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Development of Battery Management System for Electric Vehicle Applications of Ni/MH Battery

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Abstract. Electric vehicle performance is very dependent on traction batteries. For developing the electric vehicles with high performance and good reliability, the traction batteries have to be managed to get maximum performance under various operating conditions. The enhancement of the battery performance can be accomplished by implementing battery management system (BMS) that plays important roles of optimizing the control mechanism of charge and discharge of the batteries as well as monitoring battery status. In this study the battery management system has been developed for maximizing the use of Ni/MH batteries in electric vehicle. This system provides several tasks: the control of charging and discharging, overcharge and over-discharge protection, the calculation and display of state of charge, safety and thermal management. The BMS was installed in and tested using the DEV5-5 electric vehicle developed by Daewoo Motor Co. and Institute for Advanced Engineering in Korea. The 18 modules of Panasonic Ni/MH battery, 12 V-95 Ah, were used in the DEV5-5. The high accuracy within the range of 3% and the good reliability were shown in the test results. The BMS can also improve the performance and cycle life of Ni/MH battery pack as well as the reliability and safety of the electric vehicles (EV).

초 록 : 전기자동차의 성능은 축전지의 성능에 의해 크게 좌우된다. 그러므로 우수한 성능과 높은 신뢰성을 가진 전기자동차를 개발하기 위해서는 다양한 운영조건에서 축전지가 최대의 성능을 가질 수 있게 잘 관리되어야 한다. 축전지의 성능 향상은 축전지 관리 시스템(BMS)의 적용에 의해 달성될 수 있으며 BMS는 축전지의 상태 감시 뿐만 아니라 축전지의 충전 및 방전을 최적화하는 중요한 역할을 수행한다. 이 연구에서는 전기자동차에 적용된 니켈 메탈 하이드라이드 전지(Ni/MH battery)의 이용을 최대화하기 위한 역할을 수행하는 BMS를 개발하였다. 이 시스템은 축전지의 충전 및 방전 제어, 과충전 및 과방전 방지, 잔존용량 계산 및 표시, 안전관리 및 열관리 등의 기능을 가진다. 금번 개발된 BMS를 대우자동차와 고등기술원이 공동 개발한 DEV5-5 전기자동차에 장착하여 시험을 수행하였다. 이 차량에는 파나소닉사의 12V-95Ah 사양의 Ni/MH battery 18 모듈이 적용되었다. 시험결과 이 시스템은 3% 이내의 높은 정확성을 가지고 있으며 우수한 신뢰성을 나타내었다. 이 BMS는 전기자동차의 신뢰성과 안전도 뿐만 아니라 Ni/MH battery pack의 성능과 수명을 향상시킬 것이다.

Key words : Electric vehicle (EV), Battery management system (BMS), Ni/MH battery, State of charge, Thermal management, Control of charging and discharging.

1. Introduction

A number of battery modules on electric vehicles or hybrid electric vehicles are connected in series to make high system voltage. From the early stage of EV development, it had been known that the initial capacity among modules were not much different from all others, but it became greater with the longer driving range of the electric vehicle and charge/discharge cycles of the batteries. The battery modules indicating higher capacity deviations from all others should be overcharged or over-discharged to make the modules balance at the end of recharge and discharge respectively.[1] In this case, the performance of the batteries could become worse by the overcharge as well as the over-discharge repeatedly. In order to solve these problems, all of battery modules must be managed individually by proper controlling during recharge and discharge.

