Considerations to Improve the Practical Design of Universal and Full-Effective NiCd/NiMH Battery Fast-Chargers

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Abstract- **An effective fast-charger for NiCd/NiMH batteries used in portable applications must be able to estimate previous battery charge state and to make decisions to minimize charging time without negative effects on battery-life. In this paper, some new methods for estimating and making decisions are presented. Due to these methods can be easily implemented, effective and universal battery fast-chargers can be obtained by using few and inexpensive components.**

I. SYSTEM OVERVIEW

Battery pressure and temperature increase quickly during fast-charging process. Therefore, fast-charge must be carefully monitored to avoid damage in the battery.

A flow diagram of the optimized fast-charge method proposed in this paper can be seen in Fig. 1. The complete process has two different steps.

The process begins with the determination of battery state:

- Measurement of open-circuit battery voltage to detect if battery is damaged.
- Measurement of battery voltage on discharging in order to know battery charge state.

After this, battery state is known. Then, the second stage (charge process) can begin.

- Depending on battery charge state, the charging process is modified. In this way, fast-charging does not have negative effects on the effective capacity of the battery and on battery cycle-life.

In the following sections each of this stages and its implementation will be described.

All methods proposed in this paper have been widely confirmed experimentally. A universal test-bench for fast-charging was previously developed in order to facilitate research. The implemented test-bench allows us to make all type of charging/discharging tests (through specially designed power stages) at constant ambient temperature (ICP 800 electronically controlled oven, Memmert), the monitoring of main parameters (2620A Data Acquisition Unit, Fluke) and the story of data sampled for a later study (LabView + bus GPIB).

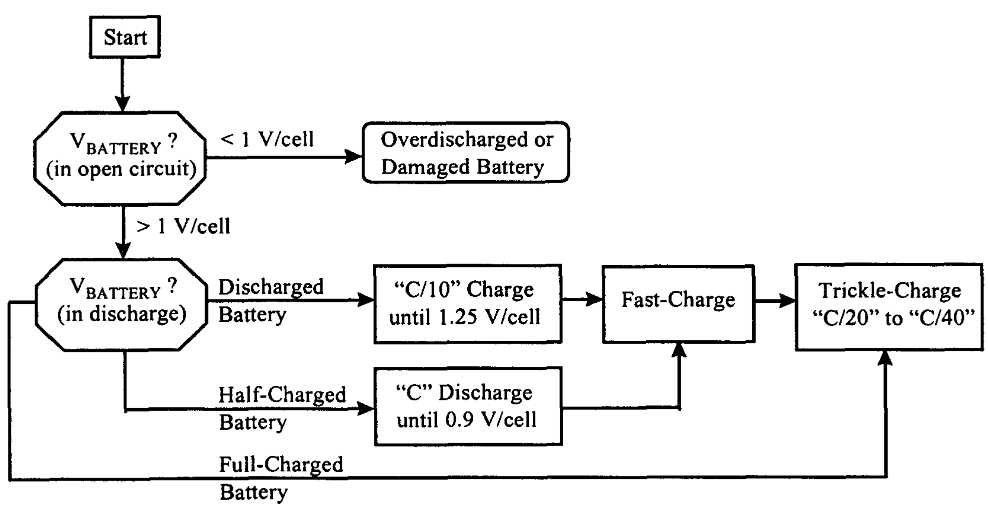

Fig. 1. Flow diagram of optimized fast-charge method.

II. ESTIMATION OF BATTERY STATE

Determining battery state is the first stage to minimize charging time without negative effects on battery life. Different methods ("memorizing of battery charging/discharging history" or "measurement of internal impedance" [1]) have so far been proposed to give an accurate indication of battery charge state (remaining energy) but the implementation of these methods becomes difficult (they are not practical).

The solution is the following: Knowing exactly the energy remaining in a battery is very interesting but it is not necessary if the main objective is to achieve a safe fast-charge of the battery. In this case, an approximate knowledge of the battery charge state (full-charged, half charged or discharged) is sufficient: depending on the initial state of the battery, the charging process must be modified to avoid any damage to the battery.

