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Development of battery management system for nickel–metal hydride batteries in electric vehicle applications

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Abstract

Electric vehicle (EV) performance is very dependent on traction batteries. For developing electric vehicles with high performance and good reliability, the traction batteries have to be managed to obtain maximum performance under various operating conditions. Enhancement of battery performance can be accomplished by implementing a battery management system (BMS) that plays an important role in optimizing the control mechanism of charge and discharge of the batteries as well as monitoring the battery status. In this study, a BMS has been developed for maximizing the use of Ni–MH batteries in electric vehicles. This system performs several tasks: the control of charging and discharging, overcharge and over-discharge protection, the calculation and display of state-of-charge (SOC), safety, and thermal management. The BMS is installed in and tested in a DEV5-5 electric vehicle developed by Daewoo Motor Co. and the Institute for Advanced Engineering in Korea. Eighteen modules of a Panasonic nickel–metal hydride (Ni–MH) battery, 12 V, 95 A h, are used in the DEV5-5. High accuracy within a range of 3% and good reliability are obtained. The BMS can also improve the performance and cycle-life of the Ni–MH battery peak, as well as the reliability and the safety of the electric vehicles. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Electric vehicle; Battery management system; Ni–MH battery; State-of-charge; Thermal management, control of charging and discharging

1. Introduction

A number of battery modules in electric vehicles (EVs) or hybrid electric vehicles (HEVs) are connected in series to provide a high system voltage. From the early stage of EV development, it has been found that the initial capacity varies little between battery modules, but differences in the capacities become greater with charge/discharge cycling of the batteries. Battery modules with higher capacity deviations from the others should be overcharged or over-discharged to balance the modules at the end of recharge and discharge, respectively [1]. In this case, the performance of the batteries could become worse on repeated overcharge or over-discharge. In order to solve this problem, all of battery modules must be managed individually during recharge and discharge.

Driving range information in EVs is important for drivers not only to avoid breaking down on the road but also to improve the utilization of battery with maximization of available capacities, which is strongly related to the accurate calculation of the state-of-charge (SOC) of the batteries. For providing accurate battery SOC information, available capacity, self-discharge rate and ageing factors should be considered under all conditions that the EVs could be driven. The available capacity of a battery decreases rapidly with drop in temperature and larger discharge currents. Thus, it is assumed that the battery SOC and the driving range of an EV are highly dependent on environmental conditions, especially ambient temperature and driving patterns of the vehicle. In addition, the capacity of the battery decreases naturally due to self-discharge when the EV is parked for a long period of time. The rate of self-discharge is dependent on both the storage temperature and the stand period: the higher the temperature and the longer the stand period, the greater is the rate of self-discharge. Such energy loss must also be considered for accurate calculation of the battery SOC. The battery capacity tends to decrease with increasing number of cycles. For example the available capacity after 300 cycles is somewhat less than that after 10 cycles. With respect to the ageing effect, this must also be taken into account when determining the battery SOC.

Heat generated from the battery is due to reversible and irreversible phenomena during charge and discharge. A

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rapid increase in temperature, particularly during the final stages of charge and discharge, may cause the battery performance to deteriorate and result in a considerable reduction in battery life [2,3]. In order to solve the thermal problem, it is necessary to control the battery within an optimal temperature range. For the best performance in an EV, the battery modules should all have nearly the same electrical characteristics, which are very much dependent on the temperature [4]. Thus, thermal management control is necessary to provide nearly the same performance among the modules in the battery pack.

Where electrical hazards are concerned, the batteries are the main issue in electric vehicles. The most serious hazards may be an electrical short-circuit, the loss of the electric isolation and the failure of electronics [5]. Overcharge may cause the venting of explosive gas from the batteries to the environment and result in excessive temperature in the batteries, which can cause a fire or explosion. To improve the safety in an EV, a battery management system (BMS) must be installed. Various parameters have to be monitored in real time to protect against electrical hazards.

In this study, a BMS is developed to improve the performance and cycle-life of the battery, as well as the safety and the reliability of EVs. The system includes functions such as charging and discharging optimization of batteries, SOC calculation and display, thermal management, and safety management.

2. Battery management system

Table 1
Functions of sub-systems in BMS

Sub-system	Function
BCU	Data acquisition and storage; data analysis and control command; SOC calculation; diagnostics
Main charger	Battery pack charging
Auxiliary charger	Battery module charging
Thermal management system	Cooling of battery pack
SOC meter	SOC display
Battery warning devices	Over-temperature, over-current, over-voltage, high voltage deviation, high temperature deviation warning
MSD	Voltage and temperature measurement of battery modules
Safety module	Power line auto-disconnect on occurrence of electrical short-circuit, loss of electric isolation and/or thermal runaway

A BMS measures current, battery pack voltage, module voltages, and temperature. The system analyzes these data and controls sub-systems to optimize the status of the traction batteries. The functions of a BMS include the following: data acquisition, charging optimization, calculation and display of SOC, thermal management, safety management, energy management, auxiliary battery management, and diagnostics.

The structure of a BMS for an EV battery is shown schematically in Fig. 1. The BMS is composed of a battery control unit (BCU), a main charger, an auxiliary charger, a thermal management system, a SOC meter, battery warning devices, a module sensing device (MSD), a safety module, etc. The functions of these sub-systems are listed in Table 1. Among the sub-systems, the BCU plays the most important role in BMS. The BCU monitors the status of the batteries in real time and sends appropriate control commands to sub-systems to accomplish the optimization of the traction batteries. A functional block diagram of the BCU is given in Fig. 2.

