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Experimental Study on Storage and Maintenance Method of Ni-MH Battery Modules for Hybrid Electric Vehicles

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Abstract: This paper investigates the performance changes of nickel–metal hydride (Ni-MH) battery modules for hybrid electric vehicles (HEVs) using different storage and maintenance methods. The effects of charge–discharge mode, maintenance period, rest time, charge rate, and storage state of charge (SOC) on the storage performance of Ni-MH battery modules are studied. Based on the experimental results and engineering application requirements, this paper proposes some important recommendations and methods for storage and maintenance of Ni-MH battery modules for HEVs. The experimental results show that, compared with the six benchmark methods, the proposed storage and maintenance method provides superior storage and maintenance outcomes and significantly saves maintenance time.

Keywords: hybrid electric vehicle (HEV); Ni-MH battery module; storage and maintenance method; experimental study

1. Introduction

At present, limited by the short range of pure electric vehicles and high cost of fuel cell vehicles, hybrid electric vehicles (HEVs) will exist for a long time as a transitional technology [1]. At present, there are four main types of vehicle power batteries: lead–acid batteries, nickel–metal hydride (Ni-MH) batteries, lithium-ion batteries, and fuel cells. Lead–acid batteries have low cost and mature technology, but low energy density. Ni-MH batteries have mature technology, and high capacity density and reliability, but their temperature adaptability and overcharging performance are poor. Lithium-ion batteries are small in size, light in weight, and high in energy density, but their safety is poor. Fuel cell is the future development direction of electric vehicles incorporating the addition of renewable fuels, but its technology is yet to make a breakthrough [2,3]. Related research results show that, although battery technology advanced quickly in recent years, Ni-MH batteries continue to serve as an important energy storage source [4,5]. As the power source of HEVs, Ni-MH batteries are widely used due to their good comprehensive performance [6–8]. Toyota continues to stay the course with Ni-MH batteries for many of its HEVs, even though most HEVs from other brands moved to using lithium-ion batteries exclusively. However, starting with the 2015 model year, Toyota's latest generation Prius has two versions, one with lithium-ion batteries and the other with Ni-MH batteries, but it cannot be ignored that Ni-MH batteries are still Toyota's main choice.

Most power batteries need to go through a storage period before they are installed on HEVs. The existing literature regarding the performance of Ni-MH battery modules is normally based on experimentation. Zhu et al. [9,10] studied the energy storage characteristics, self-discharge rates, state of health (SOH), state of charge (SOC), and energy efficiencies of Ni-MH batteries at various charge input levels, and obtained the effect of charge–discharge rate on battery energy efficiency and capacity recovery rate. Ji et al. [11] investigated the storage performance of Ni-MH batteries and found out that the battery performance degradation is caused by the performance degradation of positive electrodes after long-term storage. Zhu et al. [12] looked into the regular patterns of consistency, high–low temperature characteristics, and charge–discharge efficiency of Ni-MH battery cells through experiments. Cuscueta et al. [13] studied the electrochemical behavior of the pressure inside a sealed Ni-MH cell due to gases produced under different conditions. In the work of Viera [14], the hydrogen detected outside the battery was used to determine the termination of charging in order to prevent overcharging. Zhou et al. [15] and Wang et al. [16] investigated the effects of different electrode materials on the discharge behavior of Ni-MH batteries, and provided guidance for the storage and application of Ni-MH batteries. Meng et al. [17] proposed an SOC optimal operation range control method for Ni-MH batteries, which extends the battery life. Shi [18] and Lorenzo et al. [19] found that Ni-MH batteries have high cycle life when they are operated or stored in the temperature range of 20–30 °C; while the charge–discharge efficiency of Ni-MH batteries will decrease significantly at low temperature, the battery performance will deteriorate and cycle life will decrease when the temperature is higher than 40 °C.

The above literature findings indicate that Ni-MH batteries require suitable working or storage conditions; otherwise, their performance will be attenuated. However, the majority of these works explored the mechanism and improvement methods of performance changes of Ni-MH battery cells or modules through experiments, while no specific storage and maintenance methods were proposed for the purpose of engineering applications. Therefore, it is necessary to explore the storage and maintenance methods of Ni-MH batteries through experiments. Chen et al. studied the storage performance of Ni-MH batteries with different maintenance methods at room temperature, but did not look into the effects of charge–discharge rate and rest time on the storage performance of Ni-MH battery modules. Moreover, the results lack generality since all Ni-MH battery modules used are from one single manufacturer [20].

This paper investigates the effects of different charge–discharge modes, maintenance periods, rest time, charge rates, and storage SOC on the storage performance of Ni-MH battery modules at room temperature, and proposes a method for storage and maintenance of Ni-MH battery modules. Compared with other maintenance methods based on engineering experience, this method can reduce maintenance time and save maintenance cost on the basis of taking into account the maintenance effect.

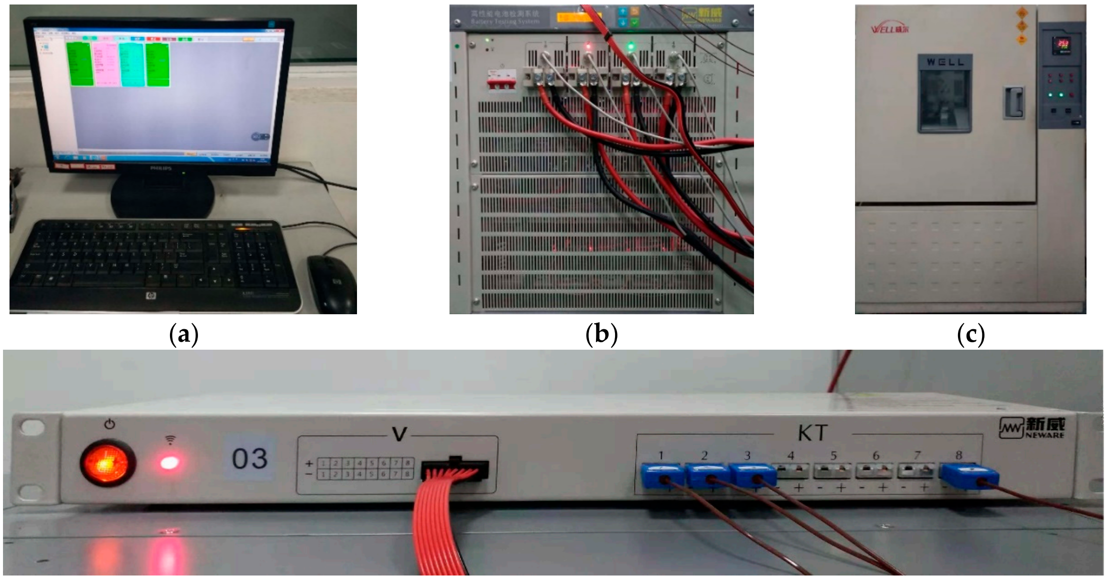
2. Experimentation

2.1. Experiment Object

The Ni-MH battery modules employed in the experiment were from two different manufactures, in order to enhance the validity of the experimental results. Every module was composed of six cylindrical Ni-MH battery cells connected in series. The specification of a cylindrical Ni-MH battery cell was 6000 mAh; thus, the parameters of modules were all 6000 mAh/7.2 V. The working temperature range of the Ni-MH battery modules was −30 °C to 60 °C, and the temperature range of storage environment was −40 °C to 75 °C. The relative humidity was no higher than 90%, and the atmospheric pressure was 86–106 kPa.

2.2. Experiment Equipment

Figure 1 demonstrates the equipment used in this experiment, including a battery control system, a battery voltage and current detection system, an incubator, and a battery temperature detection system.



(**a**) (**b**) (**c**) (**d**)

Figure 1. Nickel–metal hydride (Ni-MH) battery module storage performance test equipment: (**a**) battery control system; (**b**) voltage and current detection system; (**c**) incubator; (**d**) battery temperature detection system.

