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Multi-step constant-current charging method for an electric vehicle nickel/metal hydride battery with high-energy efficiency and long cycle life

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Abstract

This study sought to investigate methods of charging nickel/metal hydride (Ni/MH) batteries for use in an electric vehicle(EV). The specific conditions for the multi-step constant-current charging method with regulation of voltage and dT/dt were varied in an attempt to improve high-energy efficiency, shorten charging time, and increase cycle life. A commercial battery system with 12 modules was subjected to a discharge/charge cycling test using patterns of dynamic stress test (DST) 120. Two-step charging with a first-step current of 0.5 CA (1 CA = 95 A) was completed in less than 2.5 h after DST120-pattern discharging to 80% DOD. Further, three-step charging with the first step of 1.0 CA reduced charging time to about 1.5 h. Multi-step constant-current charging provided a high-energy efficiency of more than 80%. The battery system withstood over 1800 cycles in a cycling test with reduction DST120-pattern discharge of 20%, but reductions in constant-current discharge of only 7%, due to a gradual decrease of discharge power, independently of the value of the charging current.

Keywords: Mutli-step constant-current charging; Ni/MH battery; Cycle life

1. Introduction

The popularity of electric vehicles (EVs) is expected to increase dramatically as a consequence of efforts to reduce automobile emissions by the efficient utilization of energy to preserve the global environment. In the field of electric power supply management, a topic of current interest is increasing night-time electrical load to provide efficient use of electric power generation equipment and to reduce air pollution, including CO_2 emissions. The widespread use of EVs with efficient utilization of energy and reduction emission depends much on the capacity to charge EV batteries using available current patterns within 5–8 h, with peak electrical draw during the period of minimum electric power use, which in Japan is 02.00–05.00 h [1]. In 1998, 10 Japanese electric power companies and the Central Research Institute of the Electric Power Industry (CRIEPI) launched another 2-year collaborative investigation of charging methods for nickel/metal hydride (Ni/MH) battery systems for EVs, following the investigation of those for valve-regulated lead–acid (VRLA) battery systems.

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For EV VRLA batteries, the multi-step constant-current charging method was discussed in the previous papers [2–4]. A new charging method involving a four-step constant current with 0.5 CA (1 CA = 95 A) for the first-step constant-current successfully charges a VRLA battery system within 5 h. This work also clarified the mechanisms of battery degradation, demonstrating that multi-step constant-current methods suppressed heat evolution and water loss during charging, thereby suggesting a potential method for prolonging the cycle durability of batteries [3]. Thereafter, we investigated a new high energy efficiency charging operation, which completes charging in less time with a higher energy efficiency of more than 80 Wh% during discharge/charge [4]. While, the fast charging condition was proposed with extension of driving distance by a day and a long cycle life [5].

In this study, we examined the charging conditions of multi-step constant current in order to prolong cycle lives, enhance discharge/charge energy efficiency, and reduce the charging time required for EV Ni/MH battery systems. Also investigated during this study were the mechanisms involving the memory effects caused by shallow-depth discharge, and battery performance in low-temperature conditions for daily driving.

2. Experiment

2.1. Battery system

The 14 kWh battery system consists of 12 series-connected modules of an EV commercialized Ni/MH battery (12 V/95 Ah, JEVS type-B), as shown in Fig. 1. This type of commercial battery system is mounted in a Toyota-RAV4L EV and Honda-EV Plus. The modules were set in a battery box equipped with four fans (0.2 kW) that provided airflow from the bottom to the top for cooling during the cycling test (Table 1).

Fig. 1. Ni/MH battery system in a box with four fans.

Table 1
Performance of the Ni/MH battery

Ni/MH module	
Capacity	12 V, 95 Ah
Size	H: 175 mm, W: 116 mm, L: 388 mm
Weight	18.8 kg per module
Energy density	61 Wh/kg, 145 Wh/l

To examine the effect of the low temperature environment, we set the battery box in a freezing room at a temperature of -10 °C.

