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ELECTRICAL AND THERMAL ANALYSIS OF AN ENVIRONMENTALLY SAFE MICROPROCESSOR-BASED NI-CD FAST BATTERY CHARGER

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Ultra fast charging capability of Ni-Cd batteries is used to present a safe and fast charging algorithm which prevents battery damages and maximizes its lifetime. The algorithm uses a combination of battery voltage (amplitude and slop), operating temperature and charging time slope to achieve a safe charging process. Before any charging action, battery state is determined, battery is intentionally discharged (to avoid memory effects), slowly charged to a safe voltage level (to maximize it's life time), and then charged very rapidly. For terminating the charging action, accurate end-charge techniques are used (to avoid over charging) and finally, the battery enters the trickle mode. Based on the proposed algorithm, a fast microprocessor Ni-Cd battery charger is constructed and tested. Measured results are demonstrated and compared for two fast charging techniques (pulsed-current and ReFlex) along with two end charge detection methods ($-\Delta V$ and Δt). Also, measured temperatures are compared with results obtained by a mathematical model (lumped parameter method) generated for the battery.

Keywords: Ni-Cd, Fast Charging, Microprocessor, Lumped Parameter, Satellite

INTRODUCTION

Many cordless and portable equipment and appliances use Nickel-Cadmium (Ni-Cd) batteries as an environmentally safe source of energy. In addition, it ensures a safe and economical fast charging process. The ultra-fast charging capability, fine performance and high capacity of these batteries along with their limited weight and size are very attractive and distinct properties for many light and compact appliances such as mobile phones, desk top computers, portable audio equipment and cordless power tools.

In literatures, many charging techniques are investigated and proposed [1-5]. These techniques use a variety of battery characteristics (voltage, temperature) to achieve a fast charging process. The problem with these methods is the ignorance of battery safety factors that could cause temporary or permanent damages as well as decrease battery lifetime. These factors are very important in many applications such as satellites and spacecraft systems where battery replacement is not recommended or possible and battery lifetime is of important consideration.

In this paper, a safe and fast charging method for Ni-Cd batteries is presented and constructed. Also, a temperature model based on the lumped parameter method is suggested and used. Main advantages of the proposed charging method are: i) optimal starting and ending points for fast charging action (based on battery states) and, ii) consideration of critical safety factors such as battery temperature which prevents battery damage and maximizes it's life time.

CHARACTERISTICS OF NI-CD BATTERIES

Ability to recharge is one of the most important characteristics of Ni-Cd batteries, but the numbers of charge/discharge cycles are limited. Its cycle life depends on Depth Of Discharge (DOD), quality of charging and discharging, operating temperature and rate of charge and discharge currents. Another characteristic of Ni-Cd batteries is the dependency of internal impedance to its charge-state as shown in Figure 1. Therefore, increasing charge-state (e.g., storing more energy in the battery) or reducing the operating temperature, will increase the internal impedance. This property will be used in the following sections to determine end-charge of the battery.

If a Ni-Cd battery is alternately charged and discharged with a low DOD, the battery voltage and capacity will gradually decrease. In another word, the battery memorizes the history and conditions of charge/discharge states and tries to adapt to it. This phenomenon, which is typical of most batteries, is called "memory effect". Some manufacturers like Sanyo and Panasonic, claim limited (or cancellation) of "memory effect" in their products. One of the distinct behaviors of Ni-Cd batteries is their wide operating temperature band, with an upper limit of $45^{\circ}C$. They can withstand a fair amount of physical, electrical and thermal abuse without serious problems and permanent damage [1]. Ni-Cd batteries also have a flat voltage profile, which drops sharply in the neighborhood of discharge-state (Figure 2); a distinct characteristic, which could be used to identify battery-state. In addition, the temperature behavior shows a sharp increase near its full charge state, as shown in Figure 2.