2.3. Experiment Procedure

A total of nine storage and maintenance methods (see Table 1) were implemented and compared in this experiment. The overall storage time of the Ni-MH battery module was 360 days. During the storage period, the parameters were measured according to the nine methods in Table 1. The experimental process refers to the standard IEC 61436, and the whole experiment process was carried out at room temperature (i.e., 20 ± 5 °C).

During the experiment, we set up four samples (two from manufacturer A and two from manufacturer B) for each method. A total of 36 sample modules were used for the nine methods, and the experimental results were averaged to eliminate possible manufacturing errors or individual feature differences of the battery modules.

Table 1. Storage and maintenance methods of nickel–metal hydride (Ni-MH) battery modules. SOC—state of charge.

Method Number	Maintenance Period	Storage SOC	Charge Rate	Rest Time	Charge–Discharge Mode	Experiment Process	Number of Samples
1	90 days	50% SOC	1 C	5 min	DDC [1]	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (1 C) for 30 min.	4
2	90 days	30% SOC	1 C	5 min	DDC	1. Discharge to cut-off voltage. 2. Rest for 5 min; 3. Charge (1 C) for 18 min.	4
3	90 days	30% SOC	1 C	15 min	DDC	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (1 C) for 18 min.	4
4	90 days	50% SOC	1 C	30 min	FDC + 10% [2]	1. Discharge to cut-off voltage; 2. Rest for 30 min; 3. Charge (1 C) for 1 h and then charge (0.5 C) for 12 min; 4. Rest for 30 min; 5. Discharge for 30 min.	4
5	120 days	50% SOC	1 C	5 min	FDC + 10%	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (1 C) for 1 h and then charge (0.5 C) for 12 min; 4. Rest for 5 min; 5. Discharge for 30 min.	4
6	90 days	50% SOC	1 C	5 min	FDC + 10%	1. Discharge to cut-off voltage; 2. Rest for 5 min;	4

						3. Charge (1 C) for 1 h and then Charge (0.5 C) for 12 min; 4. Rest for 5 min; 5. Discharge for 30 min.	
7	90 days	50% SOC	0.5 C	5 min	FDC [3]	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (0.5 C) for 2 h; 4. Rest for 5 min; 5. Discharge for 30 min.	4
8	90 days	50% SOC	1 C	5 min	FDC	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (1 C) for 1 h; 4. Rest for 5 min; 5. Discharge for 30 min.	4
9	90 days	50% SOC	2 C	5 min	FDC	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (2 C) for 30 min; 4. Rest for 5 min; 5. Discharge for 30 min.	4

[1] Direct discharge and charge; [2] full discharge and charge plus 10% overcharge; [3] full discharge and charge. Note: All discharge rates used in experiments 1–9 were 1 C.

2.4. Test Items

The Ni-MH battery modules were stored and maintained based on the established experimental methods. Before and after maintenance, the battery module performance was tested with the same test items. These test items included capacity, charge–discharge power, charge–discharge efficiency, open-circuit voltage (OCV), and resistance.

2.4.1. The Capacity Test

The detailed capacity test flow is shown in Figure 2. Note that, if the discharge capacity of the Ni-MH battery modules is lower than 95% of the rated value, this process should be repeated (for a maximum of 3 times) until the capacity becomes greater than or equal to 95% of the rated value.

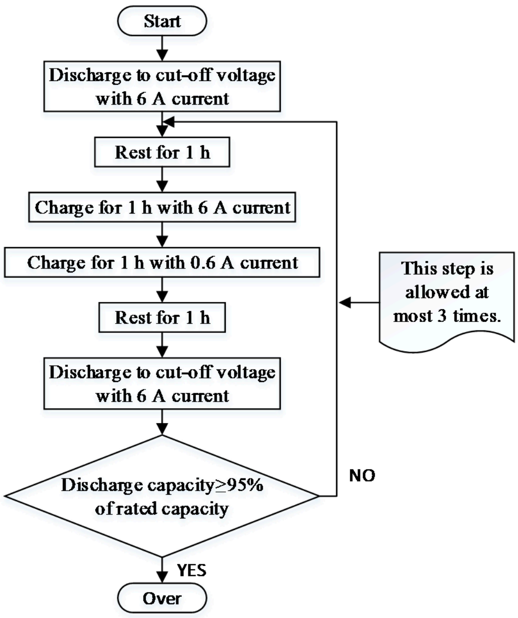


Figure 2. Capacity test flow of Ni-MH battery modules.

2.4.2. The Charge–Discharge Power Test

We used the HPPC (hybrid pulse power characteristic) test to calculate the charge and discharge powers of Ni-MH battery modules with different SOC values—80%, 50%, and 20%. The detailed charge–discharge power test flow is shown in Figure 3.

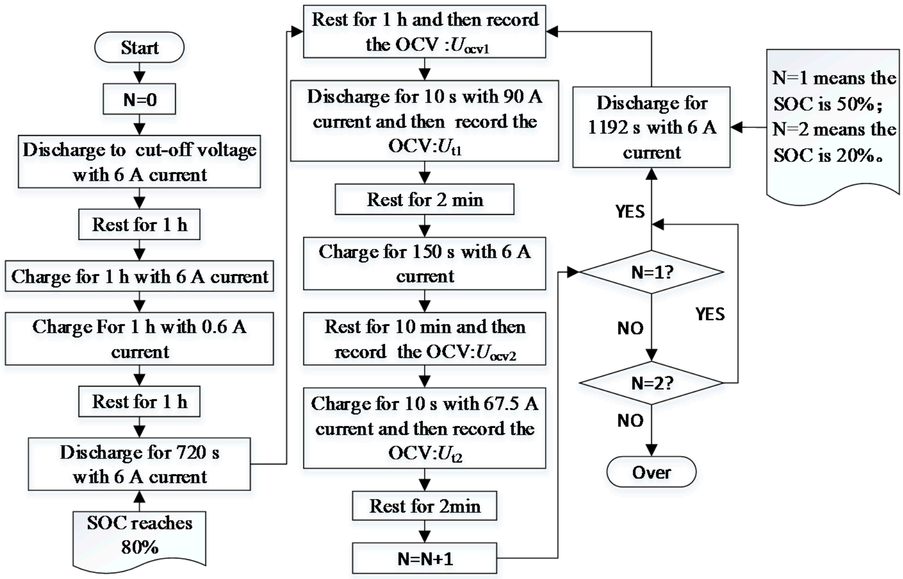


Figure 3. Charge–discharge power test flow of Ni-MH battery modules.

The charge–discharge resistance can be calculated using the following equations:

$$R_d = (U_{ocv1} - U_{t1})/I_{maxd}, \tag{1}$$

$$R_c = (U_{t2} - U_{ocv2})/I_{maxc}, \tag{2}$$

where I_{maxc} = 0.75 I_{maxd}, I_{maxd} = 90 A is the discharge current, I_{maxc} = 67.5 A is the charge current, R_d is discharge resistance, R_c is charge resistance, U_{ocv1} is the initial OCV before discharging at each SOC value, U_{ocv2} is the initial OCV before charging at each SOC value, U_{t1} is the OCV after discharging for 10 s with 90-A current at each SOC, and U_{t2} is the OCV after charging for 10 s with 67.5-A current at each SOC.

The peak discharge power can be calculated using the following equations:

$$P_{1d} = U_{d-cutoff} \times (U_{ocv1} - U_{d-cutoff})/R_d, \tag{3}$$

$$P_{2d} = I_{maxd} \times (U_{ocv1} - R_d \times I_{maxd}), \tag{4}$$

$$P_d = min\{P_{1d}, P_{2d}\}, \tag{5}$$

where P_{1d} is the peak discharge power limited by the discharge cut-off voltage, P_{2d} is the measured peak discharge power, $U_{d\text{-}cutoff}$ is the discharge cut-off voltage, and P_d is the final value of the discharge power.