The method proposed to determine battery state is based on measurement of battery voltage under several specific conditions; so, the measurement system becomes very simple. This method consists of:

A. Detection of damaged battery

Battery damage is detected by measuring the open-circuit battery voltage (see Fig.2). Battery manufacturers recommend not to discharge batteries below 1 V/cell. Therefore, an open-circuit battery voltage less than 1V/cell shows an overdischarged battery and usually a damaged battery.

In this case, a low charge current (C/10) is applied. If the battery is overdischarged due to self-discharge or occasional bad use, battery voltage reaches 1.25 V/cell - this voltage is the value that a discharged cell in good conditions reaches at the start of charging - after a few minutes (5 minutes). However, if the battery is damaged, battery voltage remains lower than this value because charge is not accepted.

Therefore, if battery voltage reaches 1.25 V/cell in less than 5 minutes, a low charge current must be applied until battery is recovered. However, if battery voltage remains lower than 1V/cell after 1 or 2 minutes or lower than 1.25 V/cell after a few minutes, the charging procedure must be ended because the battery has irreversible damage.

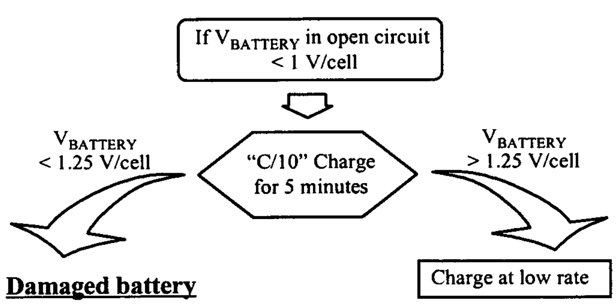

Fig 2. Detection of irreversible damage in the battery.

B. Estimation of battery charge state

The above method (measurement of open-circuit battery voltage) fails to clearly represent the energy stored in a battery at an specific time. However, if battery voltage is read while the battery is being discharged, some interesting conclusions can be drawn [2].

Fig. 3 shows some voltage-versus-energy curves for NiCd or Ni-MH cells that have been discharged at the same rate (age and/or temperature could be the cause of differences).

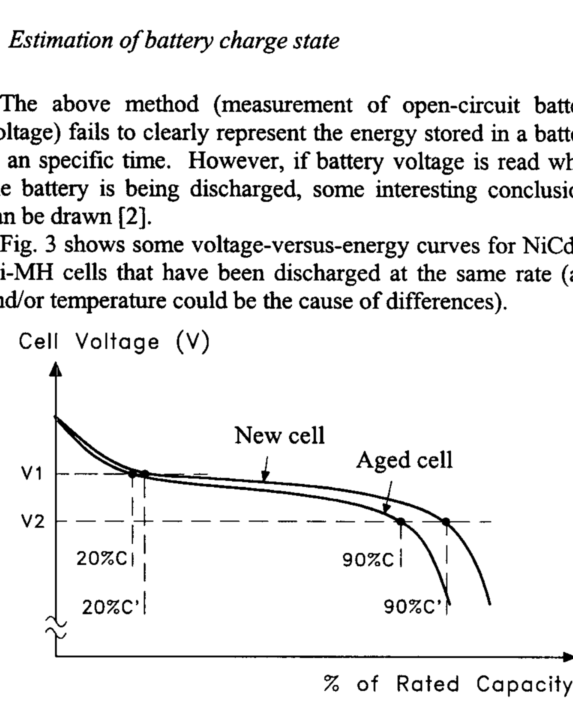

Fig. 3. Voltage versus energy curves for different NiCd or NiMH cells discharged at the same rate.

Curves look essentially flat but it can be concluded that:

- If (V_{cell}) >V1 the cell is:
  fully charged (remaining energy > 80% of total energy)
- If (V_{cell}) <V2 the cell is:
  discharged (remaining energy < 10% of total energy)
- If V2 < (V_{cell}) < V1 the cell is half-charged

It should be pointed out that discharging profiles in NiCd and NiMH batteries depend too much on discharge rate. Therefore, to draw conclusions from several results, the same discharge rate must be always used.