CHARGE-STATE ESTIMATION OF NI-CD BATTERIES

Overcharging a fully-charged or a half-charged battery could cause permanent damages and decrease life time [2]. This is mainly due to the "memory effect" and temperature increase of the battery. Therefore, charge-state (e.g., the amount of energy stored in the battery) must be determined before any charging process. In literature, three general methods are proposed for the estimation of charge-state [2]:

a) Using measured internal impedance: this method involves complicated and complex calculations since the battery's internal impedance depends on charge-state as well as the environmental temperature and battery age [4]. Moreover, the validity and accuracy of this method has not been investigated and reported for Ni-Cd batteries.

b) Using charge/discharge history: memorizing the charge/discharge history of the battery is not a very accurate or preferred way of estimating charge-state, since:

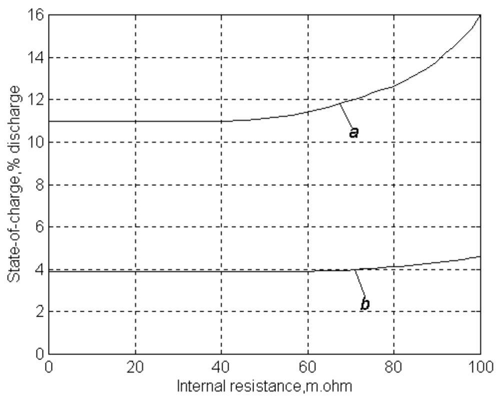

Figure 1. Internal resistance of sealed Ni-Cd cells at 20 ° c and discharged rate of 0.2 C: a) AA-size, 600mAh; b) sub-csize, 1300mAh [1].

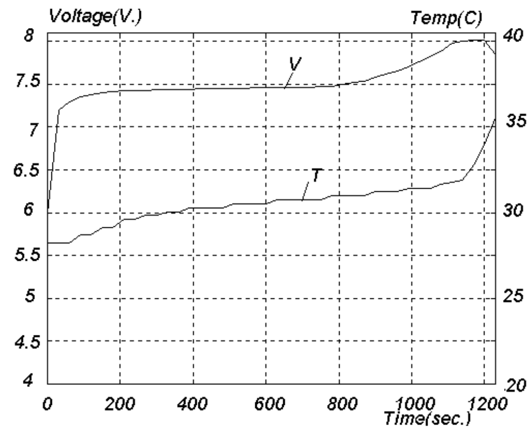

Figure 2. Measured voltage and temperature evolution in Ni-Cd cells during a 4C charge in half an hour [2].

i) Effective battery capacity is a nonlinear function of discharging current, environmental temperature and battery age, and

ii) When more than one battery is used, recording and keeping track of charge/discharge history is not very practical.

c) Forcing **the battery to discharged condition:** considering the difficulties associated with charge-state estimation and keeping in mind the flat voltage profile of Ni-Cd batteries (Figure 2), one could attentively fully discharge the battery before any charging process. In order to identify the full-discharge state, the voltage amplitude is used and full-discharge state is assumed when the voltage drops below a certain value. But this is not an accurate approach since voltage amplitude depends on operating temperature and battery age. Instead, a sharp voltage drop is used as an indication of full discharge condition. This method is also used in this paper for the proper charging of Ni-Cd battery.

FAST CHARGING METHODS

General approach for charging Ni-Cd batteries is "constant current charging". Under normal charging conditions, the amount of oxygen produced by the positive electrode is equal to the oxygen consumption by the negative electrode. If the rate of charge current, is high production of oxygen is more than consumption. Thus, oxygen accumulates on negative electrode and consequently internal impedance, pressure and temperature increase rapidly. This could cause permanent battery damage. To overcome these problems, manufacturers build batteries with fast gas composition capability. However, for fast charging this approach is not effective and one of the following methods could be used:

a) Pulsed-current method: a pulsed-current charging approach (Figure 3) is used. Time delays between pulses allow the cell chemistry to recover.

b) ReFlex method: to avoid gas accumulation problems, a current charging (positive) pulse followed by a short duration and a high discharging current (negative) pulse is applied during the fast charging process (Figure 4). This technique also reduces the internal cell pressure, temperature and impedance [2].