2.2. Discharging conditions and measurement of discharge capability and power density

During the cycling test, the system was discharged by pattern of dynamic stress test (DST) with maximum discharge power of 120 W/kg (DST120) [6] to 80% of the nominal capacity (76 Ah). The discharge capacity of the system was measured with both a constant current of 0.2 CA and the DST120 pattern until 10.0 V per module. Discharge power density was measured with a 5 s pulse discharge every 50 or 100 cycles. The discharge power density was calculated by measuring the terminal voltage of the discharge with 19 A (0.2 CA), 95 A (1.0 CA) and 190 A (2.0 CA) in 5 s, in accordance with the JEVS D707 [7]. This measurement was carried out at both 50 and 80% DOD.

The daily distance driven for the vehicles used to commute to work was reported to be an average of about 50 km [8]. Assuming that the driving distance per charge is about 200 km for an EV with a Ni/MH battery system, the system is estimated to be discharged repeatedly to 25% DOD. To examine the effect of discharging to a shallow DOD, we discharged the system to 25% DOD, then recharged the system using one-step constant-current charging.

2.3. Charging conditions

To examine the effect of the amount of the charging current, we charged the systems using multi-step constant-current charging at a constant current ranging from 95 A (1.0 CA) to 13 A (0.14 CA) for the first-step charging current. This is shown in Table 2. The battery system was charged by multi-step constant-current charging with regulation of the module voltage and the rising ratio of the battery temperature (dT/dt). In multi-step constant-current charging, the first- or second-step charging with 47.5 A (0.5 CA) and 95 A (1.0 CA) were regulated by a module voltage of 14.7 V per module. The last-step constant current of 13 A (0.14 CA) and 20 A (0.21 CA) in multi-step charging was regulated by increasing the battery temperature by 0.13 °C/min (dT/dt).

Table 2
Charging time and energy efficiency under each charging condition

Charging condition	Charging time	Energy efficiency
One-step 13 A	6 h 14 min	84 Wh%
One-step 20 A	4 h 04 min	85 Wh%
Two-step 47.5 A + 13 A	2 h 30 min	81 Wh%
Two-step 47.5 A + 20 A	1 h 59 min	82 Wh%
Three-step 95 A + 47.5 A + 13 A	1 h 40 min	80 Wh%

Under certain conditions, the battery systems were charged with a constant current of 3 A (0.03 CA) for 2 h to equalize the state of charge for cells comprising the system, either every time or every 10 cycles.

3. Results and discussion

3.1. Multi-step constant-current charging

For a VRLA battery, multi-step constant-current charging methods can reduce charging times [2]. The multi-step constant-current charging method was applied to the Ni/MH battery system.

In the one-step method, the first step was regulated only by d*T*/d*t*. In multi-step methods involving multiple steps, the first- or second-step charge was regulated by the battery voltage of 14.7 V per module (Figs. 2 and 3). An increase in the magnitude of charging current from 13 to 20 A in the one-step method could reduce the charging time by 2 h. Two-step constant-current charging with 47.5 A + 13 A was completed in 2.5 h without an equalizing charge using 3 A for 2 h. With two-step charging, increasing the second-step current from 13 to 20 A reduced the charging time by 30 min to only 2 h. Furthermore, the three-step method with the first step of 95 A completed charging in approximately 1.5 h (Figs. 2 and 3, Table 2). Battery temperature rose to 35 °C during the first-step charge with 95 A, but rapidly declined thereafter when the charging current was reduced from 95 to 47.5 A by regulating the battery voltage (Fig. 2). During the first-step charging with 47.5 A in the two-step charging method, the battery temperature rose to 30 °C, with the rate of temperature declined slowly somewhat following the switch to the second-step charge.