Driving range information in electric vehicle 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 much related to the accurate calculation of state of charge (SOC) of the batteries in electric vehicles. For providing accurate battery SOC information, the available capacity, the self-discharge rate and the aging factors should be considered at all conditions that electric vehicles could be driven. The available capacity of battery decreases rapidly with temperature drops and larger discharge current. It is assumed that the battery SOC and the driving range of electric vehicle are highly dependent on environmental conditions, especially ambient temperature and driving

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patterns of the vehicle. In addition, the capacity of battery decreases naturally due to the self-discharge when the electric vehicle is parked for a long period of time. The rate of self-discharge is dependent on storage temperatures and the stand period: the higher the temperature and the longer the stand period, the greater the rate of self-discharge. It can be known from the information that such energy loss must also be considered for an accurate calculation of the battery SOC. The battery capacity tends to be decreased with increasing the number of cycles. For examples, the available capacity after 300 cycles is rather smaller than that in 10 cycles. From the point of aging effect, it is also considered to determine the accurate battery SOC.

Heat generated from the battery is due to reversible and irreversible phenomena during charge and discharge. A rapid increase in temperature, particularly at the final stages of charge and discharge, may cause the battery performance to be deteriorated 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 electric vehicle, the battery modules should almost have nearly the same electrical characteristics as others, which are very much dependent on the temperatures.[4] It can be seen that thermal management control is necessary to provide the nearly same performances among the modules in the battery pack under controlled temperatures.

Where electrical hazards are concerned, the batteries are the main issue in electric vehicles. Most serious hazard may be an electrical short-circuit, the loss of electric isolation and the failure of electronics.[5] Overcharge may cause to vent the explosive gas to environment and result in excessive temperatures in batteries, which give rise to a fire or explosion. To improve the safety in electric vehicle, the management system must also be considered. Some of parameters have to be monitored in real time to protect the electrical hazards.

In this study, a battery management system (BMS) for electric vehicle applications was developed to improve the performance and cycle life of the battery as well as the safety and the reliability of electric vehicles. The system developed includes the functions such as charging and discharging optimization of batteries, SOC calculation and display, thermal management, safety management, and etc.

2. Battery Management System

BMS measures current, battery pack voltage, module voltages, temperature, and analyzes these data, and controls subsystems to optimize the status of traction batteries. The functions of a BMS can be explained as followings:

- Data acquisition
- Charging optimization
- Calculation and display of the SOC
- Thermal management
- Safety management
- Energy management
- Auxiliary battery management
- Diagnostics

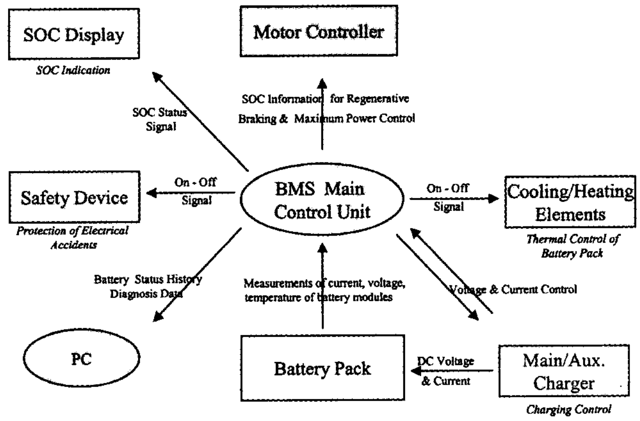

Fig. 1. Schematic structure of BMS.

Table 1. Functions of subsystems in BMS

Subsystems	Functions
BCU	. Data acquisition & storage . Data analysis & 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 deviations warning
MSD	. Voltages & temperatures measurement of battery modules

Fig. 1 indicates the schematic structure of BMS for the application of electric vehicle battery. The BMS is composed of battery control unit (BCU), main charger, auxiliary charger, thermal management system, SOC meter, battery warning devices, module sensing device (MSD), safety module and etc. Table 1 presents the tasks of these subsystems. Among the subsystems the BCU plays the most important role in BMS. The BCU monitors the status of batteries in real time and sends appropriate control commands to subsystems to accomplish the optimization of the traction batteries. Fig. 2 shows the functional block diagram of BCU.