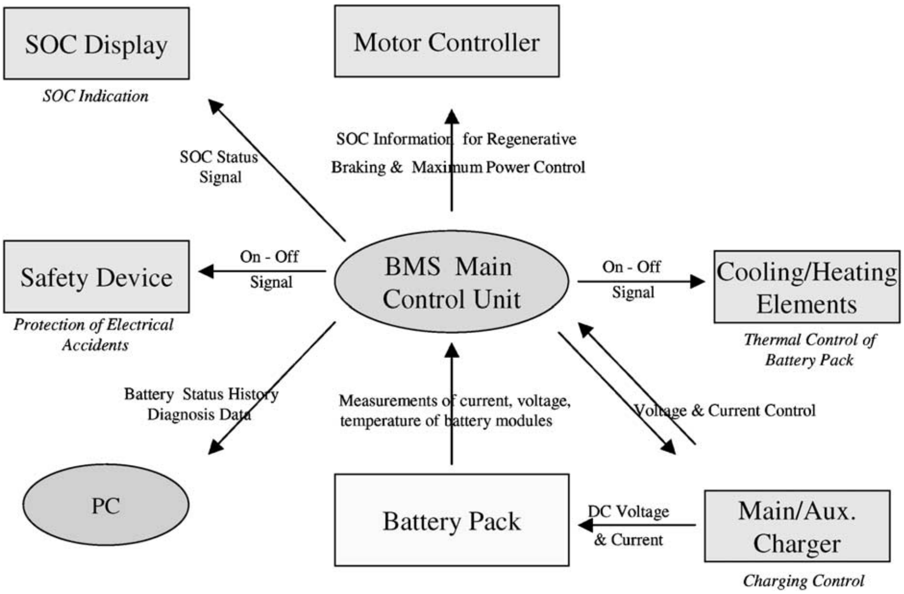

Fig. 1. Schematic structure of BMS.

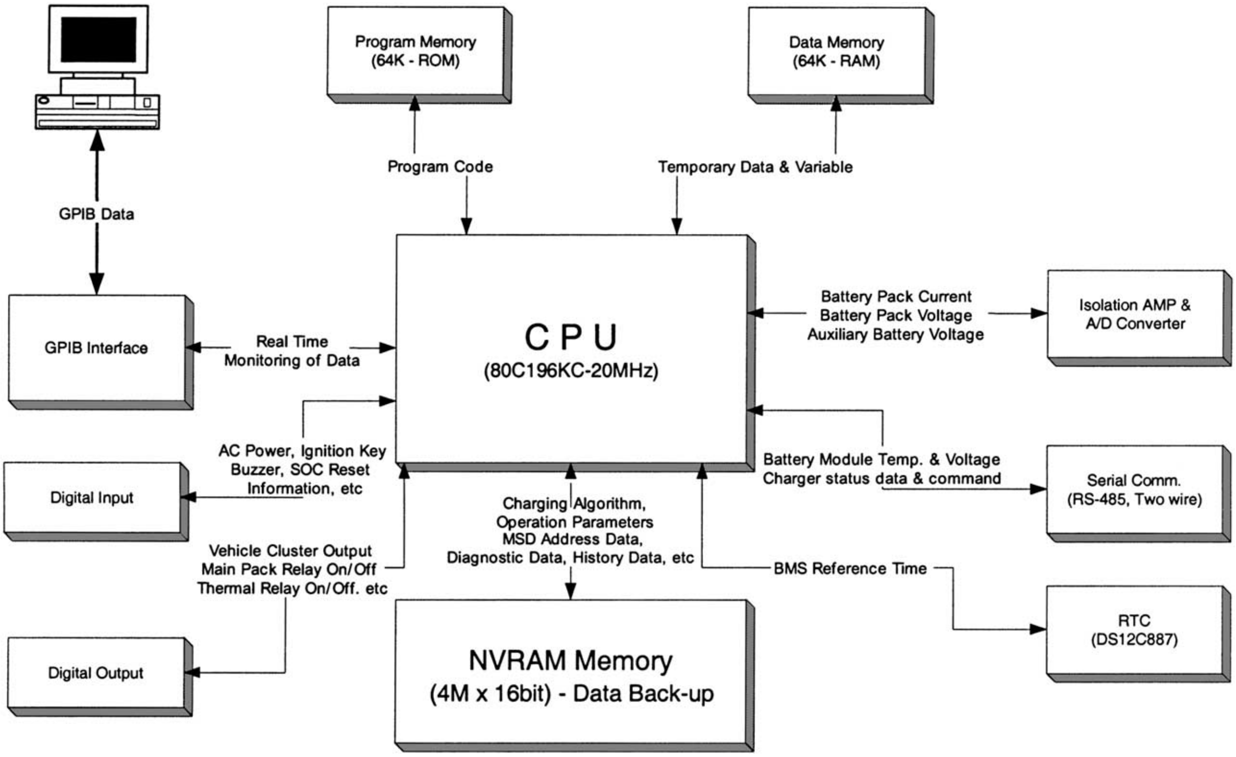

Fig. 2. Functional block diagram of BCU in BMS.

3. Data acquisition

The measured and calculated data as input information were used in control algorithms of the BMS. The sampling time is 1 s and the accuracy of all data is ±4%. A MSD was used to prevent the effect of electromagnetic noise in measuring the voltage and temperature of each battery module. This device transmits signals to the BCU after conversion from the measured analog to digital. The data recorded in the BMS are as follows: input/output current of battery pack; voltage of battery pack; voltages of battery modules; ambient temperature; temperature of battery module.