In order to reduce the necessary discharging-time to obtain a relation between battery voltage and battery charge state, a high discharging current has been chosen. Thus, the method proposed consists of reading battery voltage for a short time (1 minute) while the battery is being discharged at a "C" rate. Battery voltage at the end of this short discharging process shows battery charge state.

Although the parameter "C" (nominal battery capacity) must be known, this fact do not imply getting further information from the battery: "C" is a necessary parameter for fast-charging process (current rate is a multiple of "C").

III. CHARGE METHOD

Previous discussion establishes three zones of charge state for NiCd and NiMH batteries (see Fig.4).

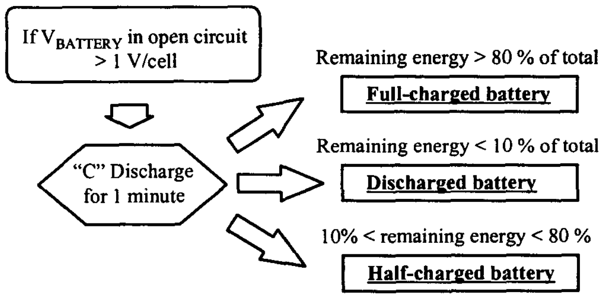

Fig. 4. Battery charge state estimation method.

Knowing the charge state of the battery (full-charged, half-charged or discharged) before beginning the fast-charge process is necessary because:

a) Full-charged battery: Fast-charge in this zone is dangerous and it could become destructive by increasing the temperature on overcharging.

Thus, only a trickle charge (a current rate just slightly above the self-discharge rate) must be applied until the battery is removed from the charger. In this way, battery is kept in the right conditions for using at any given time. Ni-MH batteries are more sensitive than NiCd batteries at low-level continuous charge [3], but a trickle charge at low enough current ("C/20" to "C/40") is not problematic.

b) Half-charged battery: If battery charge is started in this zone, the effective capacity of the battery could be reduced.

Tests show that the effective capacity of NiMH batteries remains similar of nominal capacity (see Fig. 5) after more than 100 cycles of charge/partial discharge (in this case, until the 25 % of nominal capacity); the reduction (a 10 % with a final voltage of 1.15 V/cell) in the effective capacity of NiCd batteries (see Fig. 6) disappears after one full-discharge. The main conclusion is "memory effect" does not have influence in usual applications (the battery is occasionally full-discharged).

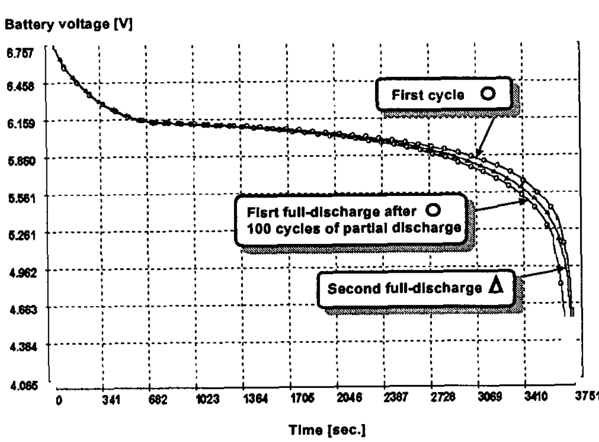

Fig. 5. Full-discharge curves of a 6V NiMH battery under specific conditions.

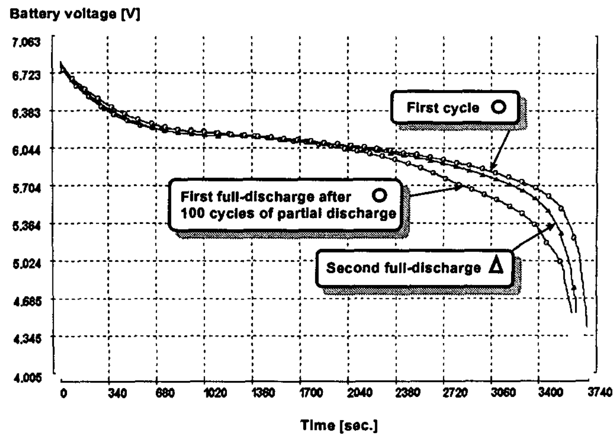

Fig. 6. Full-discharge curves of a 6V NiCd battery under specific conditions.