The peak charge power is computed using the following equations:

$$P_{1c} = U_{c-cutoff} \times (U_{c-cutoff} - U_{ocv2})/R_c, \tag{6}$$

$$P_{2c} = I_{maxc} \times (U_{ocv2} + R_c \times I_{maxc}), \tag{7}$$

$$P_c = min\{P_{1c}, P_{2c}\}, \tag{8}$$

where P_{1c} is the peak charge power limited by the charge cut-off voltage, P_{2c} is the measured peak charge power, $U_{c\text{-}cutoff}$ is the charge cut-off voltage, and P_c is the final value of the charge power.

2.4.3. The Charge–Discharge Efficiency Test

The detailed charge–discharge efficiency test flow is shown in Figure 4. The charge–discharge efficiency can be calculated using the following equations:

$$\eta_c = W_{I1}/W_{20\text{A}} \times 100\%, \tag{9}$$

$$\eta_d = W_{-50\text{A}}/W_{I1} \times 100\%, \tag{10}$$

where η_c is the charge efficiency, η_d is the discharge efficiency, W_{I1} denotes the discharge energy during the 36-min discharging process with 6-A current, W_{20A} represents the charging energy during the 648-s charging process with 20-A current, and W_{-50A} is the discharging energy during the 259-s discharging process with 50-A current.

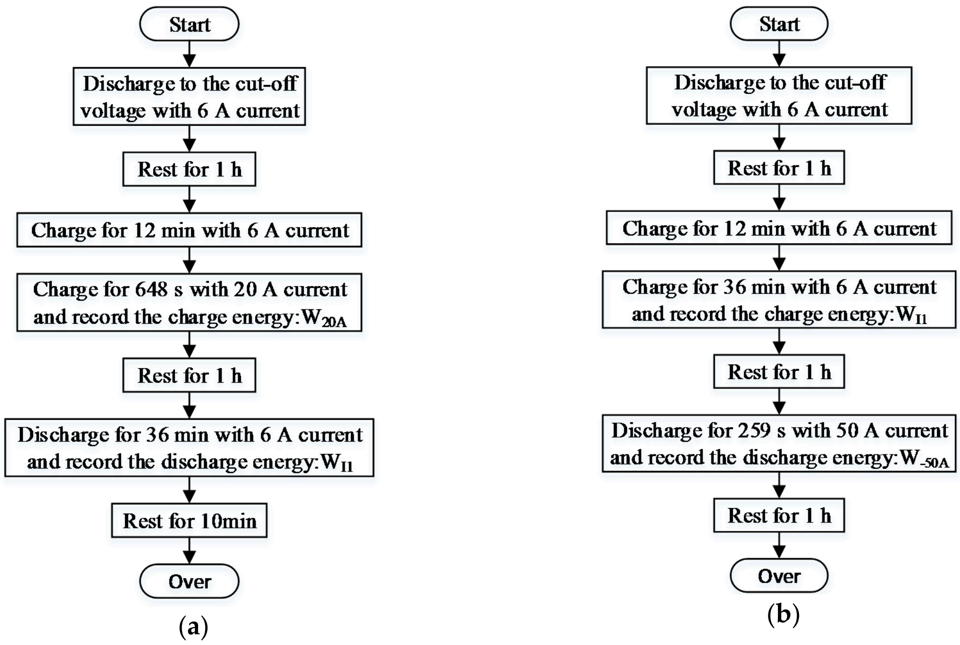


Figure 4. Charge–discharge efficiency test flow of Ni-MH battery modules: (**a**) charge efficiency test; (**b**) discharge efficiency test.

3. Effects of Storage and Maintenance Modes on Battery Performance

In the experimental studies, the effects of different storage and maintenance modes on the battery capacity could be evaluated by the change of charge retention rate and capacity recovery rate, and the effects of different storage and maintenance modes on the power performance were evaluated by the change rate of charge-discharge power. The efficiency of battery module was evaluated by the change rate of charge–discharge efficiency.

The charge retention rate and capacity recovery rate can be calculated according to the following equations:

$$\varphi_1 = C_1/C_0 \times 100\%, \quad (11)$$

$$\varphi_2 = C_2/C_0 \times 100\%, \quad (12)$$

where φ_1 is the charge retention rate, φ_2 is the capacity recovery rate, C_0 is the capacity before storage, C_1 denotes the residual capacity after storage, and C_2 represents the capacity that the battery module can regain after storage.

The change rate of charge–discharge power can be computed using the following equations:

$$\varphi_{c1} = (P_{c2} - P_{c1})/P_{c1} \times 100\%, \quad (13)$$

$$\varphi_{d1} = (P_{d2} - P_{d1})/P_{d1} \times 100\%, \quad (14)$$

where φ_{c1} is the change rate of charge power, φ_{d1} is the change rate of discharge power, P_{c1} and P_{c2} are the charge powers of the performance initial test and performance retest, and P_{d1} and P_{d2} are the discharge powers of the performance initial test and performance retest.

The change rate of charge–discharge efficiency can be computed using the following equations:

$$\varphi_{c2} = (\eta_{c2} - \eta_{c1})/\eta_{c1} \times 100\%, \quad (15)$$

$$\varphi_{d2} = (\eta_{d2} - \eta_{d1})/\eta_{d1} \times 100\%, \quad (16)$$

where φ_{c2} is the change rate of charge efficiency, φ_{d2} is the change rate of discharge efficiency, η_{c1} and η_{c2} denote the charge efficiencies of the performance initial test and performance retest, and η_{d1} and η_{d2} represent the charge efficiencies of the performance initial test and performance retest.

Note that in the following experimental results, the "−" sign represents "reduction", as opposed to "negative value".

3.1. Effects of Charge–Discharge Modes on Battery Performance

The effects of different charge–discharge maintenance modes on the storage performance of Ni-MH battery modules were investigated by means of comparing the test results of methods 1, 6, and 8.

3.1.1. Effects of Charge–Discharge Modes on Battery Capacity

Figure 5 demonstrates the charge retention rates and the capacity recovery rates of Ni-MH battery modules, maintained by different charge–discharge methods. It can be seen in Figure 5a that the charge retention rates maintained by the direct discharge and charge (*DDC*) mode were significantly reduced. However, when maintained by the full discharge and charge (*FDC*) + *10%* mode, batteries from both manufacturers A and B presented the highest capacity retention rates. Moreover, Figure 5b shows that different charge–discharge maintenance modes had negligible effects on the capacity recovery rates.

In short, the *FDC + 10%* maintenance mode proved to be the best approach to maintain the charge retention of Ni-MH battery modules, and the three charge–discharge maintenance modes did not make a difference in the capacity recovery rate.

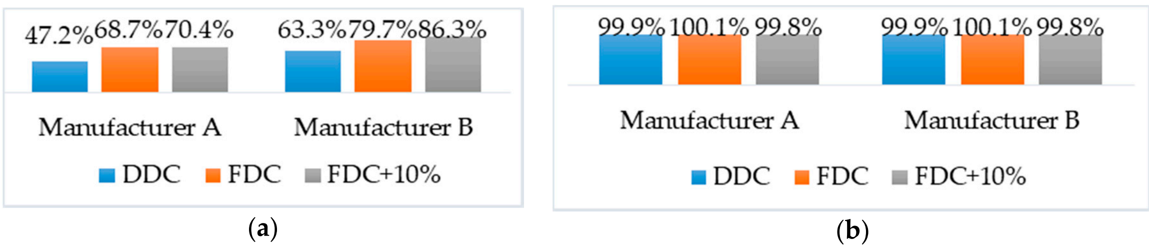


Figure 5. Effects of different charge–discharge modes on capacity of Ni-MH battery modules: (**a**) charge retention rate; (**b**) capacity recovery rate.