4. Charging system

In order to minimize capacity deviations among the modules in the battery pack, an advanced charging algorithm that recharges the battery pack and modules independently was developed. The charging algorithm improves the charging efficiency and prolongs the cycle-life of batteries because the overcharge of the batteries is prevented by equalization of the modules. The charging system in the BMS has two chargers. The main charger recharges the battery pack, while the auxiliary charger recharges each module with a lower capacity than the others at the final stage of recharging to equalize the module capacity in the battery pack. The BCU uses a MUX to connect the auxiliary charger to the modules and measures and analyzes all of the battery voltage and the temperature data to select the modules which have lower capacity than the others.

The specifications of the main charger and the auxiliary charger are given in Table 2. The charging system in the BMS was integrated and tested in the DEV5-5 electric vehicle shown in Fig. 3. The specifications of this EV are listed in Table 3. The profiles of the charging current of the main charger and of the auxiliary charger, together with the voltages of battery modules during recharge, are presented in Fig. 4. The main charger supplies a two-step constant current at 10 and 5 A. The auxiliary charger supplies a constant current of 2 A during the second step. The average voltages of the 18 modules is 13.9 V after 30 min from the beginning of recharging. Module 8 shows the greatest deviation of voltage from the average, viz. 0.3 V, while module 14 shows 0.1 V. At the second recharging step, the auxiliary charger picked out module 8 and supplied 2 A

Table 2
Specifications of main charger and auxiliary charger

	Main charger	Auxiliary charger
Input voltage	200 V (ac)	200 V (ac)
Output voltage	320 V (maximum)	16 V (maximum)
Maximum power	33 kW	60 W
Charge method	Constant current, constant voltage	Constant current
Accuracy	±10%	±1.0%

Fig. 3. DEV5-5 electric vehicle developed by IAE and Daewoo Motor Co.

Table 3
Specifications of DEV5-5 electric vehicle

Vehicle		Motor and inverter		Battery	
Type	Four-seat passenger	Motor type	The ac induction	Type	Ni–MH battery[a]
Curb weight	1250 kg	Maximum power	52 kW	Number of modules	18
GVW	1510 kg	Maximum torque	180 N m	Capacity	95 A h
Length	3734 mm	Maximum rpm	9700	Voltage	216 V
Width	1715 mm	Inverter	IGBT	Total energy	20.5 kW h
Height	1580 mm				

[a] Ni–MH: nickel–metal hydride.

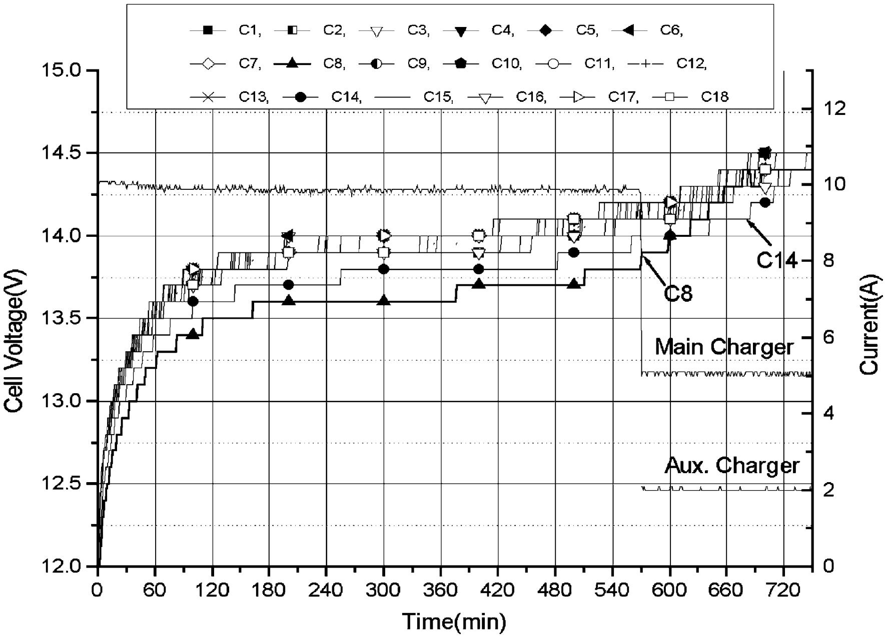

Fig. 4. Charging profiles during recharging of DEV5-5 electric vehicle (C1–C18: 18 battery modules).

until the module gave the average voltages for all module. Immediately after module 8 recharging, the auxiliary charger switched to module 14 and eventually the deviation in voltage among the 18 modules was less than 0.1 V. A lower voltage deviation than average represents less deviation in capacity. This advanced charging algorithm can improve the performance and the reliability of the Ni–MH battery pack.

5. SOC calculation and display

An accurate measure of SOC of the battery is one of the important issues in the development of EV technology. Due to the complex dynamic behavior of individual modules in series connection under various environmental conditions, the methods proposed for SOC estimation do not perform satisfactorily because of an accumulative error throughout the duty cycles.

