

Apply a Piece-wise Peukert's Equation with Temperature Correction Factor to NiMH Battery State of Charge Estimation

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Abstract

Battery state of charge is related with available capacity. Battery available capacity varies with temperature and discharge current. A good way to forecast available capacity is Peukert's equation. In order to verify the practicability of Peukert's equation at room temperature and low temperature, 1/3C, 1C, 2C, 3C rate discharge experiments were undertaken. The result indicates Peukert's equation is suitable for estimating available battery of NiMH battery in 25 °C. The result also indicates, at low temperatures, Peukert's equation is practical for NiMH battery at low current and unpractical in high current. Based on the result, a piece-wise Peukert's equation with Temperature Correction Factor to NiMH Battery State of Charge (SOC) estimation has been proposed. The proposed method improves the precision of SOC estimation.

Keywords

state of charge, available capacity, NiMH battery, low temperature, piece-wise Peukert's equation

1. INTRODUCTION

State of charge (SOC) symbols the residual capacity of battery and it is written as the percent of residual capacity by nominal capacity. The estimation of SOC of NiMH battery is a key technology of energy management system in EV/HEV. The precise SOC monitors and controls the battery in order to maintain its optimum potential and extend its life, moreover it is benefit for controller to implement control strategy in HEV. Without precise SOC estimation, battery dies when it is overcharged or overdischarged [Jung et al., 2002].

The NiMH battery applies widely in electric vehicles, photovoltaic system and standby power of communication system. Its specific energy is much higher than lead acid battery, and the lead acid battery is substituted by the NiMH and the Li-ion battery in many fields. Though the specific energy of the Li-ion battery is higher than the NiMH battery, the Li-ion battery security problem is still to be solved that limits its development. Therefore, the NiMH battery is a good energy source in these fields. But battery available capacity is difficult to estimate. A famous method is Peukert's equation based on the Lead acid proposed in 1897 by Peukert [Peukert, 1897], which describes the relationship between battery available capacity and discharge current. The Peukert's equation is now widely accept-

ed as a method of available capacity estimation for the Lead acid battery. Peukert's equation shows (1):

$$C_I = KI^{(1-n)} \quad (1)$$

where n and k are constant obtained by data of maximum discharge current and minimum current, and the calculated process is shown in appendix. Peukert's equation showed the available capacity decreases with the discharge current increasing [Bumby et al., 1985]. Peukert's equation is verified by lead acid [Peukert, 1897; Bumby, 1985; Chan, 2000; Vervae, 2002; Song, 1998], which estimated the capacity with Peukert's equation. [Chan et al., 2000]'s opinion is that Peukert's equation is only suited for lead acid battery, but no experiment analysis and demonstration are shown. [Doerffel and Sharkh, 2006] analyzed the Li-ion battery, the results show Peukert's equation is good at estimation available capacity under constant current discharge, but is not suitable in variable current profile. Peukert's equation's practicability of the NiMH battery makes the authors carry out this experimental study. To the best of the authors' knowledge, no in-depth studies of the NiMH battery have been published.

Experiments and the discussion of practicability in 25 °C, 0 °C, -12 °C, -18 °C are in Section two. The proposed Piece-wise Peukert's equation is in Section Three. In Section four, the verification of proposed method for SOC estimation has been discussed. Conclusion is in Section five.

2. EXPERIMENTS AT ROOM AND LOW TEMPERATURE

2.1 An Experiments apparatus

A 27Ah/1.2V NiMH battery was tested in these experiments. The battery test system for these experiments is shown in Figure 1, which includes the Arbin BT2000 Battery Test Instrument, data acquisition card, computer, and the NiMH battery. The battery voltage and current were measured by sensors of Arbin BT2000. Measured data were stored in computer. The specifications of the Arbin BT2000 battery test instrument are shown in Table 1. During the process of measuring the battery voltage and current, data were recorded in an excel file automatically. This monitor system can show current and voltage curves in real time. Before data acquisition, sample time and file path have to be set.



Fig. 1 The battery test system

Table 1 Specifications of the Arbin Bt2000 Battery Test Instrument

Maximum discharge current	100 A
Maximum charge current	100 A
Voltage range during discharging	0 V-18 V
Voltage range during charging	0 V-18 V
Current measurement accuracy	±0.1 % of Full Scale Range
Voltage measurement accuracy	±0.1 % of Full Scale Range

2.2 Experiments at room temperature

2.2.1 27 Ah NiMH battery

A 27Ah, 1.2V NiMH battery, had been used in this study at room temperature 25 °C. Constant current discharge experiments in 81 A, 54 A, 27 A, 9 A were undertaken. Table 2 shows discharge times and available capacities under different currents. With the discharge current decreasing, the available capacity increases.