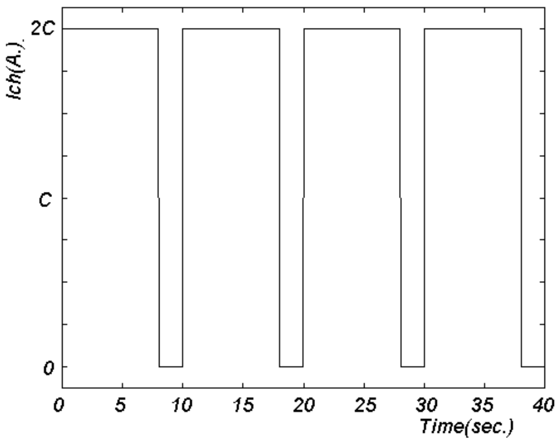

Figure 3. Current characteristics used in "pulsed-current" fast changing scheme.

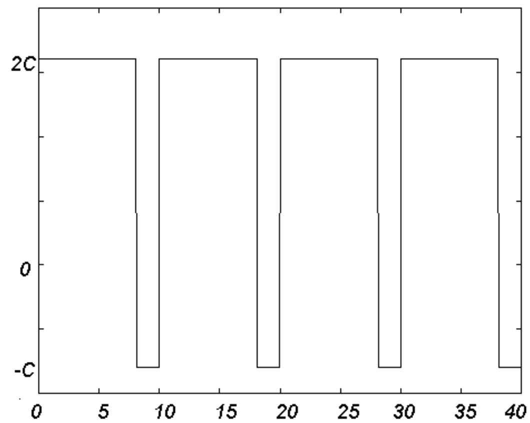

Figure 4. Current characteristics used in "ReFlex" fast charging scheme.

CHARGE-END METHODS

In order to guarantee a safe termination of fast charging and maximize the cycle life of the battery, an accurate and reliable method for charge-end identification is required. Instead of using the conventional charging methods such as "thermal detection" and "timer control", one of the following schemes are proposed:

a) Voltage difference detection $(-\Delta V)$**:** during the charging process voltage profile is flat and its amplitude is almost constant. As the battery reaches full-charge condition, the fast rise of internal impedance increases the voltage amplitude (since charging current is constant). When the battery enters the over-charge region, it's temperature rise decreases internal impedance and voltage amplitude. Therefore, as the battery passes the full-charge state and enters the over-charged region, ΔV property is changed (Figure 5). This variation is used to detect the full-charge state.

Among the limitations of this method are:

i) Due to voltage-slope changes after entering the over-charge region, this method captures the beginning of the over-charge instead of the end-charge,

ii) Very accurate instruments must be used since the amount of voltage change (ΔV) is very small for Ni-Cd batteries, and

iii) Charging currents below 0.5 C, change in battery temperature (ΔT) and voltage (ΔV) is very limited and detection is not very easy.

b) Time difference detection (Δt)**:** the change in voltage-slope is used as an indication of end-charge state. This is established as follows:

i) Slope will not be measured until battery voltage enters its flat region zone (e.g., until V=1.4 V), and

ii) Successive times for a fixed amount of voltage increase (e.g., 15 mV/cell) are measured and recorded. As shown by Figure 6, three zones can be established:

zone-1 (charging zone)- battery voltage increases at a slower rate as the battery starts charging. Thus, measured time intervals increase: $t_1 \langle t_2 \langle t_3$.

zone-2 (full-charge zone)- when the battery is near the full-charged state, its voltage increases at a much faster rate. Voltage slopes change and, therefore, measured time intervals decrease: $t_3 \rangle t_4 \rangle t_5 \rangle t_6 \rangle t_7$.

zone-3 (over-charge zone)- after reaching voltage-slope peak, measured time intervals increase again: $t_7 \langle t_8 \langle t_9$.

iii) Detecting the transition from zone-2 to zone-3 stops fast charging.

