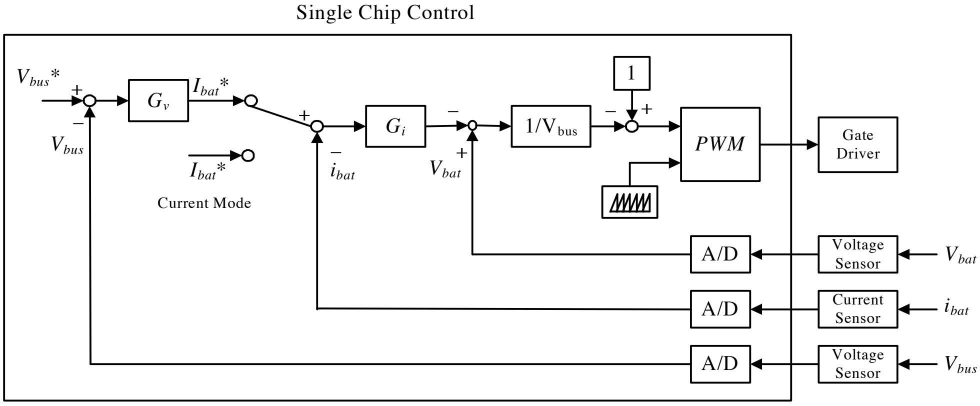


Figure 5: block diagram of bi-directional dc-dc converter

A block diagram of bi-directional dc-dc converter in boost mode could be derived is shown as Figure 5 according to equation (5). The bi-directional dc-dc converter of lithium-ion battery adopts constant-voltage control while the bi-directional dc-dc converter of lead-acid battery adopts constant-current control.

3 Experimental Results

This experiment used a set of YUASA NP5-12 (12V/5AH) lead-acid battery and a set of Molicel IBR26700A (24V/5.6AH) lithium-ion battery packs, making a total of two sets of batteries operating in parallel. Of these, the lithium-ion battery packs were custom specifications. Taking IBR26700A as an example, the single cell specification was 3.75V/2.8AH with its gravimetric energy density of 105Wh/kg, volumetric energy density of 270Wh / l, battery voltage range of 2.5V ~ 4.2V and maximum output current of 40A. This experiment uses 14 cells in series-parallel connection in which seven cells are connected in series for two units and then two units are combined in parallel to be a 24V/5.6AH lithium-ion battery pack.

To simplify the circuit, the bi-directional dc-dc converter of the lithium-ion battery is omitted and thus the output terminal of the lithium-ion battery

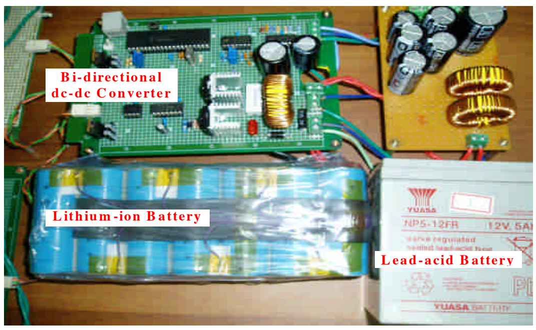


Figure 6: physical diagram of lead-acid battery and lithium-ion battery in parallel.

3.1 Design of the Bi-directional dc-dc Converter

The specification and parameter design of the bi-directional dc-dc converter is as below: battery voltage12V, output voltage 24V, battery output current 10A, switching frequency 20kHz, single chip as PIC 16F877A, L as 0.75mH, C_1 as 4700uF/50V, C_2 as 2000uF/100V, MOSFET as IRFP250.

3.1.1 One Battery Power Supply to Load

The bi-directional dc-dc converter which operated in boost mode is to enable a constant voltage of output at the V_{bus} side, therefore the dc-dc converter needs to be operated under voltage-mode control. In order to test the performance of bi-directional dc-dc converter, 48Ω-6Ω-48Ω variation of load R is simulated, the waveform of transient response of this bi-directional dc-dc converter output voltage V_{bus} and load current I_o is shown as Figure 7, reporting 24V of output voltage V_{bus}, 0.5A-4A-0.5A variation for load current I_o. Figure 8 shows constant waveform of V_{GS} for power MOSFET and load current I_o, load current I_o is 5A.