3.1.2. Effects of Charge–Discharge Modes on Battery Power

With a present SOC of 80%, 50%, and 20%, the effects of different charge–discharge maintenance modes on battery charge–discharge power were evaluated. The results are shown in Figures 6–8. It can be seen that the *FDC* maintenance mode presented itself as the best approach to maintain the power of Ni-MH battery modules.

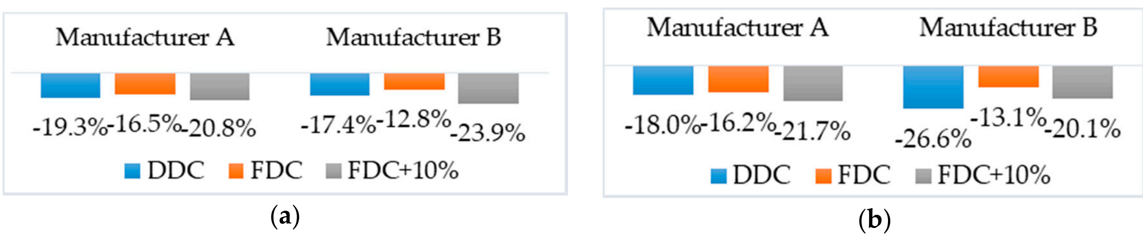


Figure 6. Effects of different charge–discharge modes on power change rate of Ni-MH battery modules with 80% state of charge (SOC): (**a**) change rate of charge power; (**b**) change rate of discharge power.

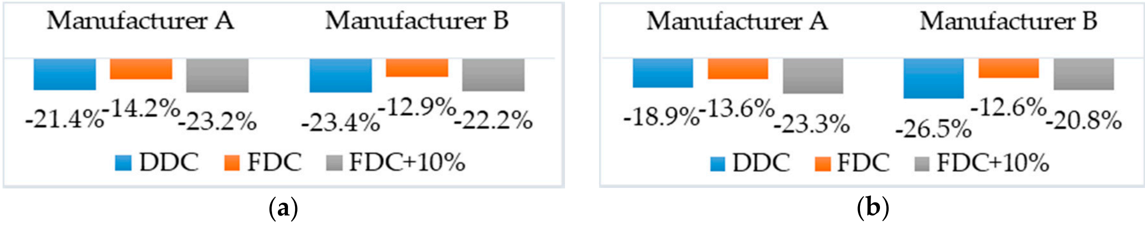


Figure 7. Effects of different charge–discharge modes on power change rate of Ni-MH battery modules with 50% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.

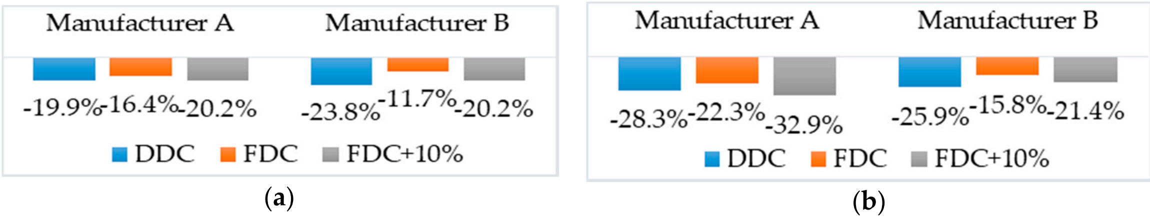


Figure 8. Effects of different charge–discharge modes on power change rate of Ni-MH battery modules with 20% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.

3.1.3. Effects of Charge–Discharge Modes on Battery Efficiency

Figure 9 shows the effects of different charge–discharge modes on the efficiency of Ni-MH battery modules. It can be seen that the *FDC* maintenance mode was the best approach to maintain the efficiency of Ni-MH battery modules, as it produced the lowest (absolute value) efficiency change rate.

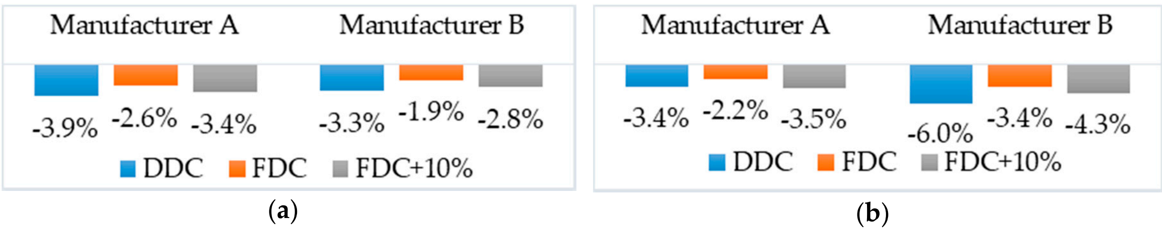


Figure 9. Effects of different charge–discharge maintenance modes on efficiency of Ni-MH battery modules: (**a**) change rate of charge efficiency; (**b**) change rate of discharge efficiency.

3.2. Effects of Maintenance Periods on Battery Performance

The effects of different maintenance periods on the storage performance of Ni-MH battery modules were investigated by comparing the test results of methods 5 and 6.

3.2.1. Effects of Maintenance Periods on Battery Capacity

Figure 10 demonstrates how the charge retention rate and capacity recovery rate vary with different maintenance periods. As shown in this figure, the 90-day maintenance period was more conducive to maintaining the capacity of Ni-MH battery modules.

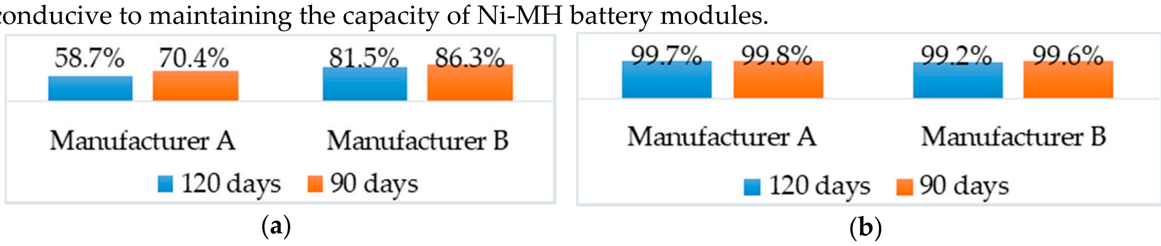
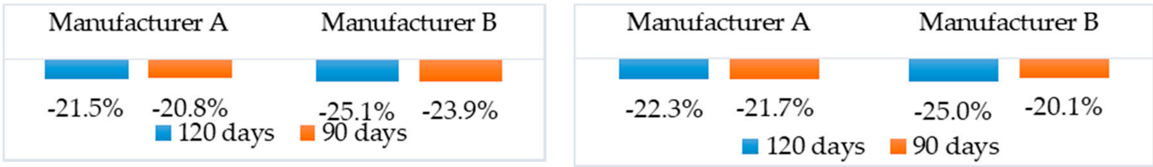


Figure 10. Effects of different maintenance periods on charge retention rate and capacity recovery rate of Ni-MH battery modules: (**a**) charge retention rate; (**b**) capacity recovery rate.

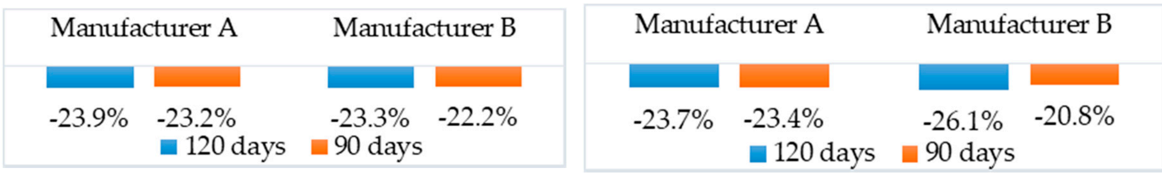
3.2.2. Effects of Maintenance Periods on Battery Power

In this study, the effects of different maintenance periods on the change rate of battery charge–discharge power were tested with different SOC values—80%, 50%, and 20%. The test results are shown in Figures 11–13. We can see that, with the 120-day maintenance period, the charge power reduction rate dropped 3.8% more and the discharge power reduction rate reduced 5.8% more, compared to those values resulting from the 90-day maintenance period. Thus, it can be considered that these two maintenance periods had equivalent effects on the charge–discharge power of Ni-MH battery modules.