Peukert coefficients n and K are obtained using maximum current 81 A and minimum current 9 A. The

Table 2 25 °C discharge times and available capacities under different currents

Discharge current [A]	Discharge time [h]	Available capacity [Ah]
81	0.2833	22.95
54	0.4468	24.126
27	0.9775	26.3906
9	3.23	29.07

coefficients n and K are shown below, Table 3 shows Calculated Capacities and Errors.

$$C_I = KI^{(1-n)} = 36.93 * I^{(1-1.1085)}, I \subseteq [9A, 81A] \quad (2)$$

Table 3 Calculated capacities and errors at various currents

Discharge current [A]	Available capacity [Ah]	Calculated capacity [Ah]	Error [%]
81	22.95	22.925	0.11
54	24.126	23.956	0.704
27	26.3906	25.8271	2.135
9	29.07	29.0967	0.0009

Peukert coefficient n range is 1 to 1.2 in NiMH battery at 25 °C. The maximum error of calculated data is 2.5906 %. It is practical to apply Peukert's equation to estimate available capacity of The NiMH battery at room temperature 25 °C.

2.3 Experiments at low temperature

Battery available capacity is dependent with temperature, but temperature is not considered in traditional Peukert's equation. Therefore a research in-deep of Peukert's equation at low temperatures is undertaken in below. At three temperatures 0 °C, -12 °C, -18 °C, experiments at 9 A, 27 A, 54 A, 81 A current discharge are undertaken.

Discharge times and available capacities under 1/3 C, 1 C, 2 C, 3 C rate (9 A, 27 A, 54 A, 81 A) at 0 °C display in Table 4. The available capacity decreases with temperature decreasing at the same current.

$$C_I = KI^{(1-n)} = 33.445 * I^{(1-1.128)}, I \subseteq [9A, 81A] \quad (3)$$

Discharge times and available capacities under 1/3 C, 1 C, 2 C, 3 C rate at -12 °C display in Table 5. Peukert coefficient n under -12 °C is shown in Table 6. Maximum current is 81 A and minimum current is 9 A. The Peukert's equation requests the coefficient n is between 1 and 2, otherwise, the Peukert's equation loses

Table 4 0 °C discharge times and available capacities under different currents

Discharge current [A]	Discharge time [h]	Available capacity [Ah]
81	0.234	18.966
54	0.376	20.295
27	0.847	22.883
9	2.799	25.1960

Table 5 -12 °C discharge times and available capacities under different currents

Discharge current [A]	Discharge time [h]	Available capacity [Ah]
81	0.0038	0.3069
54	0.247	13.3366
27	0.579	15.633
9	1.801	16.2126

Table 6 Peukert coefficient n under -12 °C

Max current and Min Current	Peukert coefficient n
81 A, 9 A	2.8040
54 A, 9 A	1.1092

its physical meanings. But coefficient n calculated by 81 A data and 9 A data is 2.8040, which is larger than 2. The available capacity of 81 A is 0.3069 Ah, which is far less than 22.95 Ah at 25 °C. The result indicates Peukert’s equation is not suitable for 81 A at -12 °C. Therefore, maximum current has to be selected again. 54 A is selected as a new maximum current. n calculated by 54 A data and 9 A data is 1.1092, which is between 1 and 2.

$$C_I = KI^{(1-n)} = 19.2474 * I^{(1-1.1092)}, I \subseteq [9A, 54A] \quad (4)$$

Discharge times and available capacities under 1/3 C, 1 C, 2 C, 3 C rate (9 A, 27 A, 54 A, 81 A) at -18 °C display in Table 7. Peukert coefficient n under -18 °C is shown in Table 8. Coefficient n calculated by maximum current 81 A data and minimum current 9A data is 4.7569, which is larger than 2. Coefficient n calculated by maximum current 54 A data and minimum current 60 A data is 3.3798, which is also larger than 2. The available capacity of 81 A is 0.00316 Ah, which is far less than 22.95 Ah at 25 °C. The available capacity of 54 A is 0.1716 Ah, which is also far less than 22.95 Ah at 25 °C. The data indicate Peukert’s equation is

Table 7 -18 °C Discharge times and available capacities under different currents

Discharge current [A]	Discharge time [h]	Available capacity [Ah]
81	0.00004	0.00316
54	0.0032	0.1716
27	0.415	11.15
9	1.355	12.12