3. Data acquisitions

The measured and calculated data as input information were used in control algorithms of BMS. The sampling time is one second and the accuracy of all data is less than $\pm 0.4\%$. MSD was used to prevent the effect of electromagnetic noise in measuring voltages and temperatures of each battery modules. MSD transmits the signals to BCU after conversion from the measured analog to digital. The data in BMS are as follows:

- Input/output current of battery pack

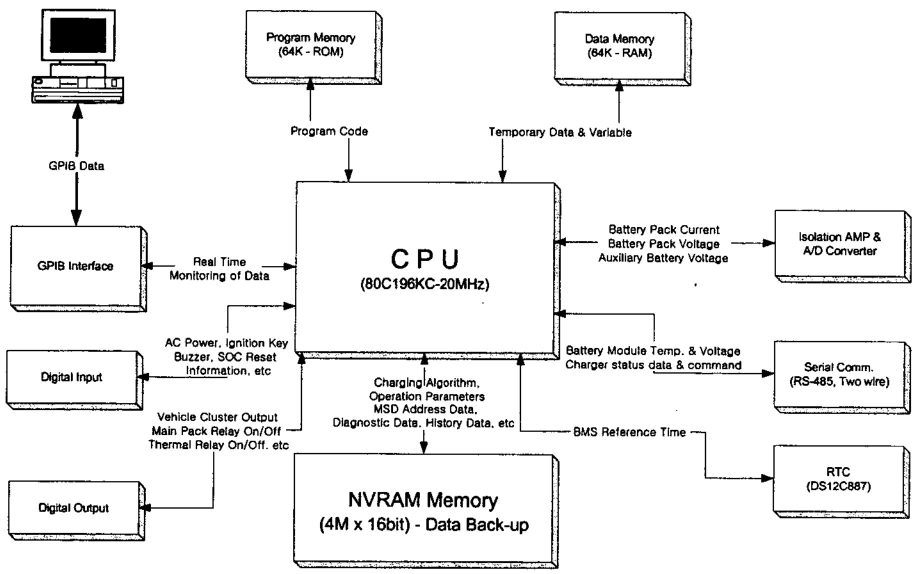

Fig. 2. Functional block diagram of BCU in BMS.

- Voltage of battery pack
- Voltages of battery modules
- Ambient temperature
- Temperatures of battery modules

4. Charging system

In order to minimize capacity deviations from all others among modules in battery pack, the advanced charging algorithm that recharges the battery pack and modules independently was developed. The charging algorithm developed improves charging efficiency and prolongs cycle life of batteries because the overcharge of the batteries is prevented by the equalization of modules. Charging system in BMS has two chargers; Main charger recharges the battery pack. Auxiliary charger recharges each module with lower capacity than another at the final stage of recharging to equalize the module capacity in battery pack. The BCU using MUX connecting the auxiliary charger to the modules in the BMS measures and analyzes all of battery voltage and temperature data to select the modules indicating lower capacity than others.

Table 2 shows the specifications of the main charger and the auxiliary charger. The charging system in the BMS was integrated and tested in the DEV5-5 shown in Fig. 3 and the specifications of DEV5-5 was indicated in Table 3. The profiles of charging current of the main charger, the auxiliary charger and the voltages of battery modules during recharge are represented in Fig. 4. As can be seen in Fig. 4, the main charger supplied 2 steps constant currents, indicating 10 A and 5 A and the auxiliary charger supplied constant current, indicating 2 A at the second step. Average voltage of 18 modules was 13.9 V after 300 min from starting point of recharging. In Fig. 4, C_8 and C_{14} are representing module 8 and module 14 respectively. Module 8 represented the maximum deviation of voltage from the average, 0.3 V, and module 14 showed 0.1 V. At the second recharging step the auxiliary charger pick out the module 8 and supplied 2 A

Table 2. Specifications of the main charger and auxiliary charger

	Main charger	Auxiliary charger
Input voltage	AC220 V	AC220 V
Output voltage	320 V Max.	16 V Max.
Maximum power	3.3 kW	60 W
Charge method	Constant current, constant voltage	Constant current
Accuracy	1.0%	1.0%