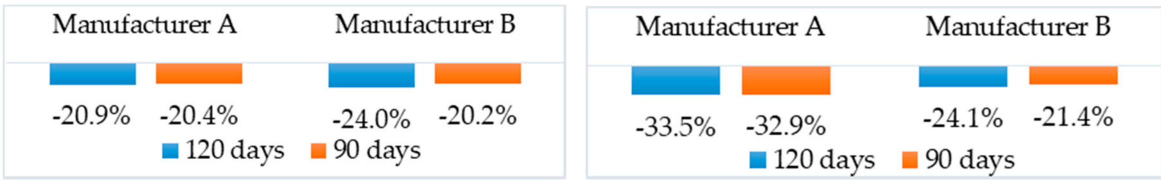
(**a**) (**b**)

Figure 11. Effects of different maintenance periods on power change rate of Ni-MH battery modules with 80% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.



(**a**) (**b**)

Figure 12. Effects of different maintenance periods on power change rate of Ni-MH battery modules with 50% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.

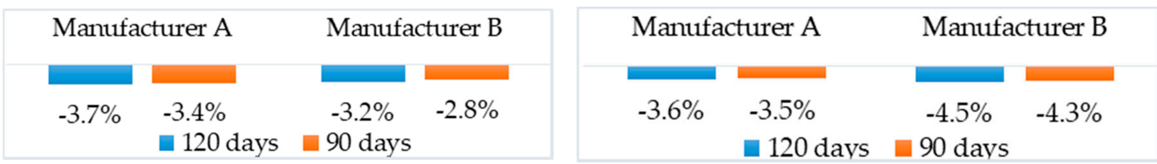


(**a**) (**b**)

Figure 13. Effects of different maintenance periods on power change rate of Ni-MH battery modules with 20% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.

3.2.3. Effects of Maintenance Periods on Battery Efficiency

Figure 14 shows how different maintenance periods affect the efficiency of Ni-MH battery modules. We can see that the 90-day maintenance period performed slightly better than the 120-day maintenance period, in terms of maintaining the battery charge–discharge efficiency of the Ni-MH battery modules. Because the performance difference was insignificant, in general, these two maintenance periods had similar effects on the battery charge–discharge efficiency.



(**a**) (**b**)

Figure 14. Effects of different maintenance periods on efficiency change rate of Ni-MH battery modules: (**a**) change rate of charge efficiency; (**b**) change rate of discharge efficiency.

3.3. Effects of Rest Time on Battery Performance

As seen from Table 1, both methods 2 and 3 adopted the *DDC* mode, with the rest times during maintenance being 5 min and 15 min, respectively. Moreover, we see that both methods 4 and 6 used the *FDC* + 10% maintenance mode, and the rest times were chosen as 5 min and 30 min, respectively. The effects of 5-min and 15-min rest times on the storage performance of Ni-MH battery modules were investigated by means of comparing the test results of methods 2 and 3. Additionally, the effects of 5-min and 30-min rest times on the performance of the battery were also evaluated by comparing the test results of methods 4 and 6.

3.3.1. Effects of Rest Time on Battery Capacity

Tables 2 and 3 demonstrate the effects of 5-min, 15-min, and 30-min rest times on Ni-MH battery capacity. It is seen in the two tables that these three types of rest time made only subtle differences in the maintenance of battery capacity.

Table 2. Effects of different rest times on capacity of Ni-MH battery modules (*DDC* mode).

Manufacturer	Method Number	Rest Time (min)	Charge Retention Rate	Discharge Capacity (Ah)	Initial Capacity (Ah)	Capacity Recovery Rate
A	2	5	63.6%	5.76	5.78	99.6%
	3	15	65.1%	5.74	5.78	99.3%
B	2	5	61.1%	5.7	5.7	99.5%
	3	15	61.1%	5.7	5.8	98.1%

Table 3. Effects of different rest times on capacity of Ni-MH battery modules (*FDC* + 10% mode).

Manufacturer	Method Number	Rest Time (min)	Charge Retention Rate	Discharge Capacity (Ah)	Initial Capacity (Ah)	Capacity Recovery Rate
A	6	30	76.2%	5.81	5.82	99.3%
	4	5	70.4%	5.77	5.78	99.8%
B	6	30	84.3%	5.96	5.98	99.2%
	4	5	86.3%	5.94	5.97	99.6%

3.3.2. Effects of Rest Time on Battery Power

With a present SOC of 80%, 50%, and 20%, the effects of different rest times on battery charge–discharge power were evaluated. The test results of methods 2, 3, 4, and 6 show that the 5-min rest time presented itself as the best approach to maintain the power of Ni-MH battery modules. The test results are listed in Tables 4 and 5.

Table 4. Effects of different rest times on power change rate of Ni-MH battery modules with different SOC (*DDC* mode).

SOC Value	Manufacturer	Method Number	Rest Time (min)	Change Rate of Charge Power	Change Rate of Discharge Power
80% SOC	A	2	5	−10.3%	−11.9%
		3	15	−13.7%	−13.6%
	B	2	5	−11.9%	−22.6%
		3	15	−13.2%	−26.6%
50% SOC	A	2	5	−10.5%	−9.4%
		3	15	−16.8%	−14.4%
	B	2	5	−21.4%	−22.8%
		3	15	−26.4%	−27.3%
20% SOC	A	2	5	−11.2%	−20.8%
		3	15	−16.8%	−25.8%
	B	2	5	−22.7%	−11.9%
		3	15	−28.5%	−12.2%

Table 5. Effects of different rest times on power change rate of Ni-MH battery modules with different SOC (*FDC* + 10% mode).

SOC Value	Manufacturer	Method Number	Rest Time (min)	Change Rate of Charge Power	Change Rate of Discharge Power
80% SOC	A	6	30	−21.7%	−22.2%
		4	5	−20.8%	−21.7%
	B	6	30	−23.2%	−20.1%
		4	5	−22.9%	−20.1%
50% SOC	A	6	30	−23.3%	−23.6%
		4	5	−23.2%	−23.4%
	B	6	30	−21.8%	−21.1%
		4	5	−21.6%	−20.8%
20% SOC	A	6	30	−22.1%	−33.5%
		4	5	−20.4%	−32.9%
	B	6	30	−21.0%	−21.4%
		4	5	−20.2%	−21.4%

3.3.3. Effects of Rest Time on Battery Efficiency

The effects of different rest times on battery charge–discharge efficiency were evaluated. Both sets of test results show that the 5-min rest time was the best approach to maintain the efficiency of Ni-MH battery modules, as it produced the lowest (absolute value) efficiency change rate. The test results are listed in Tables 6 and 7.

Table 6. Effects of different rest times on efficiency change rate of Ni-MH battery modules (*DDC* mode).

Manufacturer	Method Number	Rest Time (min)	Change Rate of Charge Efficiency	Change Rate of Discharge Efficiency
A	2	5	−2.9%	−1.5%
	11	15	−3.5%	−2.7%
B	2	5	−4.1%	−7.1%
	11	15	−4.1%	−14.5%

Table 7. Effects of different rest times on efficiency change rate of Ni-MH battery modules (*FDC* + 10% mode).

Manufacturer	Method Number	Rest Time (min)	Change Rate of Charge Efficiency	Change Rate of Discharge Efficiency
A	3	30	−3.5%	−3.6%
	12	5	−3.4%	−3.5%
B	3	30	−3.0%	−5.6%
	12	5	−2.8%	−4.3%

3.4. Effects of Charge Rates on Battery Performance

The effects of different charge rates on the storage performance of Ni-MH battery modules were investigated by comparing the test results of methods 7, 8 and 9.