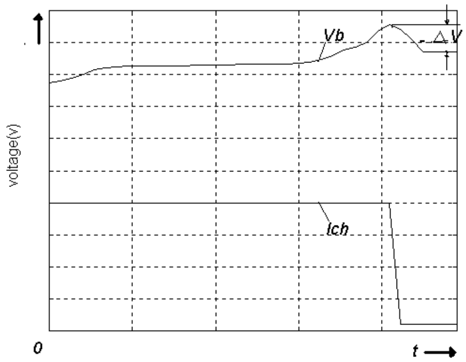

Figure 5. Voltage difference detection scheme used for charge control of a Ni-Cd battery[1].

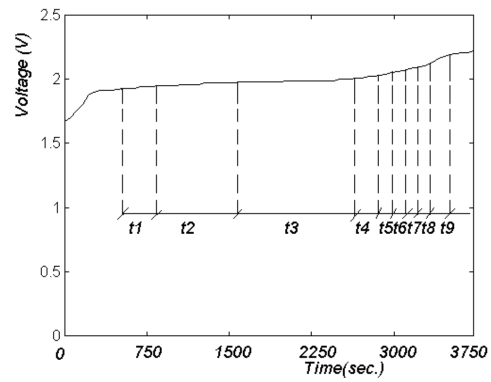

Figure 6. Time difference detection scheme used for charge control of a Ni-Cd battery.

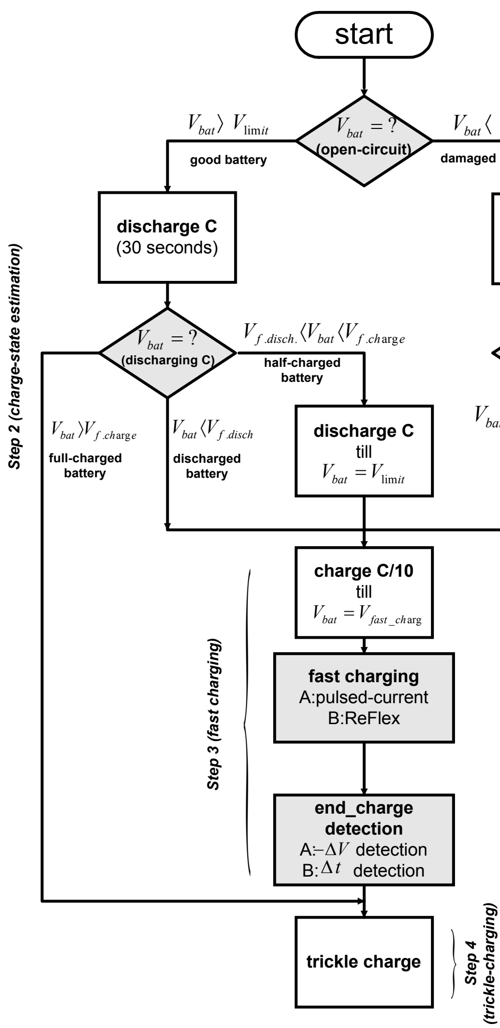

Figure 7. The proposed fast charging method for Ni-Cd batteries.

THE PROPOSED FAST CHARGING METHOD

Figure 7 shows flow diagram for the proposed optimized fast charging method of Ni-Cd batteries. This approach is capable of detecting and recovering (if possible) batteries that are damaged. Also, this approach determines the charge-state (full charged, half charged, full discharge) and applies an optimal fast charging technique without causing any undesired effects (such as permanent cell damage, memory effects, decrease of battery age, increase of battery temperature). If the battery is not fully discharged, first, it is intentionally discharged and then, it is smoothly charged to a safe voltage level $(V_{fast\,charge})$. Finally, it is rapidly charged using a proper fast charging scheme. The flow diagram consists of the steps in Figure 7.