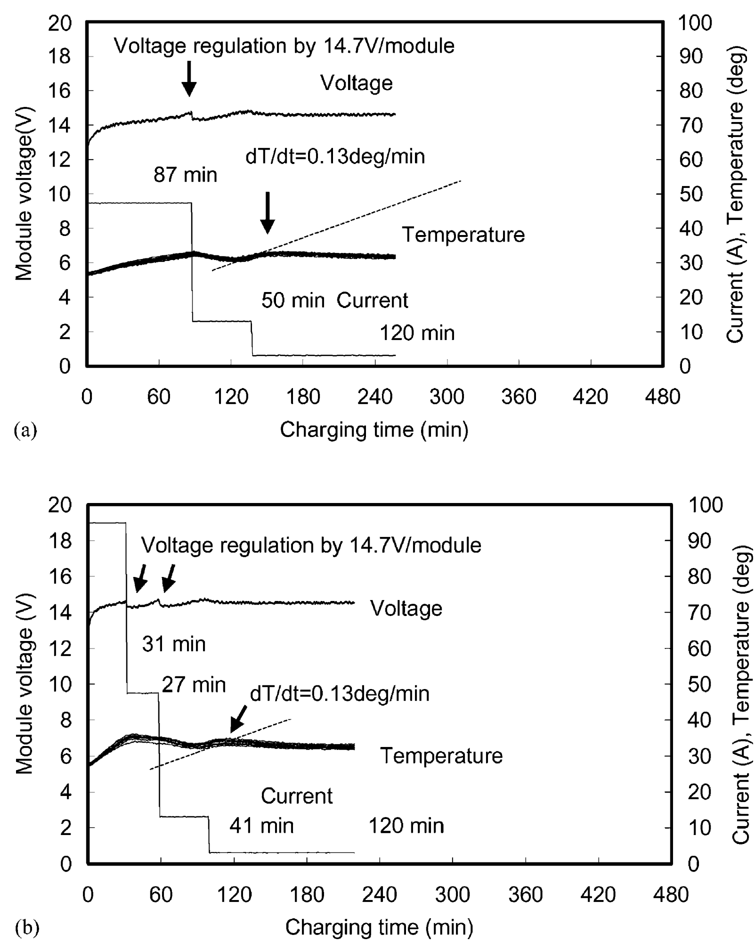

Fig. 2. Profiles of multi-step charging with an equalizing charge using 3 A for 120 min every 10 cycles, (a) two-step (47.5 A + 13 A), and (b) three-step (95 A + 47.5 A + 13 A).

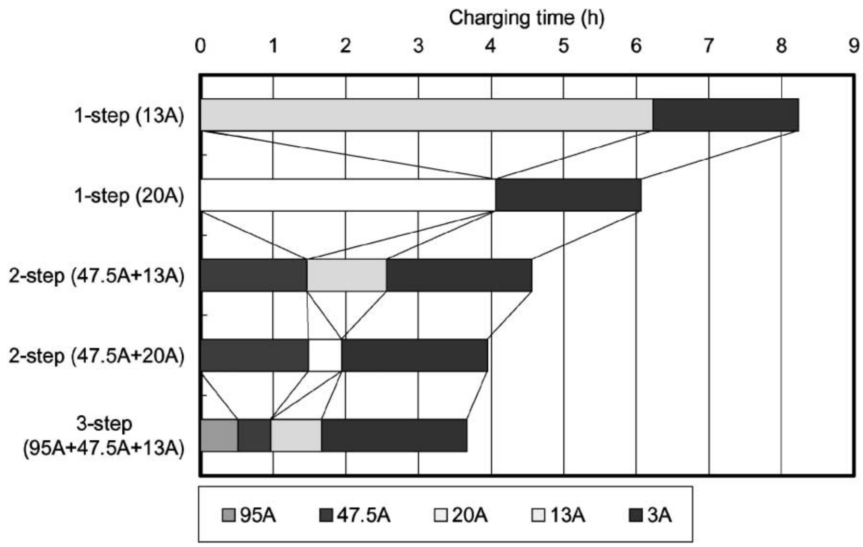

Fig. 3. Charging time under each condition with an equalizing charge using 3 A for 2 h.