A practical method for predicting the SOC of a Ni–MH battery in the DEV5-5 has been developed. A ‘coulomb-counting’ technique is used in this study, as shown by Eq. (1):

$$\text{SOC }(\%)=\frac{\text{rated capacity}-\text{used capacity}+\text{charged capacity}}{\text{rated capacity}}\times 100 \qquad (1)$$

To provide an accurate calculation of the SOC of a Ni–MH battery, many factors which affect the SOC have been investigated. It is found that the available capacity, the self-discharge rate and the ageing effect of the battery all have to be considered in order to determine an accurate SOC. Thus, Eq. (1) can be replaced by Eq. (2) after considering the aforementioned parameters:

$$\text{SOC }(\%)=\frac{\begin{array}{c}\text{rated capacity}+\text{capacity compensation factor}\\ +\text{self-discharg effect}+\text{ageing effect}\\ -\text{used capacity}+\text{charged capacity}\end{array}}{\text{rated capacity}}\times 100 \qquad (2)$$

The available capacity of the battery may become different from the rated value when the battery is discharged under different conditions. The available capacity can decrease rapidly at low temperatures and high discharge currents, and capacity compensations under these circumstances have to be made to obtain an accurate battery SOC. In addition, even though the battery is fully charged before parking electric vehicle, the battery capacity is slowly reduced on extended periods of standing and this loss may be due to self-discharge. Self-discharge is dependent of the storage temperatures and the period of standing. Loss of capacity also occurs due to chemical degradation inside the battery with cycling.

A computer simulation has been made to predict the available capacity of a Ni–MH battery under the various temperature and discharge current conditions that electric vehicles could be driven. A general equation, which is determined by temperature and discharge current of the battery, representing the available capacity was developed for EV applications. To simulate the equation using a computer, a range of temperature form −19.5 to 36.5 °C and discharge current from 32 to 300 A were considered. Several capacity tests of the Ni–MH battery were also conducted to verify the integrity of the equation. As seen

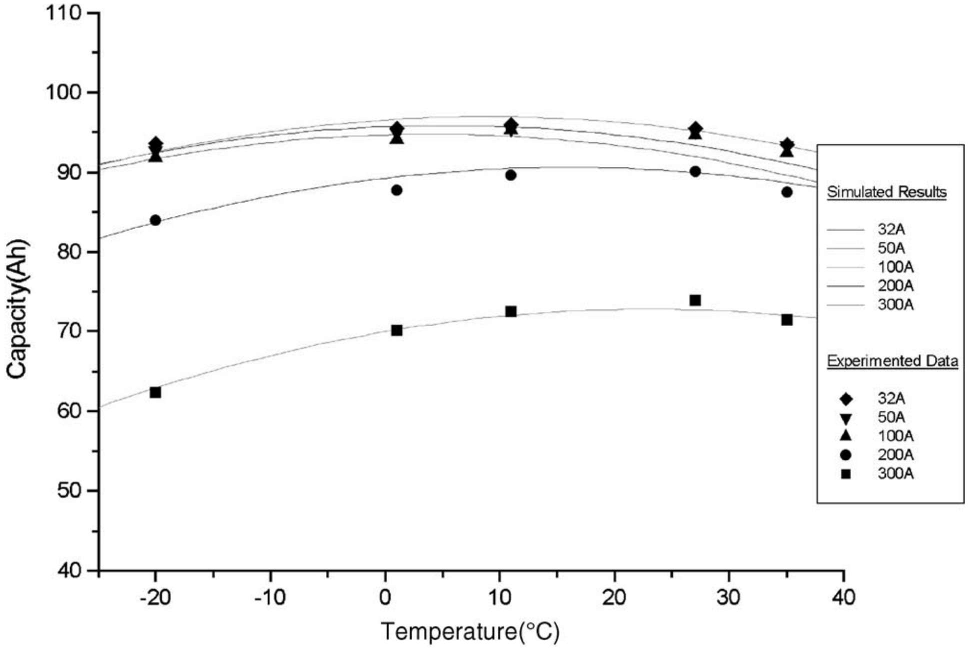

Fig. 5. Comparison of simulated capacity with experimental data of Panasonic Ni–MH battery under all conditions that the EV can be driven.

Table 4
Comparison between predicted values and experimental data of Ni–MH battery

Temperature (°C)	Discharge current (A)	Calculated capacity (A h)	Measured capacity (A h)	Accuracy (%)
−19.5	32	91.86	93.60	+1.89
	50	92.63	92.80	+0.18
	100	92.73	91.90	−0.90
	200	83.95	83.90	−0.06
	300	63.20	62.40	−1.27
1.0	32	94.76	95.50	+0.78
	50	95.80	95.01	−0.82
	100	96.68	94.14	−2.63
	200	89.46	87.72	−1.95
	300	70.27	70.17	−0.14
11.0	32	94.54	95.97	+1.51
	50	93.38	95.50	+2.27
	100	95.24	95.28	+0.04
	200	89.99	89.56	−0.48
	300	72.77	72.50	−0.37
27.0	32	91.97	95.51	+3.84
	50	93.38	95.10	+1.84
	100	95.24	94.72	−0.55
	200	89.99	90.11	+0.13
	300	72.77	73.92	+1.58
35.0	32	89.67	93.50	+4.27
	50	91.18	93.40	+2.43
	100	93.34	92.50	−0.90
	200	88.70	87.50	−1.35
	300	72.09	71.50	−0.82

in Fig. 5 and Table 4, the computing values are in good agreement with the experimental data.

In addition, the general equation developed by computer simulation also compensated the SOC by using the storage temperature and the period of standing time as input parameters. To simulate the equation, the chosen range for the temperature was from −20 to 30 °C and for the storage period was 1–15 days. Several self-discharge tests of the Ni–MH battery were made to verify the integrity of the equation. The simulated results are in good agreement with experimental data, as can be seen in Fig. 6. In addition, the ageing effect was also investigated through cycle-life tests on the Ni–MH battery.