3.4.1. Effects of Charge Rates on Battery Capacity

Figure 15 demonstrates how the charge retention rate and capacity recovery rate vary with different charge rates. As shown in this figure, the 2-C charge rate resulted in the highest charge retention rate. On the other hand, these three charge rates did not make much difference in the battery capacity recovery rates.

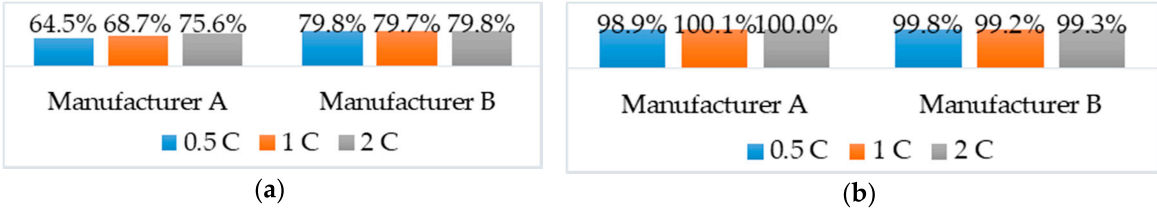


Figure 15. Effects of different charge rates on capacity of Ni-MH battery modules: (**a**) charge retention rate; (**b**) capacity recovery rate.

3.4.2. Effects of Charge Rates on Battery Power

In this study, the effects of different charge rates on the change rate of battery charge–discharge power were tested with different SOC values—80%, 50%, and 20%. The test results are shown in Figures 16–18.

The test results produced by the battery modules from manufacturer A show that the 0.5-C charge rate presented itself as the best approach to maintain the power of Ni-MH battery modules with 80% SOC, followed closely by the 1-C rate. The other test results show that the 1-C charge rate produced the lowest (absolute value) power change rate. In general, we may consider that the 1-C charge rate is more conducive to maintaining the power of Ni-MH battery modules.

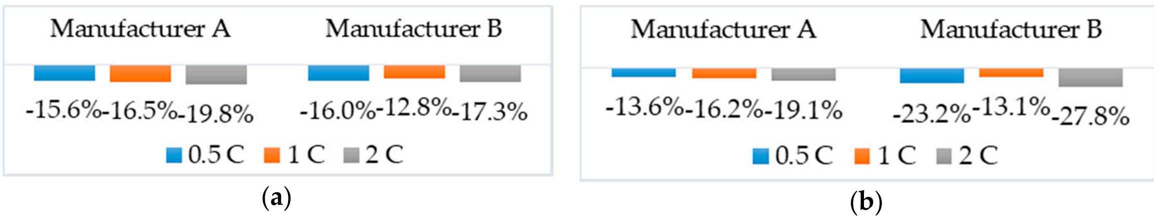


Figure 16. Effects of different charge rates on power change rate of Ni-MH battery modules with 80% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.

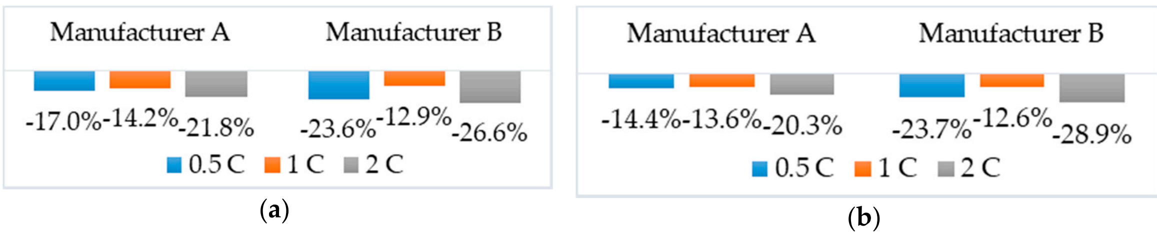


Figure 17. Effects of different charge rates on power change rate of Ni-MH battery modules with 50% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.

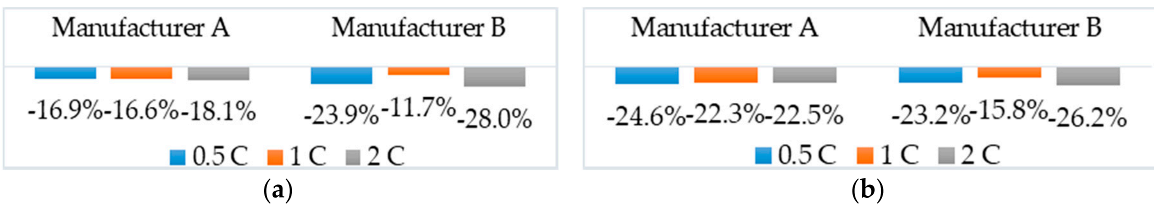


Figure 18. Effects of different charge rates on power change rate of Ni-MH battery modules with 20% SOC: (**a**) change rate of charge power; (**b**) change rate of discharge power.

3.4.3. Effects of Charge Rates on Battery Efficiency

Figure 19 shows the effect of different charge rates on the efficiency of Ni-MH battery modules. It is clearly shown that the 1-C charge rate was the best approach to maintain the efficiency of Ni-MH battery modules.

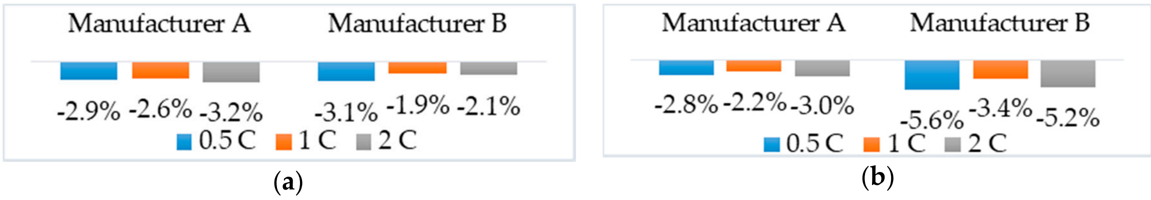


Figure 19. Effects of different charge rates on efficiency change rate of Ni-MH battery modules: (**a**) change rate of charge efficiency; (**b**) change rate of discharge efficiency.

3.5. Effects of Storage SOC on Battery Performance

The effects of different storage SOC on the storage performance of Ni-MH battery modules were investigated by means of comparing the test results of methods 1 and 2.

3.5.1. Effects of Storage SOC on Battery Capacity

Table 8 demonstrates the charge retention rates and the capacity recovery rates of Ni-MH battery modules, maintained with different storage SOC. We can see that, with the 50% storage SOC, the charge retention rate was 16.4% less with batteries from manufacturer A and 2.2% higher with batteries from manufacturer B, compared to the 30% storage SOC scenario. The average values show that 30% SOC was more conducive to maintaining the charge retention of Ni-MH battery modules. Moreover, these two storage modes had similar effects on the battery capacity recovery rates.

3.5.2. Effects of Storage SOC on Battery Power

The "storage SOC" refers to the SOC value with which the Ni-MH battery modules are stored. For example, 30% storage SOC means that the SOC value is 30% when the battery modules were initially stored. On the other hand, the "present SOC" refers to the SOC values reached during the discharge process of the performance test before or after storage, including 80%, 50%, and 20%.

Table 8. Effects of different storage SOC on capacity of Ni-MH battery modules.