Table 8 Peukert coefficient n under -18 °C

Max current and Min Current	Peukert coefficient n
81 A, 9 A	4.7569
54 A, 9 A	3.3798
27 A, 9 A	1.06723

not suitable for 81 A and 54A at -18 °C. Coefficient n calculated by 27 A data and 9 A data is 1.06723, which is between 1 and 2.

$$C_I = KI^{(1-n)} = 13.99 * I^{(1-1.067)}, I \subseteq [9A, 27A] \quad (5)$$

All data of available capacity in 9 A, 27 A, 54 A, 81 A at 25 °C, 0 °C, -12 °C, -18 °C are shown in Figure 2, which indicates that the available capacity decreases with temperature decreasing in the same current and the available capacity decreases with current improving at the same temperature. The available capacity of 81 A at -18 °C is only 0.00316 Ah.

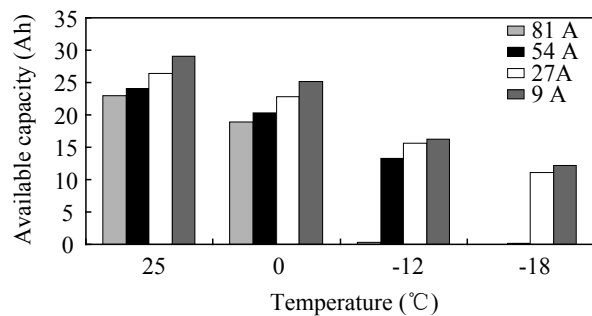


Fig. 2 The available capacity in 9 A, 27 A, 54 A, 81 A at 25 °C, 0 °C, -12 °C, -18 °C

3. THE PIECE-WISE PEUKERT’S EQUATION WITH TEMPERATURE CORRECTION FACTOR

According the result talked above, the choice of Peukert’s coefficient is not only related with discharge current, but also related with temperature. According to the value of coefficient n and K at four different

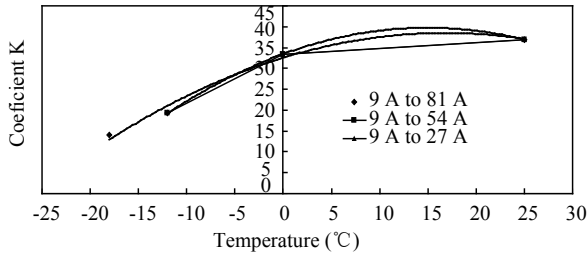


Fig. 3 The relationship of temperature and K of three current fields

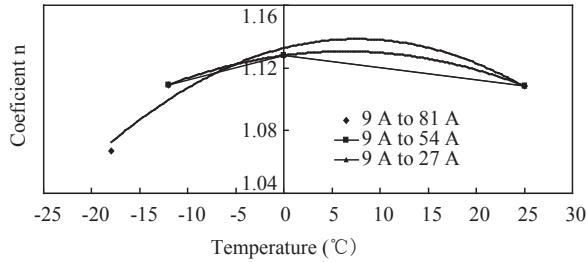


Fig. 4 The relationship of temperature and n

temperature, a relation curve of n and temperature has been set with least square fitting, which is shown in Figure 3. In the same way, a relation curve of K and temperature also has been set with least square fitting, which is shown in Figure 4. Based on the two relation curves talked above, a formula of n and temperature, which is shown in formula (6), and a formula of K and temperature, which is shown in formula (7) are built. A piece-wise Peukert's equation with temperature correction factor has been set, which is shown in formula (8).

$$K = \begin{cases} (-0.0212) \times T^2 + 0.708 \times T + 32.568 & 9A \leq I \leq 27A, -18 \leq T \leq 25 \\ (-0.0282) \times T^2 + 0.8446 \times T + 33.445 & 27A < I \leq 54A, -12 \leq T \leq 25 \\ -0.1394 \times T + 33.445 & 54A < I \leq 81A, 0 \leq T \leq 25 \end{cases} \quad (6)$$

$$n = \begin{cases} (-0.0001) \times T^2 + 0.0015 \times T + 1.1327 & 9A \leq I \leq 27A, -18 \leq T \leq 25 \\ (-0.00006) \times T^2 + 0.0008 \times T + 1.128 & 27A < I \leq 54A, -12 \leq T \leq 25 \\ (-0.0008) \times T + 1.128 & 54A < I \leq 81A, 0 \leq T \leq 25 \end{cases} \quad (7)$$