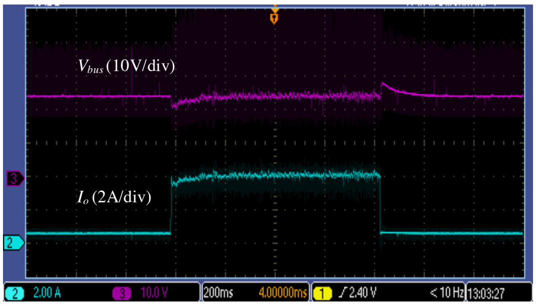


Figure 7: transient waveform of output voltage V_{bus} and load current I_0 for one battery operation

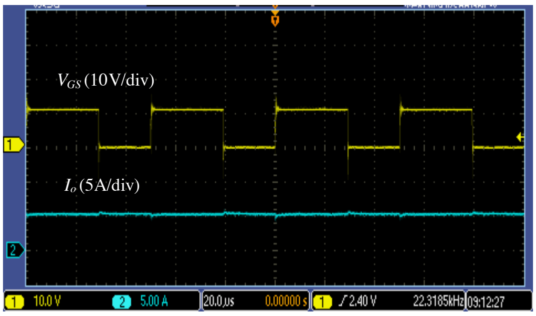


Figure 8: steady waveform of V_{GS} of power MOSFET and load current I_o

3.1.2 Experiments of Parallel Battery

The output of lithium-ion battery directly connects to the V_{bus} side and connects to loads, therefore the voltage of the V_{bus} side is 24V. The output current of lead-acid battery is calculated via single chip control core of the battery management systems, to control lead-acid battery to discharge current to the V_{bus} side with constant current. At this time, the bi-directional dc-dc converter of lead-acid battery will be operated by current-mode control, by controlling the output current of lead-acid battery to achieve the current command I_{bat}^* of the battery management systems. Figure 9 shows waveform of output current for lead-acid battery, in which the output current I_{bat} of lead-acid battery is 10A, the voltage of the V_{bus} side is 24V.

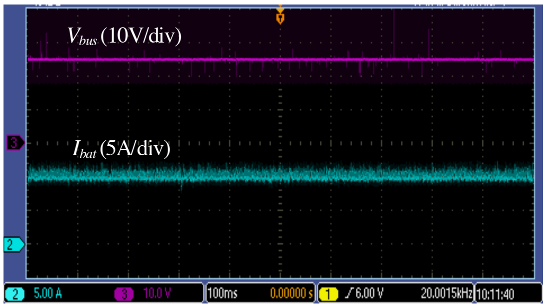


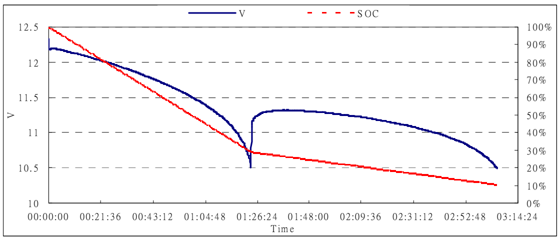
Figure 9: waveform of constant output current for lead-acid battery

3.2 Releasable Capacity of Battery Test

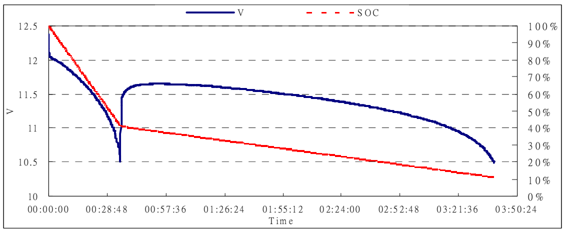
3.2.1 Discharging Lead-Acid Battery to a Load

Indicate a YUASA 12V/5AH lead-acid battery provides power to the load. Next, a two-stage current discharge is applied to determine the releasable capacity under different loads for the lead-acid battery, as well as calculate the releasable capacity by a small current discharge when the battery output voltage drops to the cut-off voltage. During the first stage, a constant discharge rate ranging from 0.5C to 2C is respectively applied to simulate the difference power under load changes. The cut-off voltage of lead-acid battery is set at 10.5V. When the output voltage drops to 10.5V, the second stage starts and the output current is transferred into a constant small current of 0.1C for discharge. The cut-off voltage in the second stage is also 10.5V.