While we expected the increase in temperature to accelerate, leading to degradation caused by the higher charging current, no actual differences were observed between different charging conditions in the behavior of discharge capacity and power density in the cycling test (Figs. 4 and 5). Over 1500 cycles, the constant-current discharge capacity decreased slightly retaining at approximately 90%, while, both DST120-pattern discharge capacity and

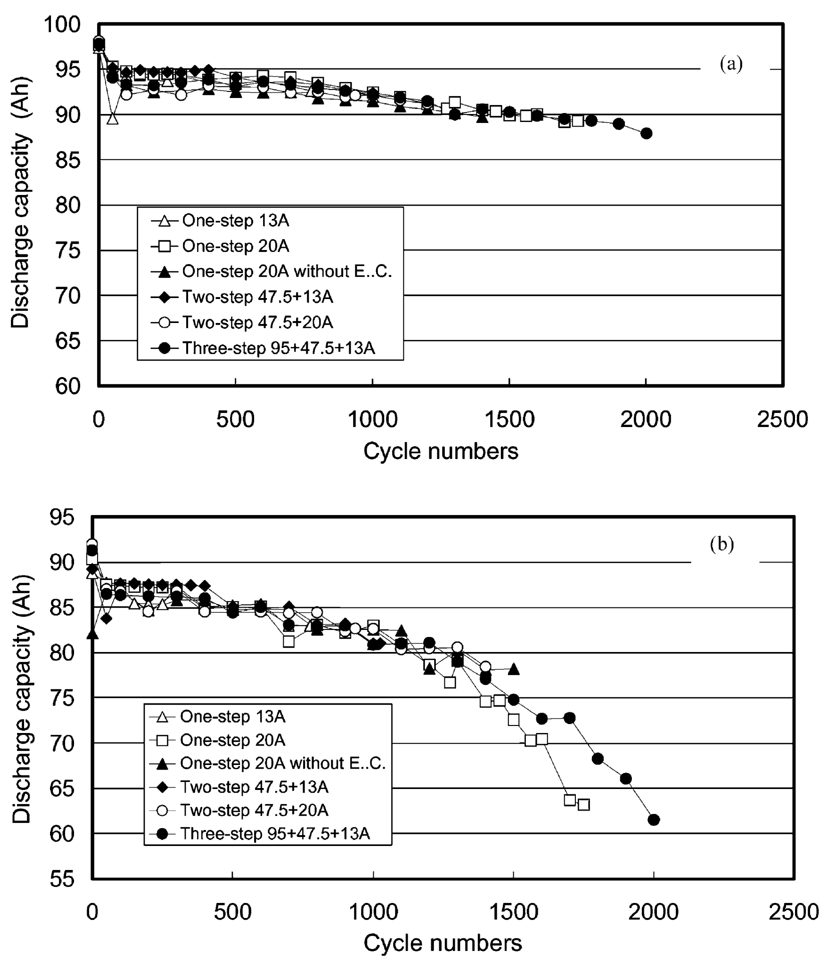

Fig. 4. Discharge capacity with (a) constant current of 19 A, and (b) DST120 pattern during cycling tests under each charging condition.

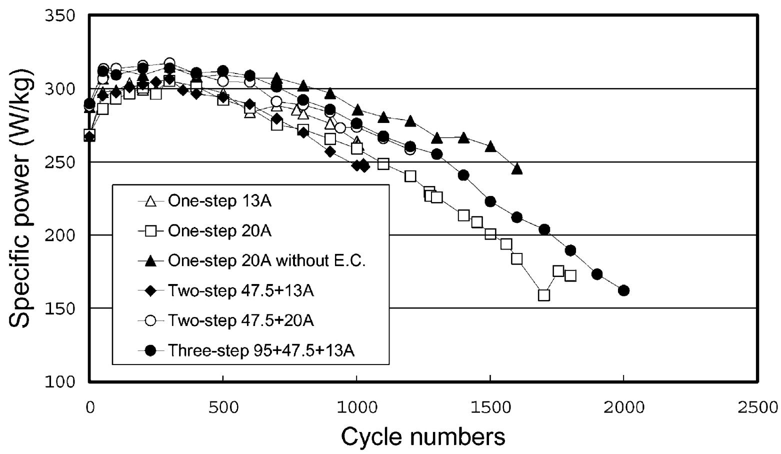

Fig. 5. Power density during cycling tests under each charging condition.

specific power gradually decrease to about 60% up to 1700 cycles.

A cycling test involving more than 1500 cycles decreased the DST120-pattern discharge capacity by 20%, due to a gradual decrease in discharge power (Fig. 5). However, the constant-current discharge capacity declined by a mere 7%. Post-study analyses of the modules showed that the decline in discharge power after extended cycling was due to an increase of the internal resistance resulting from oxidization of cathodic metal hydride and transformation of electrolyte water from the separator to the cathode.