Table 3. Specifications of DEV5-5 electric vehicle

Vehicle		Motor & Inverter		Battery	
Type	4seats passenger	Motor Type	AC Induction	Type	Ni/MH battery
Curb weight	1,250 kg	Max power	52 kW	No. of module	18
GVW	1,510 kg	Max torque	180 Nm	Capacity	95 Ah
Length	3,734 mm	Max RPM	9,700	Voltage	216
Width	1,715 mm	Inverter	IGBT	Total energy	20.5 kWh
Height	1,580 mm				

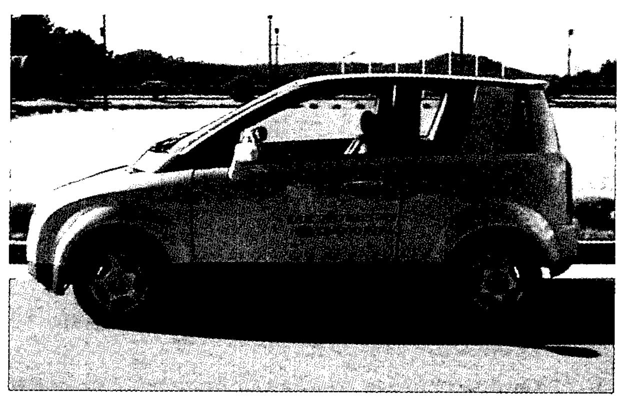

Fig. 3. DEV5-5 electric vehicle developed by IAE and Daewoo Motor Co..

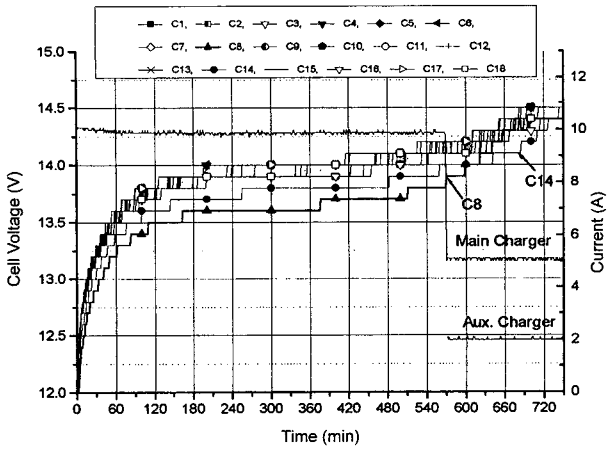

Fig. 4. Charging profiles during recharging of DEV5-5 electric vehicle.

until attaining a point in an average voltage of modules. Immediately after the module 8 recharging, the auxiliary charger switched to the module 14 indicating maximum voltage deviations and eventually the deviation became less than 0.1 V among 18 modules. The lower voltage deviation than average is representing the less deviation in capacity. This advanced charging algorithm can improve the performance and the reliability of Ni/MH battery pack.

5. SOC calculation and display

Presenting the accurate SOC of battery is one of important issues in the development and deployment of electric vehicle technology. Due to complex dynamic behavior of individual modules in series connection under various environmental conditions, the methods for SOC estimation proposed most recently do not satisfactorily perform because of the accumulative error throughout the duty cycles.

A practical method for predicting the SOC of Ni/MH battery in the DEV5-5 has been developed. The coulomb counting techniques is involved in this study as shown in Eq (1).

$$\text{SOC}(\%) = \{(\text{the rated capacity - used capacity + charged capacity})/\text{the rated capacity}\} \times 100 \quad (1)$$

For accurate calculation of SOC for Ni/MH battery, many factors affecting on the SOC through various battery tests are investigated. From the test it has been known that the available capacity, the self-discharge rate and the aging effect of the battery has to be considered to determine the accurate SOC. Eq (1) can be replaced to Eq (2) after considering the above parameters.