From this point of view, discharging a half-charged battery before beginning the fast-charge process would not be necessary. However, batteries can lose effective capacity due to overcharging, overdischarging, self-discharging and so on (these losses are often mistakenly attributed to the "memory effect") and experts agree about the best way to avoid all these problems: discharging the battery before charging [4].

Therefore, discharging a half-charged battery to 1 V/cell or 0.9 V/cell (the end voltage must be modified depending on discharging rate used) is convenient. In this way, the total time of charge process increases but the cycle life and the effective capacity of the battery are not reduced. Also, this step simplifies considerably the design of accurate fast-charge end methods (the battery charge state in fast-charge starting is always known).

c) Discharged battery: Fast-charge in this zone can result in permanent damage if battery is fully discharged.

Thus, the battery must be charged with a low current (C/10) until battery voltage increases to 1.25 V/cell. Then, the fast-charge can take place. Due to battery powered devices switching off before the battery being full-discharged, battery voltage usually increases to 1.25 V/cell when charging process is started. However, if the battery is fully discharged or overdischarged its voltage increases more slowly.

IV. FAST-CHARGE END METHOD

In NiCd and NiMH batteries, internal pressure and temperature increase quickly during the overcharge (after the battery reaches full charge). Thus, fast-charge end must be determined accurately and reliably to avoid any damage to the battery. Due to testing cell pressure means that a sensor has to be placed in the cell, the use of this parameter as an outward expression of cell state is ruled out. Therefore, only temperature and voltage sensing methods are employed to determine the end of fast-charge. Moreover, a total-charging- time termination can be used as a safety provision.

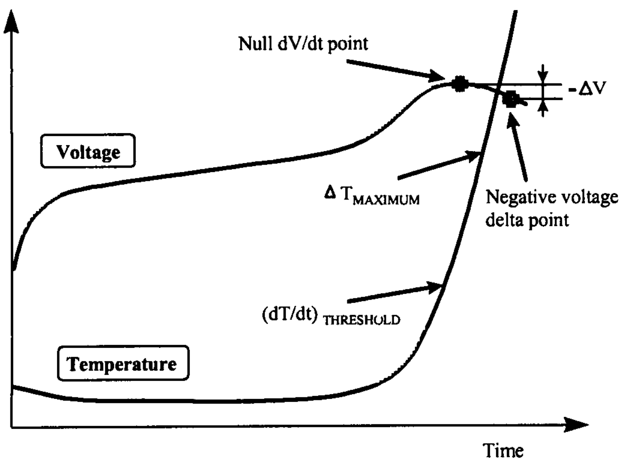

Fig. 7. Different fast-charge end methods.

Different methods have so far been proposed [5] (see Fig. 7) but they have not resulted enough accurate or practical.

<u>Disadvantages of temperature sensing methods</u> ($T_{MAXIMUM}$, $dT/dt_{THRESHOLD}$): A thermistor must be placed inside battery pack. Battery temperature evolution depends on charge rate and on battery size and configuration. Battery may be undercharged at high ambient temperature and damaged at low ambient temperature. At high charge rates, battery temperature is modified slower than battery pressure and a safety charge can not be guaranteed.

<u>Disadvantages of traditional voltage sensing methods</u>: Battery receive marginal overcharge by the time fast-charge stops: "$-\Delta V$", "$dV/dt = 0$". A very accurate voltage measurement is required (in order to avoid problems with NiMH batteries) and a complex calculation process is necessary: "$dV/dt_{MAXIMUM}$".

<u>New fast-charge end method</u>: In order to maximize the cycle-life of the battery and to simplify the implementation of fast-chargers, a new fast-charge end method is proposed [6]. This method is based on a simple and easily implemented algorithm (see Fig. 8.a.). Steps are the following:

1°) Calculation is disabled until battery voltage reaches 1.4 V/cell in order to avoid false estimates.