The Ni/MH battery system was no longer able to power the EV after 1800 cycles due to the reduction of power discharge to less than 150 W/kg, the minimal value required by an EV [9]. The used Ni/MH battery system can be recycled for use in energy storage systems, which require 3–5 kW for about a 20 kWh battery system, rather than being used for high power discharge performance.

For the VRLA battery system, the optimum charging condition successfully prolongs the cycle life to no less than 500 cycles [4]. In contrast, the Ni/MH battery kept discharge capacity almost constant for more than 1500 cycles, independent of charging conditions. It has the discharge/charge energy efficiency of 80–84%, which is 3% higher than the high-efficiency operation method of the VRLA system (Table 3).

Table 3
Performance of the Ni/MH battery system for an EV

	Ni/MH battery system	VRLA battery system
Energy density	60 Wh/kg	35 Wh/kg
Power density	280–300 W/kg (@ 50% DOD)	200 W/kg
Cycle life	1000–1500 cycles[a]	500 cycles[b]
Energy efficiency	76–85 Wh%[a]	74–83 Wh%[b]
Charging time	Completed in less than 2 h	

[a] By discharging until 80% DOD with DST120 patterns.
[b] By discharging until 80% DOD with SFUDS79.

3.2. Effects of continuous shallow discharge

A module battery was repeatedly discharged and charged. It was discharged with DST120 patterns until 25% DOD was attained, and then charged using the one-step method with dT/dt regulation. Discharge capacity and power density were measured every 100 cycles for a cell with an opened voltage of 1.2 V in the module battery, which had 10 cells. Discharge capacity and power density were discussed for continuously repeated shallow discharge.

Over a period involving 300 shallow cycle discharges, the power density gradually decreased by about 40%. However, in following this period of 300 cycles, no decrease was observed (Fig. 6). After a continuous shallow discharge, the power density remained above 150 W/kg, which is the power density required for EV acceleration.

It should be noted that several deep discharge cycles following several hundred shallow discharge cycles effectively prevents the battery from recovering any useful power density or discharge capacity. It is necessary for a battery shallow discharged more than several hundred cycles to be deep discharged and recharged several times in order to be recovered.

3.3. Effects of a low-temperature environment

Discharge capacities at a current draw ranging from 19 to 95 A and DST120 and SFUDS79 [10] patterns, were measured at the temperatures of −3 and −10 °C after the battery system was fully charged with 20 A for 5 h and 15 min. The system was left for more than 4 h after full charging in a low-temperature room in order to cool the battery system.

At a temperature of −10 °C, the battery system retained more than 80% of its room temperature discharge capacity, with a constant current of less than 95 A (Fig. 7). The discharge capacity with the SFUDS79 pattern was 80%, but the DST120-pattern discharge decreased the discharge capacity to less than 50% of the room temperature value. The DST120 patterns require a high power discharge, but more

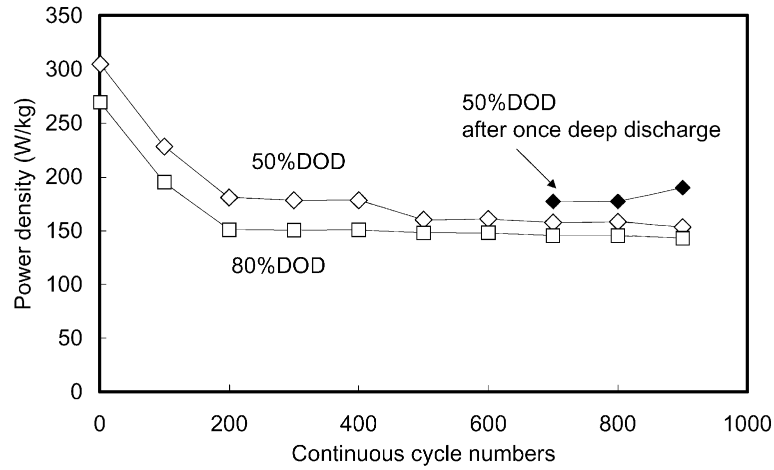

Fig. 6. Power density during a continuous cycling test with shallow discharge to 25% DOD.