$$\text{SOC}(\%) = \{(\text{the rated capacity + the capacity compensation factor + self-discharge effect + the aging effect- used capacity + charged capacity})/\text{the rated capacity}\} \times 100 \quad (2)$$

The available capacity of the battery may become different

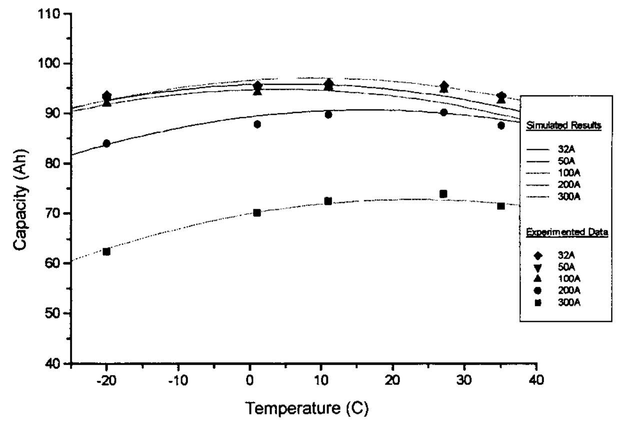

Fig. 5. Compared results of the simulated capacity with experimental data of Panasonic Ni/MH battery under all conditions that electric vehicle could be driven.

from the rated capacity when the battery is discharged at another conditions. The available capacity can be decreased rapidly at lower temperatures and higher discharge currents, and the capacity compensations under these circumstances have to be made to show the accurate battery SOC. In addition, even though the battery is fully charged before parking electric vehicle, the battery capacity is slowly reduced with the extended period of standing time and this loss may be due to self-discharge. The self-discharge is dependent on the storage temperatures and the period of standing and also the loss of capacity occurs due to the chemically degradation inside the battery with increasing cycles.

The computer simulation has been made to predict the available capacity of the Ni/MH battery at various temperatures and discharge current conditions that electric vehicle could be driven. A general equation, representing the available capacity which is determined by temperature and discharge current of the battery, was developed for the application of electric vehicle. In this study, the range of temperatures of -19.5 ~ 36.5°C and discharge current of 32 ~ 300 A were used to simulate the equation using computer. Several capacity tests of the Ni/MH battery were also conducted to verify the integrity of the equation. As seen in Fig. 5 and Table 4, the computing values were in good agreement with the experimental data.

In addition, the general equation by computer simulations was also developed to compensate the SOC using the storage temperature and the period of standing time as input parameters. The rate of self-discharge is dependent on the storage temperature and time; the higher the temperature, the greater the rate of self-discharge. We selected the range of input parameters to develop the general equation with high accuracy; the ranges of temperature of -20 ~ 30°C and storage periods of 1 ~ 15 days. Several self-discharge tests of Ni/MH battery were made to verify the integrity of the equation. The simulated results were in good agreement with experimental data as can be seen in Fig. 6. In addition to that, the aging effect was also investigated through cycle life tests of the Ni/MH battery.

Eq (3) represents the SOC function considered the effects

Table 4. Comparison between the predicted values and the experimental data of Ni/MH battery

Temperature	Discharge	Calculated	Measured	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

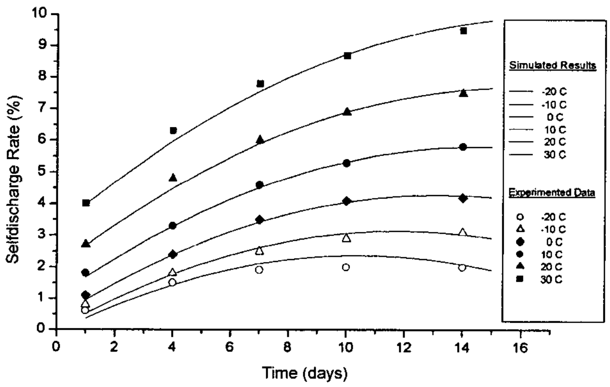

Fig. 6. Compared results of the simulated self-discharge rate with experimental data of Panasonic Ni/MH battery under temperature conditions that electric vehicle could be operated.

of the capacity compensation, self-discharge rate and aging effects of the Ni/MH battery, which are derived by the computer simulations and battery tests.