The SOC function when considering the effects of capacity compensation, self-discharge rate and ageing effects of the Ni–MH battery, which are derived by the computer simulation and battery tests, is expressed as:

$$\mathrm{SOC}\ (\%) = \frac{\begin{array}{l}(\sum a i_\mathrm{c}(t)\Delta t) + (b i_\mathrm{d} + bT + c\,10^{-4} i_\mathrm{d} T \\ -d\,10^{-4} i_\mathrm{d}^2 - e\,10^{-3} T^2) - (f + gT_\mathrm{s} + h t_\mathrm{s} + jT_\mathrm{s}^2 \\ + k t_\mathrm{s}^2 + l T_\mathrm{s} t_\mathrm{s}) - (mx - n\,10^{-4} x^2 + o\,10^{-7} x^3 \\ -p\,10^{-10} x^4) - (\sum i_\mathrm{d}(t)\Delta t)\end{array}}{C_\mathrm{r}} \times 100 \qquad (3)$$

where i_c is the charge current, i_d the discharge current, Δt the time (s), T the temperature, t_s the standing time (h), T_s the standing temperature, x the number of cycles, C_r the rated capacity, and a, b, c, d, e, f, g, h, j, k, l, m, n, o, p are the experimental constants.

The BMS with the SOC meter was installed and tested to estimate the accuracy of the system in the DEV5-5 vehicle. The results of the SOC test during recharging are shown in Fig. 7. The SOC results while driving the DEV5-5 vehicle under the urban driving dynamometer schedule (UDDS) mode are given in Fig. 8. The SOC accuracy was ±3% under all conditions in which the vehicle could be driven. The SOC is displayed to give direct information to the driver on instrument cluster of the vehicle.

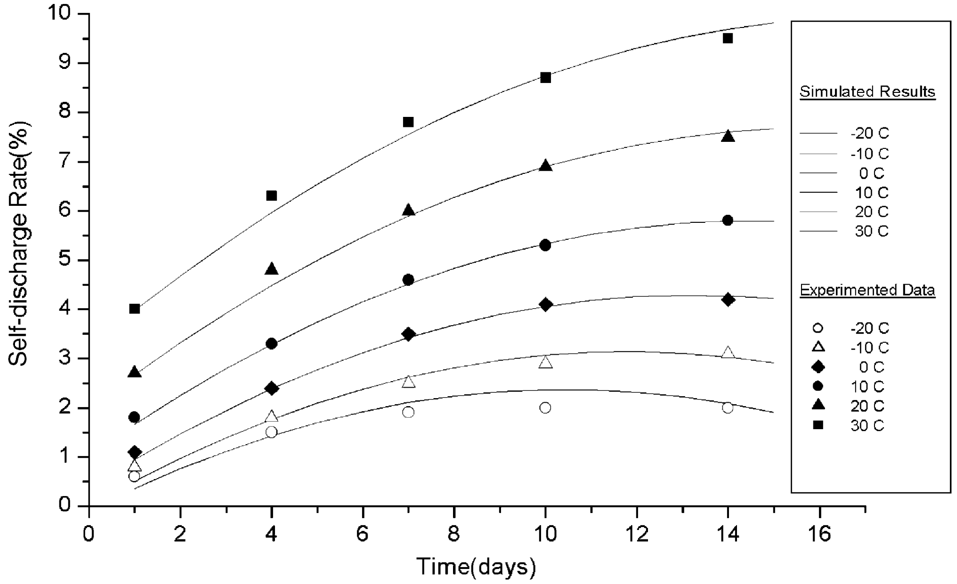

Fig. 6. Comparison of the simulated self-discharge rate with experimental data of Panasonic Ni–MH battery under temperature conditions that the EV can be operated.

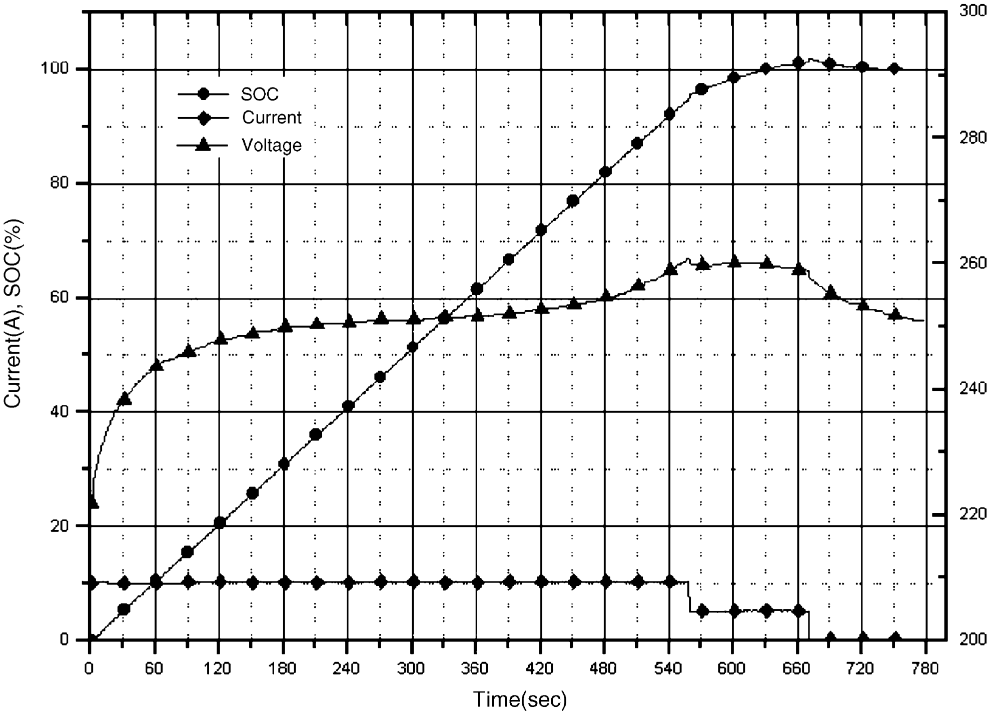

Fig. 7. Battery SOC during recharging of DEV5-5 electric vehicle.