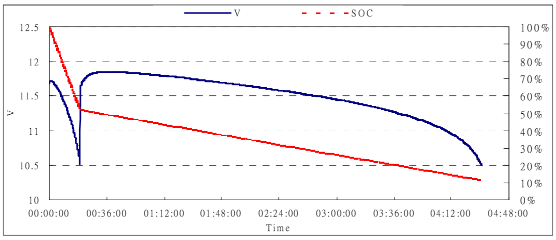
Figure 10(a) shows the profiles of the output voltage and capacity of the battery in the first stage of adopting a 0.5C constant discharge rate and in the second stage of using a 0.1C small discharge rate, in which the released capacity is about 69% of the rated battery capacity in the first stage and about 23% in the second stage. Figure 10(b) shows the released capacity is about 60% in the first stage and about 31% in the second stage under a 1C-0.1C discharge rate. Figure 10(c) shows the released capacity is about 49% in the first stage and about 40% in the second stage under a 1.5C-0.1C discharge rate. Figure 10(d) shows the released capacity is about 38% in the first stage and about 48% in the second stage under a 2C-0.1C discharge rate.



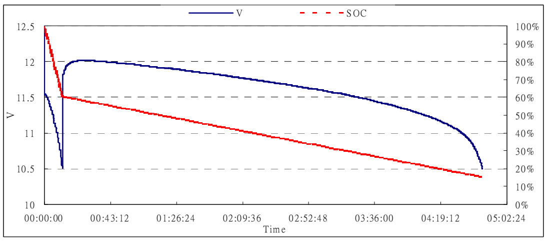
(a) 0.5C-0.1C



(b) 1.0C-0.1C



(c) 1.5C-0.1C



(d) 2C-0.1C

Figure 10: the profiles of the output voltage and capacity of the battery for two-stage discharge currents

Figure 11 shows the release of different capacities under different discharge currents of the lead-acid battery, where Q1 denotes the released capacity in the first stage while Q2 denotes the released capacity in the second stage. Experimental results indicate that the size of the battery discharge rate can significantly influence the releasable capacity to the extent that a larger discharge current leads to the failure of more energy to release. The released capacity in the second stage is the exploitation power of battery studied in this paper. This portion of power accounts for a large proportion of the capacity in lead-acid batteries. Effectively releasing it would significantly enhance the available capacity of electric vehicle batteries.

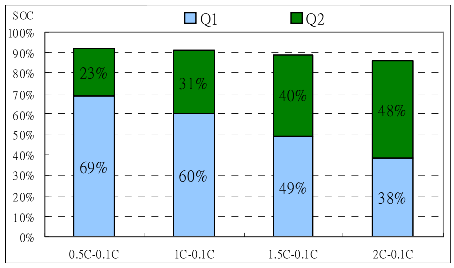


Figure 11: the released capacity under two-stage discharge currents

3.2.2 Discharging Lead-Acid Battery to Lithium-Ion Battery

Involve the assumption of lead-acid battery discharges through 1.5C to the load. When its voltage drops to the cut-off voltage, a multi-stage small discharge current is placed. The lead-acid battery initially discharges through 1.0C to the output side. When the battery voltage drops to the cut-off voltage, the size of the discharge current is reduced and, then, the battery changes to a discharge rate of 0.8C until the battery voltage drops again to the cut-off voltage. At that time, the size of the discharge current can be reduced again and the steps continued repeatedly to reduce the discharge current by reducing 0.1~0.2C per stage until the discharge current drops to 0.1C and the battery voltage drops to the cut-off voltage. Moreover, the SOC of lithium-ion battery is set as 50% in advance and, then, the above-energy charges lithium-ion battery.

Figure 12 shows the parallel operation of lead-acid and lithium-ion batteries where the lead-acid battery discharges to the lithium-ion one. The solid line represents the lead-acid battery output voltage, and the dashed line represents the discharge current. The charge/discharge lasts about 1 hour and 39 minutes. Furthermore, the lithium-ion battery capacity increases 0.72AH/24V. Correspondingly, the capacity of the lead-acid battery rises 32% of the rated capacity.