Step 1 (battery damage detection): since open circuit voltage is higher than the battery voltage under discharged conditions, the measured open circuit voltage is used to detect possible damage. Even if a battery is damaged and it's voltage is below V_{limit}, we might be able to recover damage by slowly charging it. Otherwise, permanent damage is detected and the "bad battery" could not be charged and used.

Step 2 (charge-state estimation): battery state (full charged, half charged, full discharged) is determined before entering a fast charging action. To do this, battery voltage under discharging conditions (30 seconds discharging with rate of C) is measured:

a) If battery voltage is below $V_{f.disch.}$ (e.g., 0.68 V/cell for Ni-Cd batteries), a full-discharged battery is detected. Go to step 3.

b) If battery voltage is above $V_{f.charge}$ (e.g., 1.1 V/cell for Ni-Cd batteries), a full-discharged battery is detected and no charging is required. Go to step 4.

c) Otherwise, the battery is in a half-charged condition and it must be discharged (e.g., with rate of C) until it's voltage drops to V_{limit} . Go to step 4. This is done to avoid memory effects.

Step 3 (fast charging): to avoid unrecoverable cell damage, a slow and standard current (e.g. with a rate of C/10) is applied to increase battery voltage to a safe limit during fast charging action, $V_{f.charge}$ (e.g., 1.3 V/cell for Ni-Cd batteries). Now, the desired fast charge scheme (e.g., pulsed-current or ReFlex) is safely applied to the battery and an end-charge estimation method (e.g., $-\Delta V$ or Δt) is used to terminate the charging process before it enters to the over-charged region.

Step 4 (trickle charging): the battery is kept in full charge state until it is used.

This method does not suffer from the problems associated with overcharging, since voltage-slope peaks just before the peak of voltage amplitude and, therefore, charging action is terminated without any over-charging.

CONSTRUCTED BATTERY CHARGER

The constructed microprocessor-based fast battery charger used for measurements (Figure 8) consists of the following parts:

A. Power supply circuit- The power supply is of conventional design, including: a transformer (220V/12V, 250W, 50HZ), a diode bridge rectifier (35A), a large filter capacitor (70mf), a 12V voltage regulator (IC 7812), a 5V voltage regulator (IC 7805) and a current buffer (transistor 2N 3055).

B. Charge/discharge circuit- The charge/discharge circuit is capable of implementing three charging current rates (C/100, C/10, 2C) and two discharging current rates (C/10, C). The switching action and temperature recordings are performed using five BC107 npn transistors, controlled by the microcontroller.

C. The Microcontroller circuit- The microcontroller circuit which is responsible for all control and switching actions of Figure 7 is an IC8051 consisting of: 4 input/output ports, one 8-bit CPU, 64kbyte external RAM, 64 K-byte external ROM, 128 byte internal RAM, ALU, one serial RT and two internal timer/counter...