When a charging current is applied to a discharged cell, the cell voltage increases suddenly. Thus, calculating from the beginning of fast-charging could lead to false conclusions. However, when battery voltage reaches 1.4 V/cell, charging process becomes stable and problems disappear.

2°) From this moment, the time needed for each successive 15 mV/cell increase is measured. As Fig. 8.b. shows, three zones can be established:

ZONE 1: Cell voltage rises at a slower rate as the cell accepts the charge. Thus, measured times increase: t1<t2<t3.

ZONE 2: When the cell is near full charge there is a change in voltage slope. Cell voltage rises at a much faster rate and measured times decrease: t3>t4>t5>t6>t7

ZONE 3: After voltage slope peaks, measured times increase again: t7<t8<t9

3°) Fast-charge current is switched off by detecting the transition from zone 2 to zone 3.

Due to voltage slope peaking just before the peak in battery voltage, fast-charge is ended before battery begins overcharging. In consequence, problems associated to overcharging are avoided.

Another advantages of using this method instead of traditional temperature and voltage sensing methods are:

_ It is compatible with battery packs that do not include a temperature sensor; also, there are no problems with external non-battery-related thermal effects.

_ Calculation needed to determine the correct end point is extremely simple and a very accurate voltage measurement is not necessary.

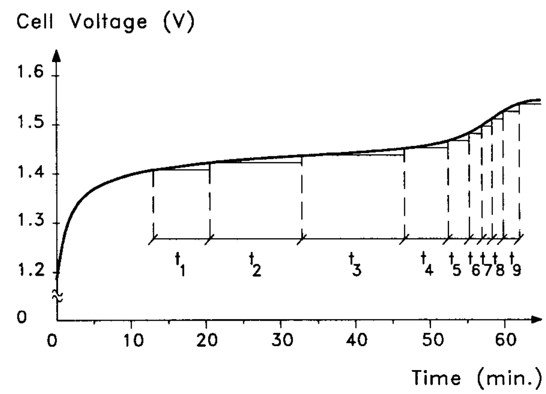

Fig. 8.a. Fast-charge end calculation method

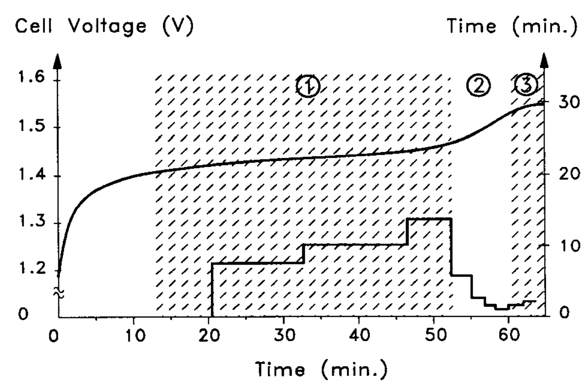

Fig. 8.b. Transition from zone 2 to zone 3 in above curves shows the end of fast-charge.

Fig.8. New algorithm to determine the end of fast-charge.

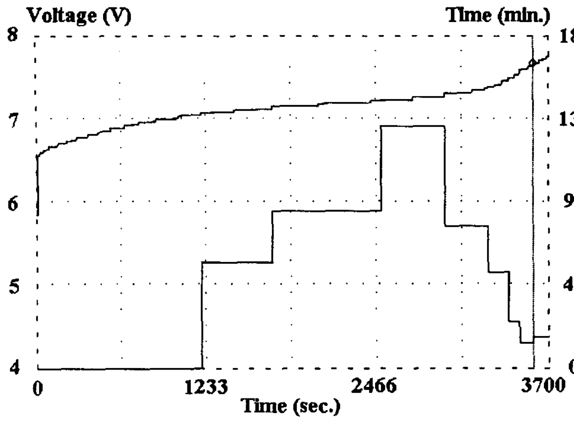

Fig. 9. Detection of fast-charge ending in a 6V NiCd battery that is being charged at a "C" rate.