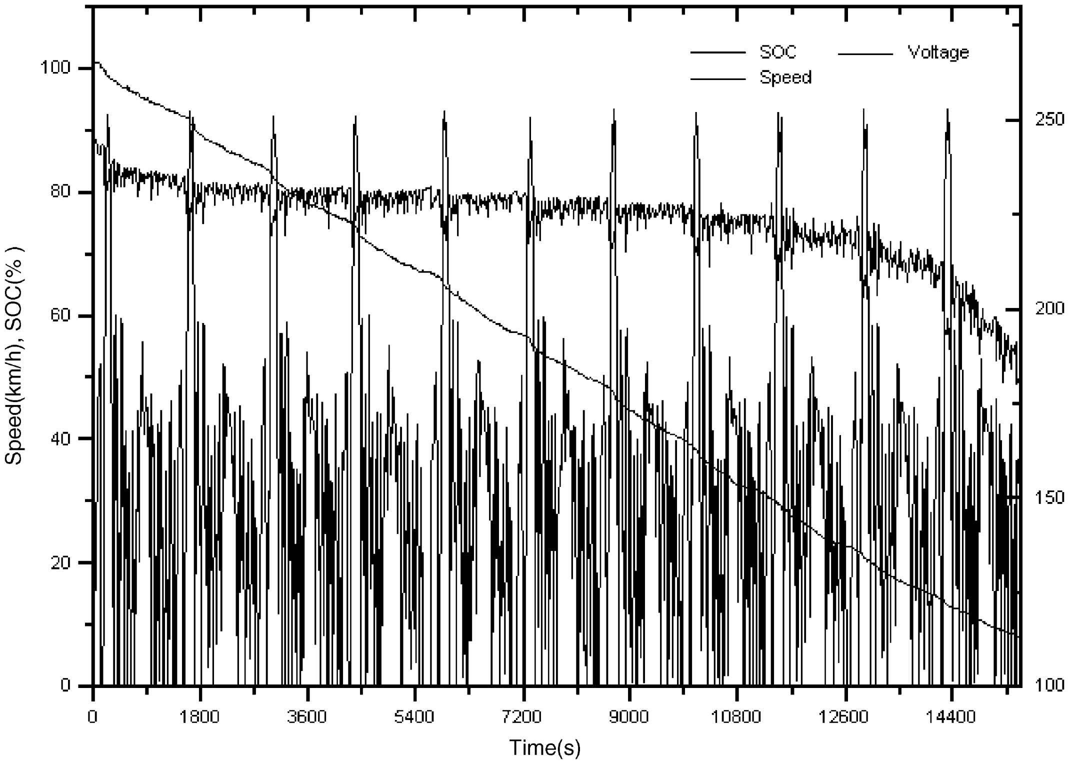

Fig. 8. Battery SOC during driving of DEV5-5 electric vehicle under UDDS mode.

6. Thermal management

Thermal management provided by the BMS is most important for high power applications in EVs and HEVs. The thermal management system in EVs controls the traction battery pack to equalize the temperature among the modules by cooling. Generally, air-cooling systems are used for EV applications because of cost and space limitations.

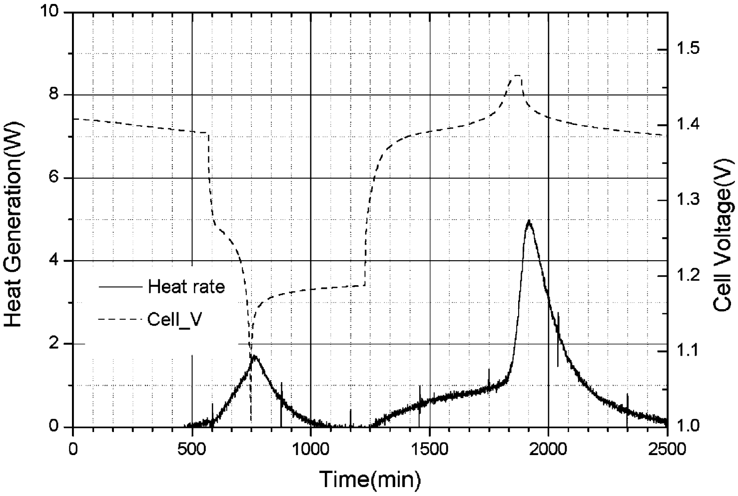

Fig. 9. Heat generation profile during discharging and recharging of Ni–MH cell.

The thermal management system consisted of three steps for the Ni–MH battery and was developed for application in the DEV5-5 vehicle. In the first step, the heat generated from the Ni–MH battery was measured by means of a calorimetric measurement method during charge and discharge. The heat generation profiles and voltage behavior of the Ni–MH battery during charging and discharging are shown in Fig. 9. The heat generation during charging is much greater than that during discharging. The energy loss by heat generation is 21.56 W h per cell during recharging and 5.83 W h per cell during discharging. The maximum heat generation as 5.17 W and the average is 2.3 W during recharging. In particular, the heat generation from the battery module during charging increases rapidly during the final stage of recharging. These results were used as input parameters for thermal analysis to optimize the battery pack design.