Manufacturer	Method Number	Storage SOC	Charge Retention Rate	Discharge Capacity (Ah)	Initial Capacity (Ah)	Capacity Recovery Rate
A	1	50% SOC	47.2%	5.77	5.78	99.9%
	2	30% SOC	63.6%	5.76	5.78	99.6%
B	1	50% SOC	63.3%	5.89	5.95	99.0%
	2	30% SOC	61.1%	5.71	5.73	99.5%

With a present SOC of 80%, 50%, and 20%, the effects of different storage SOC on battery charge–discharge power were evaluated. The test results are shown in Table 9. The 30% storage SOC clearly presented itself as the best approach to maintain the power of Ni-MH battery modules.

Table 9. Effects of different storage SOC on power change rate of Ni-MH battery modules with different SOC.

SOC Value	Manufacturer	Method Number	Storage SOC	Change Rate of Charge Power	Change Rate of Discharge Power
80% SOC	A	1	50% SOC	−19.4%	−18.1%
		2	30% SOC	−12.6%	−12.2%
	B	1	50% SOC	−17.4%	−26.8%
		2	30% SOC	−11.1%	−23.0%
50% SOC	A	1	50% SOC	−21.4%	−18.9%
		2	30% SOC	−11.3%	−10.3%
	B	1	50% SOC	−23.4%	−26.7%
		2	30% SOC	−21.6%	−23.1%
20% SOC	A	1	50% SOC	−19.8%	−28.3%
		2	30% SOC	−11.2%	−21.1%
	B	1	50% SOC	−23.8%	−26.1%
		2	30% SOC	−23.0%	−12.0%

3.5.3. Effects of Storage SOC on Battery Efficiency

Table 10 shows how different storage SOC affects the charge–discharge efficiency of Ni-MH battery modules. We can see that, for the batteries from manufacturer A with 50% storage SOC, the charge–discharge efficiency reduction rate reduced more than the 30% storage SOC scenario. However, the results were opposite for the batteries from manufacturer B. Note that the maximum difference between the test results caused by the storage SOC was only 1.9%. Thus, it can be concluded that the 30% SOC and 50% SOC had equivalent effects on the efficiency of Ni-MH battery modules.

Table 10. Effects of different storage SOC on efficiency change rate of Ni-MH battery modules.

Manufacturer	Method Number	Storage SOC	Change Rate of Charge Efficiency	Change Rate of Discharge Efficiency
A	1	50% SOC	−3.9%	−3.4%
	2	30% SOC	−2.9%	−1.5%
B	1	50% SOC	−3.3%	−6.0%
	2	30% SOC	−4.1%	−7.1%

3.6. Effects of the Nine Storage and Maintenance Methods on the Performance of Ni-MH Battery Modules

The test results of Ni-MH battery modules from manufacturers A and B were averaged to obtain the self-discharge rates, capacity recovery rates, and charge–discharge power and efficiency change rates resulting from the nine different storage and maintenance methods, as shown in Figures 20–23, respectively.

We can see from Figure 20 that the average monthly self-discharge rate of the Ni-MH battery modules with the *DDC* mode (methods 1, 2, and 3) was larger than the rest, since these modules were not fully charged and discharged, which deactivated the active substances after long-term storage [20]. Figure 21 shows that the minimum capacity recovery rate at room temperature was 98.7% with a capacity loss less than 1.3%. As seen from Figure 22, the charge–discharge power dropped obviously during the storage and maintenance, which indicates that the storage mainly affected the power characteristics of the Ni-MH battery modules. Moreover, Figure 23 demonstrates that the average efficiency reduction rates with *DDC* mode were 3.6% for charging and 5.9% for discharging, which were slightly higher than those of *FDC* mode (3.3% for charging and 4.2% for discharging) and those of *FDC* + 10% mode (2.7% for charging and 3.7% for discharging).

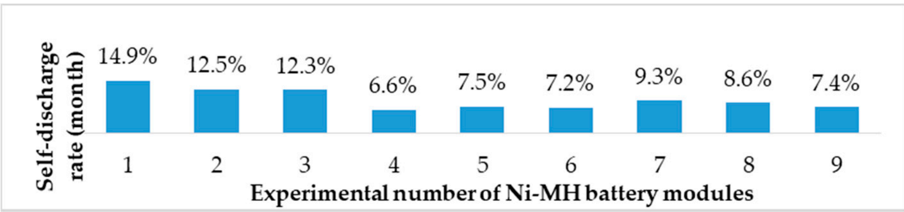


Figure 20. Effects of different storage and maintenance methods on battery self-discharge rate.

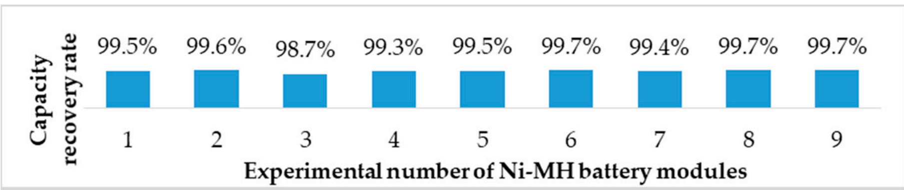


Figure 21. Effects of different storage and maintenance methods on battery capacity recovery rate.

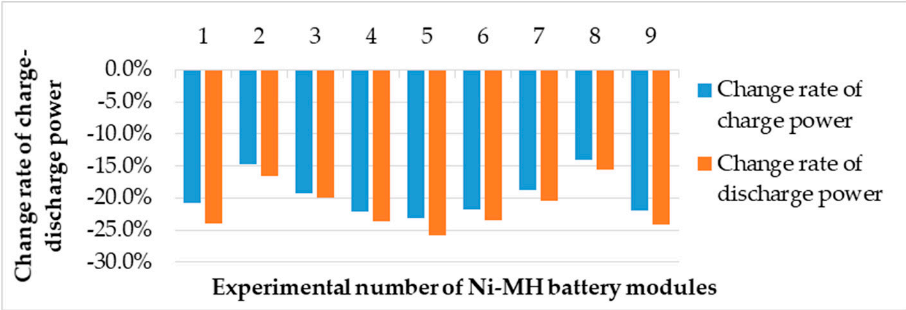


Figure 22. Effects of different storage and maintenance methods on battery change rate of power.

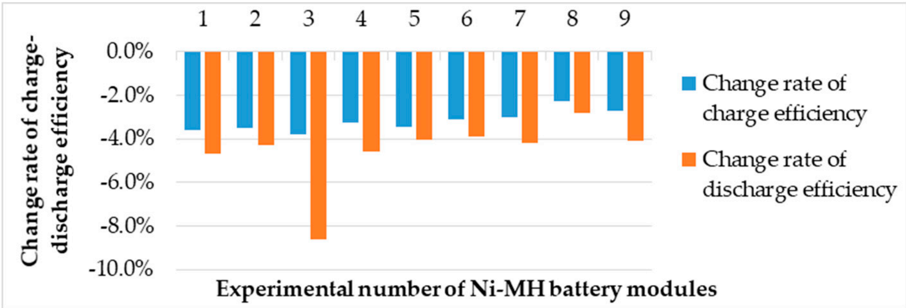


Figure 23. Effects of different storage and maintenance methods on battery change rate of efficiency.

3.7. Summary

1. Storage mainly affects the charge–discharge power performance of Ni-MH battery modules; thus, factors that affect the power performance should be prioritized. Among all the considered storage conditions in this study, the charge–discharge modes have a significant impact on power performance.
2. The test results show that the storage and maintenance methods considered in this paper, such as charge–discharge mode, maintenance period, rest time, charge rate, and storage SOC, have little effects on the capacity recovery rate of Ni-MH battery modules.
3. The *DDC* mode effectively saves the single maintenance time, but it can deactivate the active materials of the Ni-MH battery modules. Thus, it should not be solely employed to maintain the Ni-MH battery modules. The *FDC* mode presents the best comprehensive maintenance performance, and it is recommended as the preferable method.
4. The 90-day and 120-day maintenance periods provide similar comprehensive maintenance performances. However, the 120-day maintenance period is beneficial for reducing maintenance time and saving maintenance cost, and this makes it the preferable maintenance period. Note that, if the storage time is shorter than one complete maintenance period, the Ni-MH battery modules need to be maintained once before using.
5. During maintenance, the 5-min rest time is more beneficial for maintaining the charge–discharge power and efficiency of Ni-MH battery modules. A slight increase in rest time is conducive to battery charge retention, but this effect is not obvious.
6. During maintenance, the 2-C charge rate is the best for the charge retention of Ni-MH battery modules. On the other hand, the 1-C charge rate is most favorable for maintaining the charge–discharge power and efficiency of the Ni-MH battery modules.
7. The 30% storage SOC is suitable for maintaining the capacity and power, and its performance in terms of charge–discharge efficiency maintenance is equivalent to that of 50% storage SOC.