According to the piece-wise Peukert's equation with temperature correction factor, available capacity under any low temperature can be estimated. The piece-wise Peukert's equation with temperature correction factor:

$$C_{IT} = KI^{(1-n)} = \begin{cases} ((-0.0212) \times T^2 + 0.708 \times T + 32.568) \times I^{(1-((-0.0001) \times T^2 + 0.0015 \times T + 1.1327))} & 9A \leq I \leq 27A, -18 \leq T \leq 25 \\ ((-0.0282) \times T^2 + 0.8446 \times T + 33.445) \times I^{(1-((-0.00006) \times T^2 + 0.0008 \times T + 1.128))} & 27A < I \leq 54A, -12 \leq T \leq 25 \\ (0.1394 \times T + 33.445) \times I^{(1-((-0.0008) \times T + 1.128))} & 54A < I \leq 81A, 0 \leq T \leq 25 \end{cases} \quad (8)$$

4. SOC ESTIMATION BASED ON THE PIECE-WISE PEUKERT'S EQUATION WITH TEMPERATURE CORRECTION FACTOR

4.1 SOC loss mode of low temperature

Based on the piece-wise Peukert's equation with temperature correction factor, a capacity loss model and a SOC loss model model of low temperature are proposed. The capacity loss model of low temperature is shown in formula (9). The SOC loss model of low temperature is shown in in formula (10).

The capacity loss model of low temperature

$$C_{T_loss} = C_{no\ min\ al} - (-0.0212 \times T^2 + 0.708 \times T + 32.568) \times I^{(1-((-0.0001) \times T^2 + 0.0015 \times T + 1.1327))} \quad (9)$$

The SOC loss model model of low temperature

$$S_{T_loss} = C_{T_loss} / C_{no\ min\ al} = (C_{no\ min\ al} - (-0.0212 \times T^2 + 0.708 \times T + 32.568) \times I^{(1-((-0.0001) \times T^2 + 0.0015 \times T + 1.1327))}) / C_{no\ min\ al} \quad (10)$$

4.2 An improved SOC estimation method

According to the SOC loss model of low temperature, an improved SOC estimation method has been proposed, which is shown in formula (11).

$$SOC(t) = SOC(0) - \int_0^t 100 \frac{\eta_{L,T} I}{C_{no\ min\ al}} - S_{T_loss} \quad (11)$$

A 1/3 C rate current discharge experiment at -18 °C is used to verify the SOC estimation precision of the improved SOC estimation method, which is shown in Figure 5. In the first step, NiMH battery is charged to full. In the second, NiMH battery was put into icebox for 12 hours. In the third step, 1/3 C rate current discharge experiment was undertaken under -18 °C.

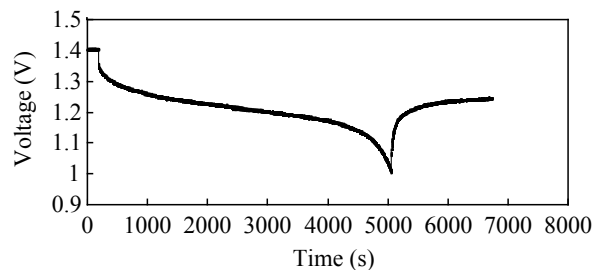


Fig. 5 Discharge experiment under -18 °C

Comparison real SOC and estimated SOC, which is shown in Figure 6. the error of proposed method is 9 %, the error of traditional Amper-hour method is 58 %. The experiment result shows that the improved SOC

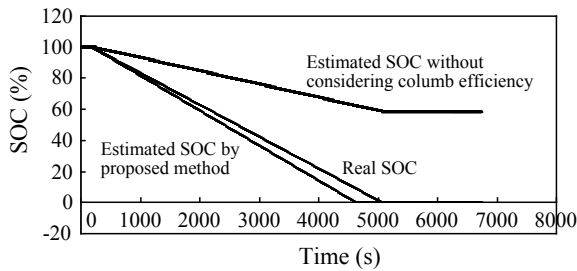


Fig. 6 Comparison of real and estimated SOC with discharge experiment at 1/3 C rate under -18 °C

estimation method improves the precision of SOC estimation because it considers that battery available capacity decreases with temperature decreasing.

5. CONCLUSION

- (1) Verifying the practicality of applying Peukert’s equation to estimate available capacity of NiMH battery.
- (2) A piece-wise Peukert’s equation with temperature correction factor is proposed.
- (3) A SOC loss model at low temperature is proposed.
- (4) The improved SOC estimation method is proposed which improves the precision of SOC estimation.

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Appendix

$$n = \frac{\lg(t_2 / t_1)}{\lg(I_1 / I_2)}$$

$$K = I_1^n t_1 = I_2^n t_2$$

- Where
- I — Discharge current
 - I_1 — Maximum discharge current
 - I_2 — Minimum discharge current
 - t_1 — discharge time in I_1
 - t_2 — discharge time in I_2