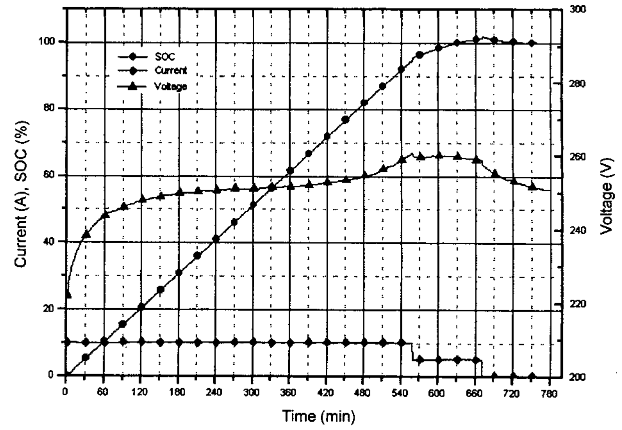

Fig. 7. SOC test results during recharging of DEV5-5 electric vehicle.

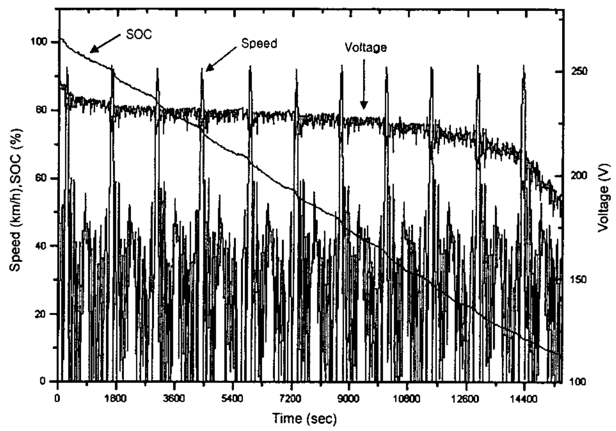

Fig. 8. SOC test results during the driving of DEV5-5 electric vehicle with UDDS mode.

$$SOC(\%) = [(\Sigma a i_c(t)^* \Delta t) + (b^* i_d + \beta^* T + c^* 10^{-4} {}^* i_d {}^* T - d^* 10^{-4} {}^* i_d^2 - e^* 10^{-3} {}^* T^2) - (f + gT_s + ht_s + jT_s^2 + kt_s^2 + lT_s t_s) - (mx - n^* 10^{-4} x^2 + o^* 10^{-7} x^3 - p^* 10^{-10} x^4) - (\Sigma i_d(t)^* \Delta t)/C_r] \times 100 \quad (3)$$

where,

i_c : charge current

i_d : discharge current

Δt: time(sec)

T : temperature

t_s : standing time(hr)

T_s: standing temperature

x : number of cycle

C_r: the rated capacity

a, b, c, d, e, f, g, h, j, k, l, m, n, o, p, β: experimental constants

The BMS with SOC meter was installed and tested to estimate the accuracy of the system in DEV5-5. Fig. 7 shows the SOC test result during recharging. Fig. 8 also shows the SOC test result during driving the DEV5-5 electric vehicle with the UDDS (urban driving dynamometer schedule) mode. The SOC accuracy was less than 3% at all conditions that the electric vehicle could be driven. The SOC has been displayed to give SOC information to vehicle driver on the cluster (SOC meter).

6. Thermal management

The thermal management in BMS is one of the most important one for high power applications of electric vehicles and hybrid electric vehicles. The thermal management system in electric vehicles controls the traction battery pack to equalize temperature among modules by cooling. Generally air-cooling systems are used for electric vehicle applications because of costs and space limitations.