D. An 8-bit, 8K-byte EPROM (IC 2764)- used for implementing the software.

E. An A/D (IC ADC 0809)- for A/D conversion of the battery's voltage and temperature.

F. Temperature sensors (IC LM35)- for all temperature measurements.

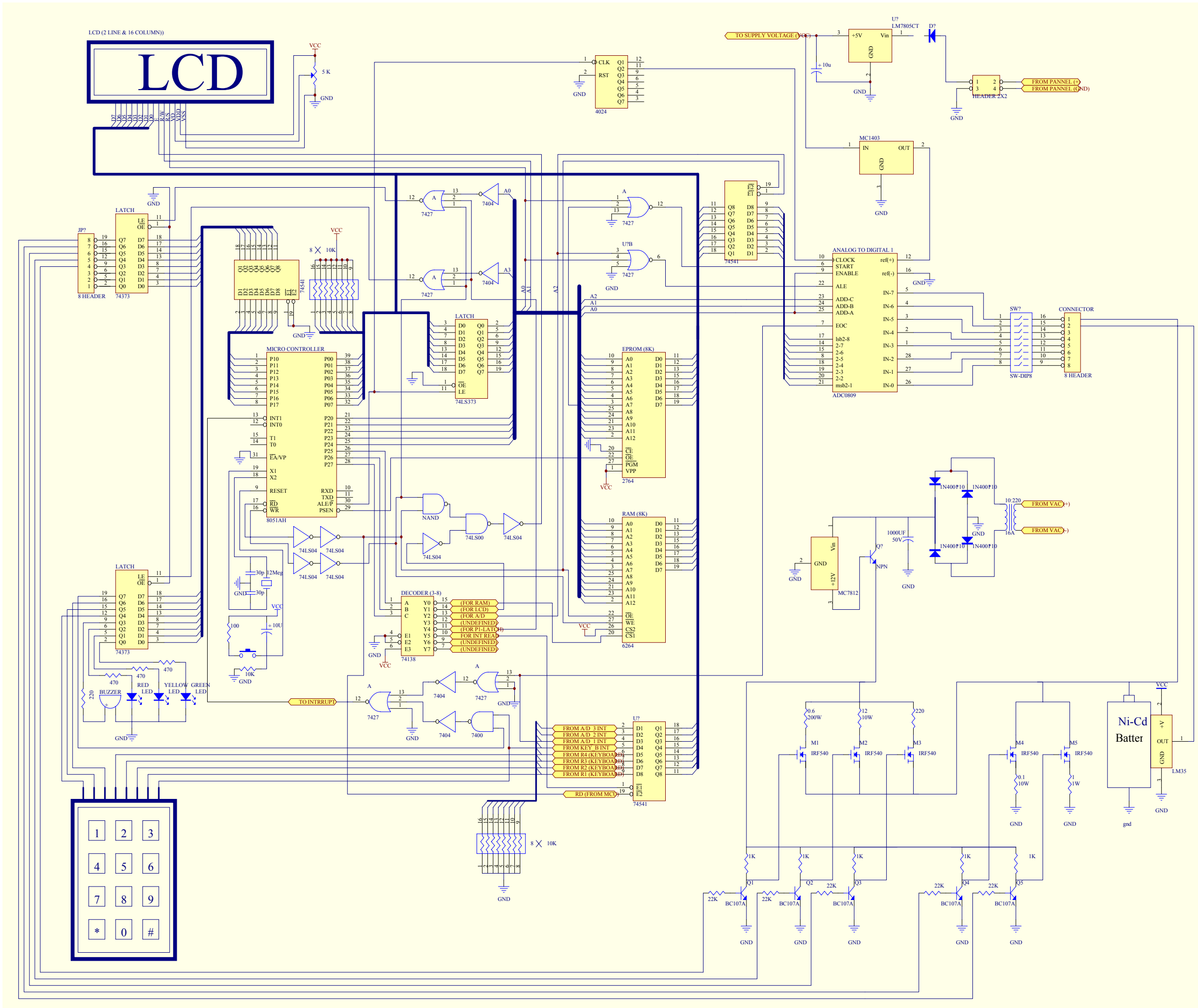

Figure 8. The constructed microprocessor-based Ni-Cd battery charger used for measurements.

THERMAL ANALYSIS OF NICKEL-CADMIUM BATTERY

As known, the battery operates in a narrow allowable temperature range. During the charging process, if the temperature of the Ni-Cd battery increases beyond its limit, the battery will be damaged. Thus, thermal design for such a system is essential. Typical design parameters for the battery are; thermo-physical and optical properties, interface conductance, internal heat dissipation, external heat flux, etc. Variation of temperature in Ni-Cd battery during charging period is investigated by the lumped parameter method. In this method, the battery is divided into 10 nodes as shown in Figure 9.