4. Discussion on Storage and Maintenance Methods for Ni-MH Battery Modules

4.1. New Storage and Maintenance Method

From the perspective of industrial applications, both the maintenance cost and effect need to be considered comprehensively. Higher efficiency of a single maintenance can lead to less total maintenance time and lower maintenance cost. Therefore, a long maintenance period, short rest time, short charge–discharge time, and low storage SOC should be employed for an appropriate maintenance plan. Based on the test results and the above discussion, a new storage and maintenance method for Ni-MH battery modules is proposed.

1. The maintenance period is selected as 120 days (set to T). When the storage time does not exceed 1T, maintenance is required once before the battery modules are put into use. If it exceeds 1T but not more than 2T, it needs to be maintained twice before being put into use, and so on.
2. During the storage period of the Ni-MH battery modules, the *FDC* mode and *DDC* mode are utilized alternatively. In other words, the *DDC* mode is used for the odd numbers of maintenances, while the *FDC* mode is employed for the even numbers of maintenances. Taking three times of maintenance during storage as an example, the first time uses *FDC*, the second uses *DDC*, and the third uses *FDC* again.
3. The rest time is set to 5 min, the charge and discharge rates are both 1 C, and the storage SOC is 30%.

The specific method is shown in the Table 11.

Table 11. New storage and maintenance method.

Maintenance Period	Storage SOC	Charge–Discharge Rate	Rest Time	Charge–Discharge Mode	Experiment Process
120 days	30% SOC	1 C	5 min	FDC	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (1 C) for 1 h; 4. Rest for 5 min; 5. Discharge for 42 min.
				DDC	1. Discharge to cut-off voltage; 2. Rest for 5 min; 3. Charge (1 C) for 18 min.

4.2. Advantages of the Proposed Storage and Maintenance Method

Assuming that a batch of Ni-MH battery modules needs to be stored for 90 to 360 days from production to application, for a single Ni-MH battery module, the total maintenance time of the proposed storage and maintenance method was compared with the six benchmark methods 4–9. The methods 1, 2, and 3 only used the *DDC* mode, which makes the Ni-MH battery module inactive. Thus, these three methods were not considered suitable any more. Method 10 represents the proposed storage maintenance method. In method 10, the *FDC* mode and *DDC* mode are utilized alternatively; thus, there are two single maintenance times, 41 min and 130 min. The single maintenance time of the *DDC* mode is 41 min and that of the *FDC* mode is 130 min. The comparison results between the seven methods are given in Table 12 and Figure 24.

Method 4 and method 10 are taken here as examples to illustrate the results. Method 4 is maintained for 192 min once, and when the number of storage days is less than 180 days, it only needs to be maintained once because the second maintenance period is not reached; thus, the total maintenance time is 192 min. When it reaches 180 days but less than 270 days, it needs to be maintained twice, and the total maintenance time is 384 min. For method 10, when the storage time is less than 240 days, it needs to be maintained once by *FDC* mode, which takes 130 min. When it reaches 240 days but less than 360 days, the second maintenance is performed by *DDC* mode, and the single maintenance time is only 41 min and the total maintenance time reached 171 min.

Table 12. Maintenance time of seven storage and maintenance methods for different storage times.

Methods Number	Maintenance Period (days)	Single Maintenance Time (min)	Total Maintenance Time (min)					
			90 Days	120 Days	180 Days	240 Days	270 Days	360 Days
1	--	--	--	--	--	--	--	--
2	--	--	--	--	--	--	--	--
3	--	--	--	--	--	--	--	--
4	90	192	192	192	384	384	576	768
5	120	142	142	142	142	284	284	426
6	90	142	142	142	284	284	426	568
7	90	190	190	190	380	380	570	760
8	90	130	130	130	260	260	390	520
9	90	100	100	100	200	200	300	400
10	120	41/130	130	130	130	171	171	301

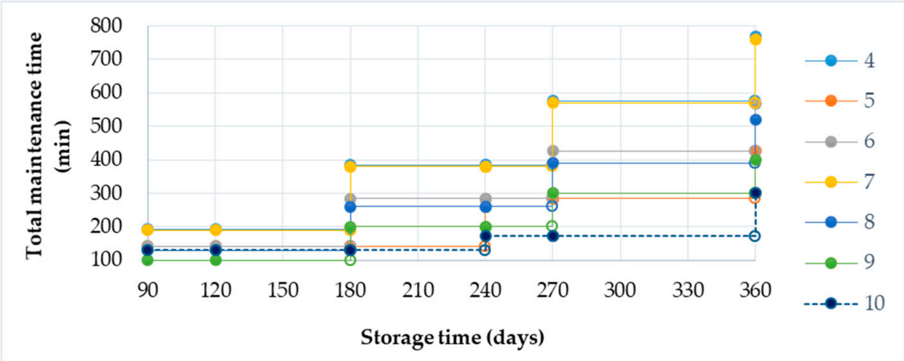


Figure 24. Maintenance time of seven storage and maintenance methods for different storage times; "○" means less than, "●" means equal.

It can be seen from Table 12 and Figure 24 that the total maintenance time increases smoothly with the increase of storage time. When the storage time is less than 180 days, the maintenance time of method 9 is 100 min, less than that of method 10. This is because both method 9 and method 10 are maintained in a *FDC* mode, but the charge rate of method 9 is 2 C, which is higher than the 1-C charge rate of method 10 thus, method 9 has a shorter single maintenance time. When the maintenance time does not reach 180 days, both methods are maintained only once, and the total time is equal to the single maintenance time; thus, method 10 takes longer to maintain. However, the analysis of the experimental results shows that the 1-C charge rate is more conducive to the maintenance of the charge–discharge power and efficiency of the Ni-MH battery module.

However, if the storage time exceeds 180 days, the advantage of saving the maintenance time endowed by the proposed method becomes more and more significant. The reason is that method 10 uses the *DDC* maintenance mode during even maintenance. The single maintenance time is only 41 min, which makes the total maintenance time increase less. Compared with the six benchmark methods, the proposed method provides superior storage and maintenance outcomes and significantly saves maintenance time.

5. Conclusions

1. The Ni-MH battery modules have high capacity recovery rates and small levels of charge–discharge efficiency reduction after storage. However, the charge and discharge powers of the stored battery modules suffer from significant reduction. Therefore, the battery maintenance methods should be properly designed to maintain the battery power performance as much as possible. Furthermore, insignificant maintenance conditions that have little effect on the battery performance can be reasonably omitted to achieve lower maintenance cost.
2. The proposed storage and maintenance method achieves better maintenance results by significantly saving the maintenance time, and it is suitable for utilization in industrial applications.

6. Future Work

Although the proposed storage and maintenance method can effectively save maintenance time, the specific maintenance effects need to be verified through experimentation. Moreover, because the number of samples is relatively small, the proposed method or conclusion can only be applied to the Ni-MH battery module (6000 mAh/7.2 V) used in this experiment for the time being.

Long-term tests (with an experimental period of 360 days) are currently being conducted to verify the impacts of the proposed storage and maintenance method on the battery performance. Further results will be released once our testing and analyses are completed based on our long-term experiments.

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