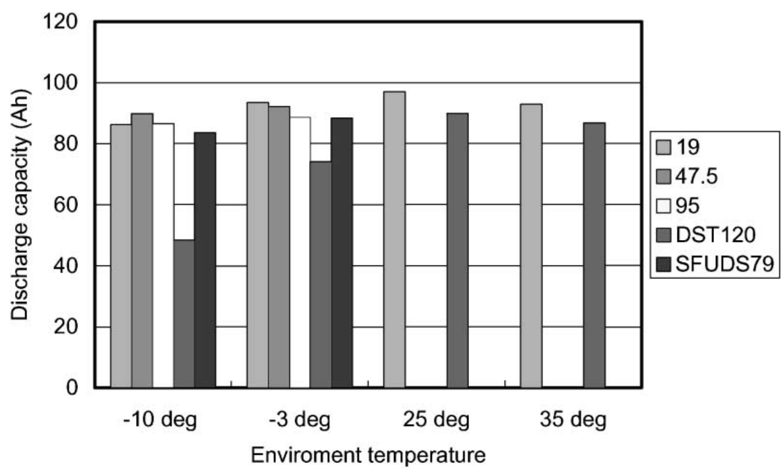

Fig. 7. Discharge capacity with a constant current of 19, 47.5 and 95 A and patterns of SFUDS79 and DST120 at each temperature.

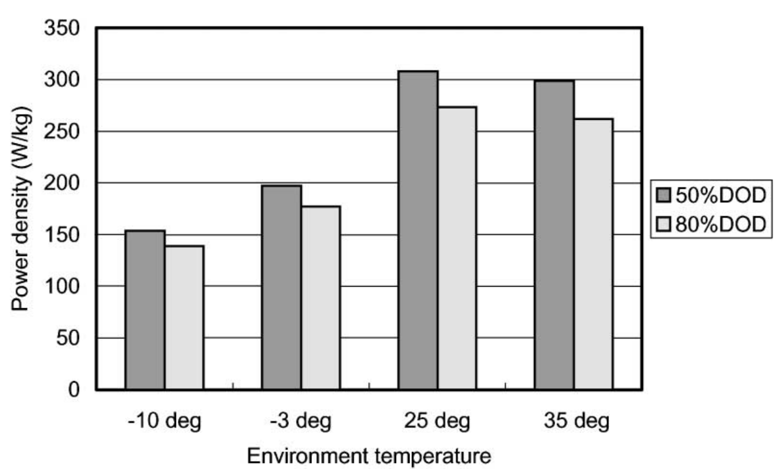

Fig. 8. Power density at 50 and 80% DOD at each temperature.

significant power density declines were observed at lower temperatures (Fig. 8). These results indicate that low operating temperatures will prevent rapid acceleration or optimal operating range for EVs incorporating such battery systems.

4. Summary

This study sought to investigate various methods for charging Ni/MH batteries for use with an electric vehicle.

In a cycling test involving more than 1500 discharge/charge cycles with a DST120-pattern discharge, the amount of DST120-pattern discharge was decreased by 20%, while that of constant-current discharge was reduced by only 7% due to a gradual decline in discharge power during cycling tests. Cycle life is independent of the magnitudes of charging current during multi-step constant-current charging. Three-step charging with 95 A + 47.5 A + 13 A resulted in complete charging in less than 2 h. This type of battery offers rapid recharge capabilities. Multi-step constant-current charging provided a high-energy efficiency of more than 80% with a discharge using a DST120 pattern by 80% DOD. Continuous shallow-depth discharge operation resulted in a drop of discharge voltage and decrease of discharge capacity, due to the memory effects. Power density declined by about 40% following 300 cycles of continuous shallow-depth discharging and recharging, but did not decline appreciably thereafter. At a temperature of $-10\ ^{\circ}C$, the discharge capacity at a constant current from 0.2 to 1.0 CA was equal to that at room temperature. However, low-temperature conditions reduced discharge power by 50%, reducing the vehicle's operating range at high speeds.

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