In the second stage, thermal modeling and analysis of the battery were conducted by means of a computational fluid dynamics (CFD) technique. Thermal analysis of the batteries using a module arrangement, fan specification and its location, and air-flow in battery pack was made to achieve proper cooling as well as temperature equalization between the modules. The battery pack was built for the EV based on the optimized design evolved through the thermal analysis.

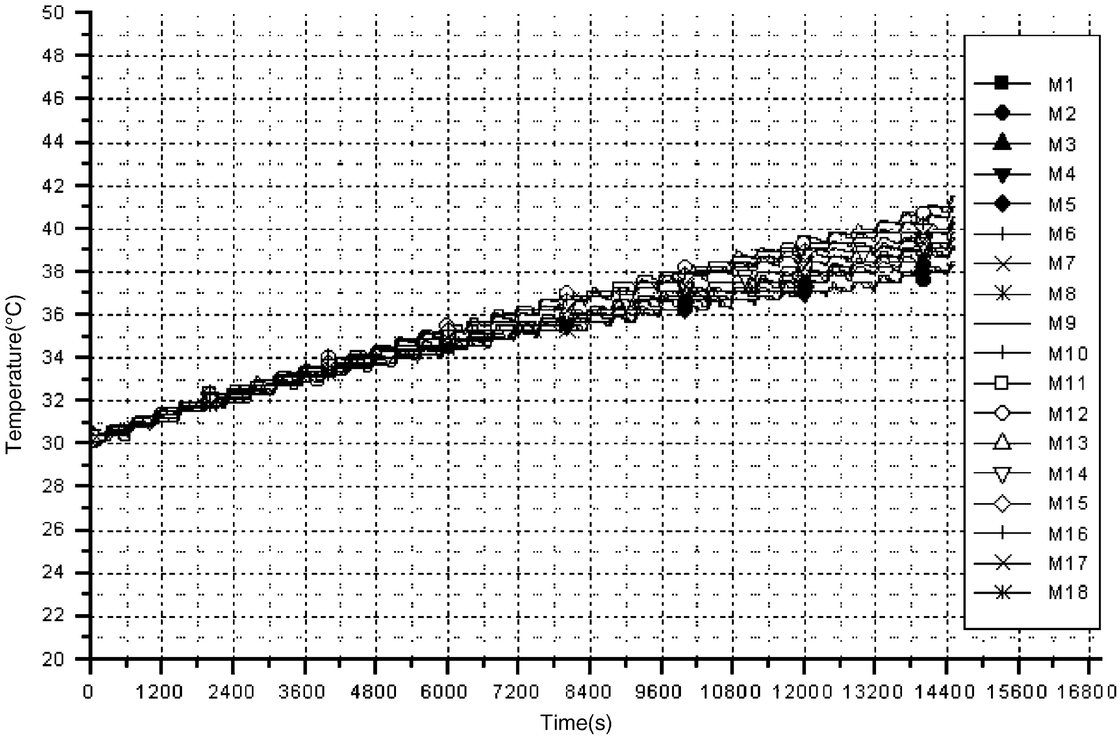

Fig. 10. Temperature profiles of Ni–MH battery modules during UDDS mode driving.

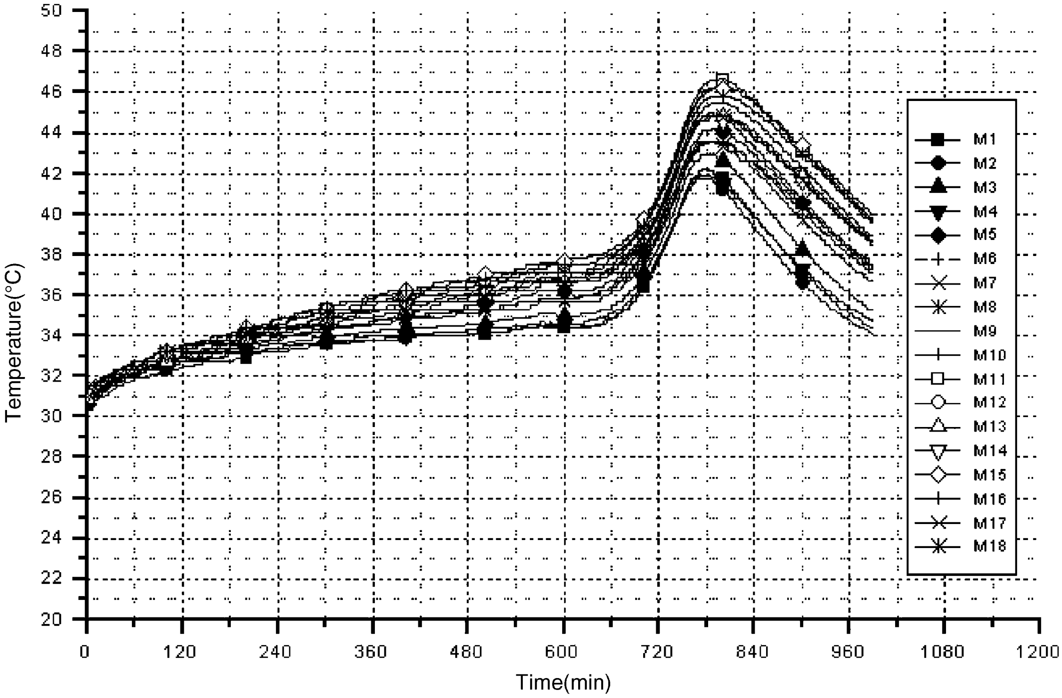

Fig. 11. Temperature profiles of Ni–MH battery modules during recharging.