The thermal management system that consisted of the 3 steps for Ni/MH battery was developed for the application of electric vehicle, DEV5-5. In the first step, the amount of heat generation from the Ni/MH battery was measured by using calorimetric measurement method during charge and discharge. Fig. 9 shows the heat generation profiles and voltage behavior of the Ni/MH battery during charging and discharging. As can be seen in Fig. 9, the heat generation during charging is much greater than that during discharging. Energy loss by heat generation was 21.56 Wh per cell during recharging and 5.83 Wh per cell during discharging. Maximum heat generation was 5.17 W and the average was 2.3 W during recharging. In particular, the heat generation from the battery module during charging increases rapidly at the final stage of recharging. These results were used as input parameters for thermal analysis to optimize the battery pack design.

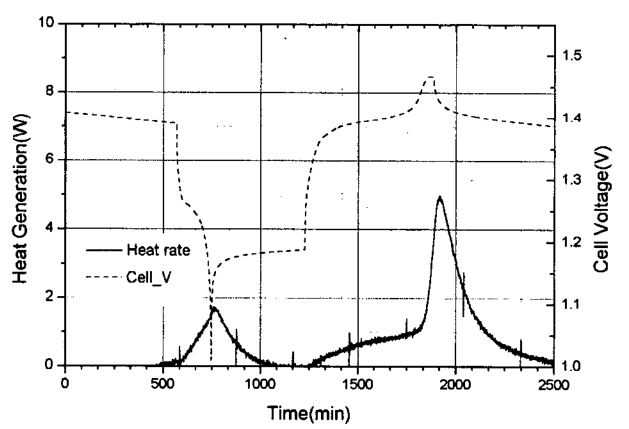

Fig. 9. Heat generation profiles during discharging and recharging of Ni/MH battery cell.

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

In the third step, the control algorithms, software and hardware for thermal management were developed for electric vehicle applications. The thermal management system was installed and tested in DEV5-5. Fig. 10 also shows the temperature profiles of individual battery modules during driving with UDDS mode. It can be seen in Fig. 10 that temperatures increased constantly during discharging and the highest temperatures for individual modules were observed at the end of discharge. The highest temperature and its deviation from the others among battery modules were 41°C and 3°C respectively during discharge. Fig. 11 shows temperature profiles during recharging. Temperatures of battery modules were slowly increased in the early and middle stage of recharging. However, the temperature was rapidly increased at the final stage of recharge. The highest temperature and its deviation among battery modules were represented about 46°C and 4°C respectively during recharge.

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

7. Safety management

Safety is one of the most important issues in electric vehicle. In particular, the electrical hazards are more critical in electric vehicle than in conventional vehicle because of delivering the high power and the high energy from traction battery.

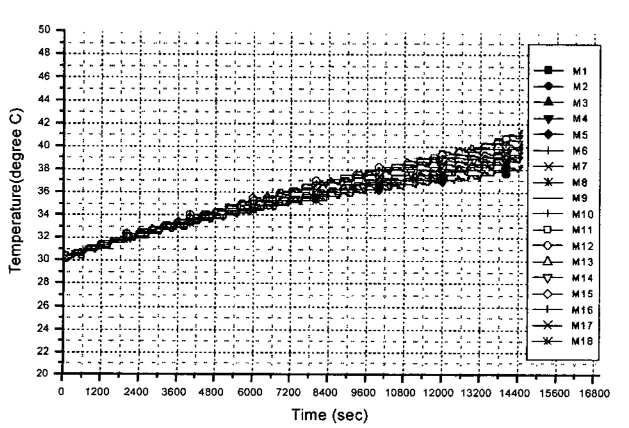

Fig. 10. Temperature profiles of Ni/MH battery modules during UDDS mode driving.