The energy equation for each node is given by:

$$mc_p \frac{dT_w}{dt} = hA(T_\infty - T_w) + \dot{Q} \qquad (1)$$

where

m = mass of battery, Kg	h = convective coefficient, $W/m^2 K$
c_p = heat capacity, KJ/Kg K	T_∞ = environment temperature, K
$\dot{Q}$ = power generation, W	t = time, sec
A = battery area, m^2	T_w = battery surface temperature, K

To solve the energy equation, we need to come up with a value for convective coefficient and power generation. The convective coefficient is calculated by [8]:

$$h = \frac{k_f}{D}\left\{0.6 + 0.387\left[\frac{Gr\,Pr}{\left(1+(0.559/Pr)^{9/16}\right)^{16/9}}\right]^{1/6}\right\}^2 \qquad (2)$$

where

$$Gr = \frac{g\beta(T_w - T_\infty)l^3}{v^2} \qquad \beta = \frac{1}{T_f},\ K^{-1}$$

$$T_f = \text{final temperature} = \frac{T_w + T_\infty}{2},\ k \qquad v = (0.1014T_f - 14.73)(10)^{-6},\ m/s^2$$

D = battery diammeter, m $\qquad$ l = battery height, m

k_f = air thermal conductivity, W / mK $\qquad$ $Pr = -0.00022T_f + 0.774$

Power generation is calculated by measured voltage (V) and current (I) as follows:

$$\dot{Q} = VI \times (1 - \eta) \qquad (3)$$

Where η is battery efficiency.

A finite difference base code is developed and used for the solution of the instantaneous sets of equations (see Figure 9). Temperature change of the battery during charging period is shown in Figure 10. Theoretical model shows the same trend as experimental results. During initial charging a sudden jump in temperature is observed and then temperature increases smoothly. Finally a sudden increase in temperature is observed due to over charging.

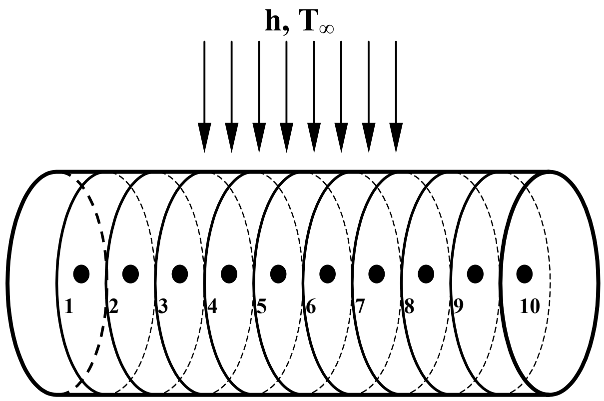

Figure 9. Nodal schematic of Ni-Cd battery.

MEASURED CHARACTERISTICS

The constructed fast battery charger (Figure 8) was used for optimal fast charging of an 8000mAh Ni-Cd battery (size C). Different fast charging methods and end-charge estimation schemes are implemented.

As an example, Figure 10 shows the measured voltage profile using pulsed-currents for charging and a "voltage-detection" scheme for end-charge estimation. Figure 11 shows similar measured characteristics using "ReFlex charging" scheme and "Δt end-state detection" approach.

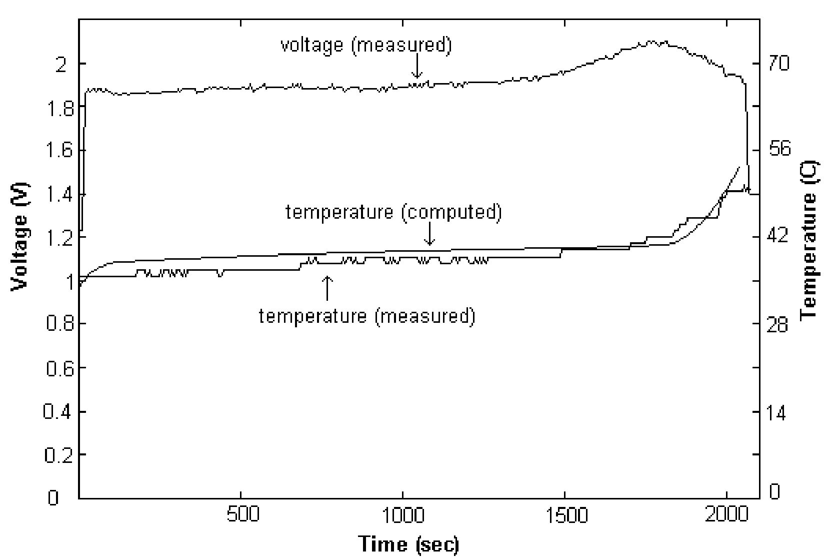

Figure 10. Measured voltage and temperature characteristics of an 8000 mAh Ni-Cd battery, using "pulsed-current charging" approach and "$-\Delta V$ end-state detection" technique. Heavy lines show computed temperature characteristics.