In the third step, the control algorithms and the software and hardware for thermal management were developed for EV applications. The thermal management system was installed and tested in the DEV5-5 vehicle. The temperature profiles of the individual battery modules during driving under the UDDS mode are presented in Fig. 10. The temperatures increase constantly during discharging and the highest temperatures for the individual modules were observed at the end of discharge. The highest temperature and its deviation from the others among battery modules were 41 and 3 °C, respectively during discharge. The temperature profiles during recharging are shown in Fig. 11. The temperature of the battery modules slowly increase during the early and the middle stages of recharging. The temperature rapidly increases, however, at the final stage of recharge. The highest temperature and its deviation among battery modules is about 46 and 4 °C, respectively during recharge.

The highest temperatures and their deviations among the modules in the battery pack are within the range recommended by the manufacturer for optimal operation. Also, the test results are in good agreement with the thermal analysis results for the battery pack.

7. Safety management

Safety is one of the most important issues with EVs. In particular, the electrical hazards are more critical in EVs than in conventional vehicles because of the requirement to deliver high power and high energy from the traction battery. The safety management is to protect the battery against critical operating conditions and its main tasks in the BMS are as follows: overcharge protection, deep discharge protection, over-temperature protection, high voltage deviation protection, high temperature deviation protection, power line cut-off in the case of a electrical short-circuit, loss of electric isolation, and/or vehicle crash.

8. Diagnostics

In general, the BMS is required to store the battery data and the back-up data is transferred to a personal computer to obtain information for better maintenance procedures. A diagnostics system was developed to improve the service capability of the EV and it involved two main tasks. The first task is to store the historical data of the battery, such as input/output current, pack voltage, module voltages, module temperatures, SOC, etc. The data can be transferred to a personal computer to analyze and discover more about the battery characteristics. The second task is to provide information for the EV driver in order to repair battery failures. The diagnostic system displays and stores the abnormal status of the battery. The measuring and warning items included in the diagnostics system of the BMS are listed in Table 5.

9. Energy management

Energy management has been developed to enhance the driving range and the energy efficiency of the EV. The main

Table 5
Display or storage data of diagnostic system in BMS

Warning display and storage		
Battery	Overcharge, deep discharge, high temperature, high voltage deviation, high temperature deviation, etc.	Module number/value
BMS	Main charger fault, auxiliary charger fault, MSD fault, communication fault, etc.	
Storage (battery)	Input/output current, pack voltage, module voltages, module temperatures, ambient temperature, SOC, etc.	Module number/value

tasks of the energy management system in BMS are as follows: output power limitation reduction, regenerative braking system control, HVAC system on/off, EPS system on/off. These functions can be controlled according to the battery SOC.

The discharge current is limited to give a longer driving range at low battery SOC. Electrical systems using high energy such as the HVAC and EPS systems are also limited to use energy at low SOC. Regenerative braking is throttled at high SOC and the amount of braking current is controlled by the battery SOC, i.e. the lower the SOC, the greater is the regenerative-breaking current.

10. Auxiliary battery management

The auxiliary battery used in the EV could be smaller than that used in a conventional vehicle because the current required to start the powertrain is much lower than that required in a conventional system. This reduces costs and simplifies the package layout of the EV. The auxiliary battery used in the DEV5-5 vehicle is a half the conventional battery in terms of capacity and size.

Auxiliary battery management was developed to reduce the capacity and the size, and improve the cycle-life of the battery. The BMS monitors continuously the status of the battery and offers protection against deep discharge that may occur when the EV is standing for an extended period of time. The BMS controls the dc–dc converter used to start the EV automatically when the auxiliary battery voltage become lower than that of the predetermined voltage which protects against deep discharge. Also, the dc–dc converter is automatically cut-off by the BMS when the battery is fully charged. This control logic in the BMS can improve the calendar life of the battery and reduce the size of the auxiliary battery.

11. Conclusion

The use of a battery management system in EVs provides an improvement in the energy efficiency and the cycle-life of the traction battery. It also enhances the safety and the reliability of EVs. The former technology reduces operating costs such as fuel costs per km of EV travel and battery replacement costs. The latter costs can enhance the acceptance of EVs.

In this study, a BMS for Ni–MH battery in EV applications has been developed. The system has several functions to optimize the control of charge and discharge of the batteries, and to monitor the battery status in real time. The BMS has been installed and tested in a DEV5-5 electric vehicle made by Daewoo Motor Co. and the Institute for Advanced Engineering in Korea. The test results indicate that the system provides high accuracy and good reliability. Battery modules in the pack exhibit similar performance in voltage and temperature behavior during driving and recharging of the electric vehicle. Results also indicate that the energy efficiency of the battery can be improved by adoption of the BMS. The system can be used in commercial EVs to improve the performance and cycle-life of Ni–MH battery packs, as well as the reliability and the safety of the vehicles.

Acknowledgements

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References

[1] T. Shinpo, H. Suzuki, in: Proceedings of the 14th International EV Symposium, Orlando, FL, USA, 15–17 December 1997.
[2] M.S. Wu, Y.Y. Wang, C.C. Wan, J. Power Sources 74 (1998) 202.
[3] N. Hirata, K. Sakai, M. Origuchi, T. Miyamoto, K. Katayama, in: Proceedings of the 14th International EV Symposium, Orlando, FL, USA, 15–17 December 1997.
[4] D. Heinemann, D. Naunin, in: Proceedings of the 14th International EV Symposium, Orlando, FL, USA, 15–17 December 1997.
[5] H. Torstensson, in: Proceedings of the 17th International EV Symposium, Montreal, Canada, 15–18 October 2000.