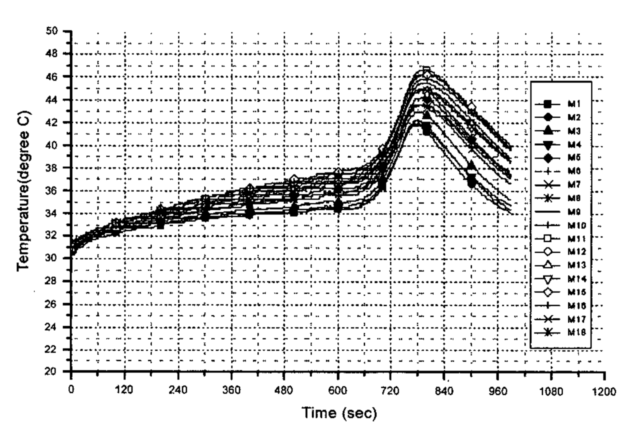

Fig. 11. Temperature profiles of Ni/MH battery modules during recharging.

Table 5. Display or storage data of diagnostic system in BMS

Warning Display & 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

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 when electrical short-circuit, loss of electric isolation and/or vehicle crash.

8. Diagnostics

In general, BMS is required to store the battery data and the backup data is transferred to PC to get information for better maintenance works. Diagnostics system was developed to improve the service capability of electric vehicle and involved two main tasks. The first one is to store the battery historical data such as input/output current, pack voltage, module voltages, module temperatures, SOC and etc. The data can be transferred to a PC to analyze and know more about the battery characteristics. Second task is to provide the information for EV driver in order to repair the battery failures. Diagnostic system displays and stores the abnormal status of battery with BMS. Table 5 represents the measuring and warning items shown in diagnostics system of the BMS.

9. Energy management

Energy management has been developed to enhance the driving range and the energy efficiency of electric vehicle. Main tasks of the energy management system in BMS are as follows. The functions could be controlled according to battery SOC.
- Output power limitation reduction
- Regenerative braking system control
- HVAC system on/off
- EPS system on/off

Discharge current was limited to make the driving range longer at low battery state of charge. Electrical systems using high energy such as HVAC and EPS system were also limited to use the energy at the low SOC. Regenerative braking was throttled at high SOC and the amount of braking current was controlled by the battery state of charge. The lower the SOC the greater the regen-brake current.

10. Auxiliary battery management

Auxiliary battery used in EV could be smaller than that of conventional vehicle because the current to start the powertrain is much lower than that of the conventional system. It is good for saving the costs and making the package layout of electric vehicle easily. The auxiliary battery used in DEV5-5 is a half of the conventional battery in terms of capacity and size.

Auxiliary battery management was developed to reduce the capacity and the size, and improve the life cycle of the battery. BMS always monitors the status of the battery and protects the deep discharge that may be occurred when electric vehicle is standing for expended period of time.

The BMS controls the DC/DC converter to start the EV automatically when the auxiliary battery voltage become lower than that of the predetermined voltage to protect the deep discharge. Also the DC/DC converter is automatically cut off by 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 battery management system in electric vehicles provides the improvement of energy efficiency and cycle life of traction battery as well as the enhancement of safety and reliability of electric vehicles. The former technology results in the operating cost save such as fuel costs per mile of the electric vehicle and battery replacement cost. The latter one can improve the performance acceptance of the electric vehicles.

In this study, the battery management system for Ni/MH battery in electric vehicle applications was developed and the system has several functions to optimize the controls of charge and discharge of the batteries and monitor the battery status in real time. The BMS was installed and tested in DEV5-5 electric vehicle made by Daewoo Motor Co. and Institute for Advanced Engineering. The test results indicate that the system provides highly accurate and good reliability in use. Battery modules in battery pack showed the similar performance in the voltage and temperature behaviors during driving and recharging of the electric vehicle. It is also known from the testing results that the energy efficiency of the battery can be improved by adoption of the BMS. The system could be used for commercial electric vehicle to improve the performance and cycle life of Ni/MH battery pack as well as the reliability and safety of the electric vehicle.

Acknowledgements

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