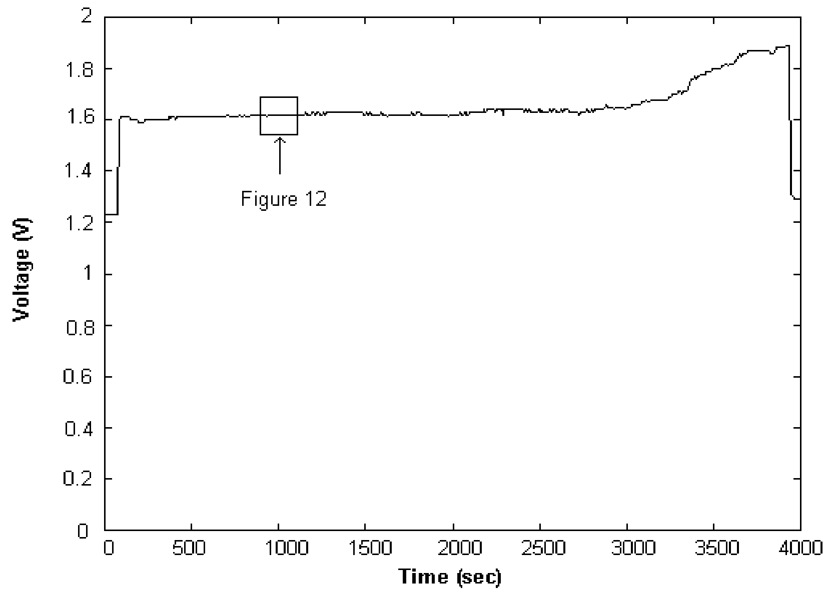

Figure 11. Measured voltage characteristics of an 8000 mAh Ni-Cd battery, using "ReFlex charging" approach and "Δt end-state detection" technique

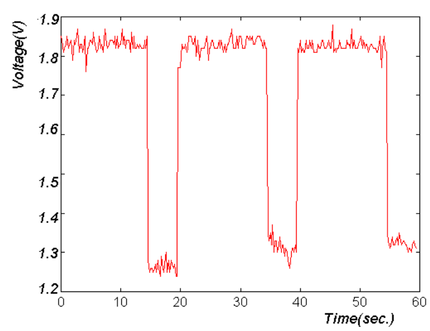

Figure 12. Detailed measured voltage characteristics of Figure 11.

CONCLUSION

A fast and safe charging algorithm for Ni-Cd batteries is presented. To investigate its performance, a microcontroller-based Ni-Cd battery charger with the following properties was constructed:

1. Two fast charging abilities (pulsed-current and ReFlex) with user option.
2. Two end-charge estimation techniques $(-\Delta V$ and $\Delta t)$ with user option.
3. Implementation of other charging methods and end-charge estimation techniques is possible.
4. Undesired memory effects are prevented by intentionally discharging the battery, slowly charging it to a safe voltage level and finally applying the fast charging current.
5. Battery overcharging problems are prevented using accurate end-charge estimation methods.
6. As a result, battery voltage level, temperature and pressure are totally controlled during the entire charging process which maximizes battery life time (cycle life).

Based on the experimental results:

1. Operating temperature and performance of the ReFlex fast charge method is better than pulsed-current technique.
2. Accuracy and performance of time detection (Δt) method for end-charge estimation is better than voltage detection $(-\Delta V)$ technique.

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