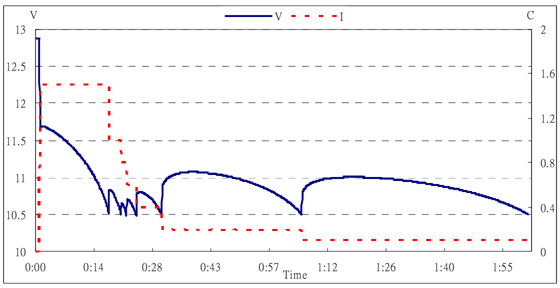


Figure 12: the parallel operation of lead-acid and lithium-ion batteries

4 Conclusions

This paper proposes a novel method to improve the efficiency of electric vehicle battery. In addition to connecting lead-acid battery with lithium-ion battery in parallel to the power supply, the proposed method combines their discharge characteristics to optimize the power management in order to improve the efficiency of battery and lower the cost of electric vehicle battery. A lead-acid battery supplies the power initially. When the lead-acid battery is discharged by the load current until its output voltage drops to the cut-off voltage, the power management unit controls the lead-acid battery and changes it to discharge continuously with a small current. This discharge can be achieved by connecting the lead-acid battery with a lithium-ion battery in parallel to supply the load power coordinately for the electric vehicle motors, or discharge to lithium-ion battery to allow the lithium-ion battery to increase energy while charging until the lead-acid battery has released all of its stored energy. The experimental result demonstrates that the available capacity can improve 30~50% of the rated capacity of the lead-acid battery.

References

[1] D. Somayajula, A. Meintz, and M. Ferdowsi, "Study on the effects of battery capacity on the performance of hybrid electric vehicles," IEEE Vehicle Power and Propulsion Conference (VPPC), September, 2008, Harbin, China. pp. 1-5.

[2] S. B. Han, M. L. Jeong, S. M. Hyung, and H. C. Gyu, "Load sharing improvement in parallel-operated lead acid batteries," in Proc IEEE ISIE'01, Jun. 2001, Vol. 2, pp. 1026-1031.

[3] L. Benini, D. Bruni, A. Macii, E. Macii, and M. Poncino, "Discharge current steering for battery lifetime optimization," IEEE Trans. Computer, Vol. 52, No.8, Aug. 2003, pp. 985-995.

[4] L. Benini, A. Macii, E. Macii, M. Poncino, and R. Scarsi, "Scheduling battery usage in mobile systems," IEEE Trans. VLSI, Vol. 11, No. 6, Dec.2003, pp. 1136-1143.

[5] C. S. Moo, K. S. Ng, and Y. C. Hsieh, "Parallel operation of battery power modules," IEEE Trans. Energy Convers., Vol. 23, No. 2, June 2008, pp. 701-707.

[6] http://www.csb-battery.com

[7] http://www.molicel.com

[8] O. Tremblay, L. A. Dessaint, A. I. Dekkiche, "A generic battery model for the dynamic simulation of hybrid electric vehicles," IEEE Vehicle Power and Propulsion Conference, VPPC, Sept. 2007, pp.284-289.

[9] M. Jain, M. Daniele, and P. K. Jain, "A bi-directional dc-dc converter topology for low power application," IEEE Transactions on Power Electronics, Vol. 15, No. 4, 2000, pp.595-606.

[10] K. Wang, C. Y. Lin, L. Zhu, D. Qu, F. C. Lee, and J. S. Lai, "Bi-directional dc to dc converters for fuel cell system," IEEE Power Electronics in Transportation, 1998, pp.47-51.

[11] J.N. Marie-Francoise, H. Gualous and A. Berthon, "DC to DC converter with neural network control for on-board electrical energy management," in Proc. IEEE IPEMC, Belfort, France, August 2004, pp.521-525.

[12] K. Jin, X. Ruan, M. Yang, M. Xu, "A hybrid fuel cell power system," IEEE Transactions on Industrial Electronics, Vol. 56, No. 4, April 2009, pp.1212–1222.

Authors

Yow-Chyi Liu received the M.S. and Ph.D. degrees in electrical engineering from National Chen-Kung University, Tainan, Taiwan, in 1994, and 2005, respectively. He is currently an Assistant Professor in the Department of Electrical Engineering, Kao Yuan University, Kaohsiung County, Taiwan. His research interests include power electronics, electric vehicles, battery, and rapid transit system.