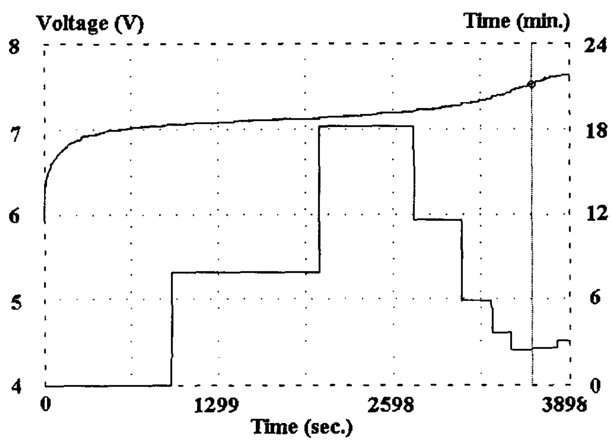

Fig. 10. Detection of fast-charge ending in a 6V NiMH battery that is being charged at a "C" rate.

Fig. 9 and Fig. 10 show some results obtained with the proposed method.

V. IMPLEMENTATION OF FAST-CHARGE METHOD

In order to implement the fast-charge method proposed in this paper, all possible fast-charger designs must include the following stages (see Fig. 11):

a) Power stages

The structure can be very simple; for example, a robust structure with two bipolar or MOS transistors (under any linear or switched mode of operation) that control charging/discharging processes.

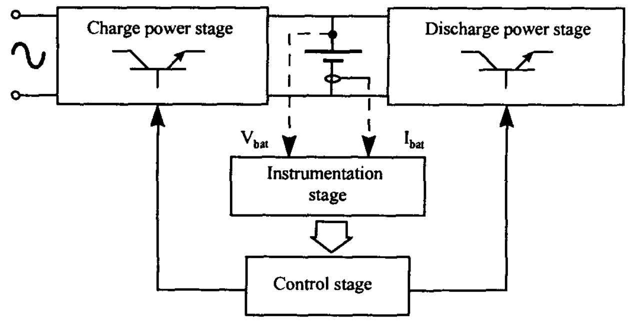

Fig. 11. Block diagram of fast-charger.

It should be pointed out that "fast-charge" means to apply a "C" or a "2C" charge rate to NiCd batteries but only a "C" charge rate to NiMH batteries. Tests show that the efficiency of charging process decreases considerably if higher rates are used [7]. Thus, battery pressure and temperature increase to dangerous values before battery reaches full-charge. (Note: A fast-charge process is considered efficient and safety if battery effective capacity increases above 90 % of nominal capacity value before cell pressure and temperature increasing quickly.)

Fig. 12 shows the evolution of different parameters in a 6V NiCd battery during a "4C" charge at 23°C of ambient temperature. As it can be seen, battery temperature increases as soon as charging starts: due to high ohmic losses generating heat, the endothermic nature of electrochemical charging reaction is cancelled. Thus, charging a NiCd battery in less than half an hour at 23°C becomes problematic.

If ambient temperature is higher than 25°C or lower than 20°C, the energy efficiency of the "4C" charging process is always below 80% and the term "charge acceptance" is also very low. The main conclusion is the following: a NiCd battery can not be fully charged on these operating conditions without a serious risk of damage.

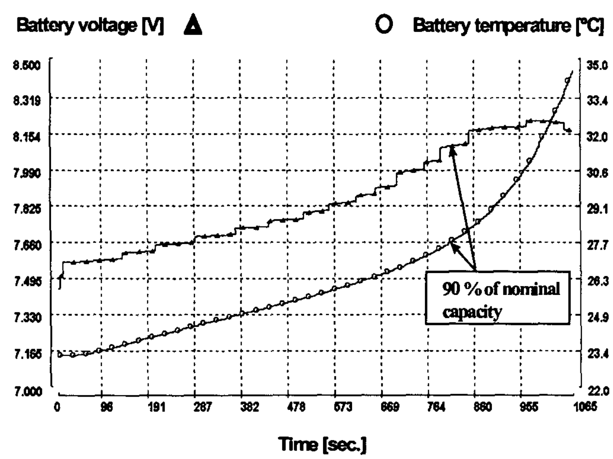

Fig. 12. Voltage and temperature evolution in a 6V NiCd battery during a "4C" charging at 23°C of ambient temperature.

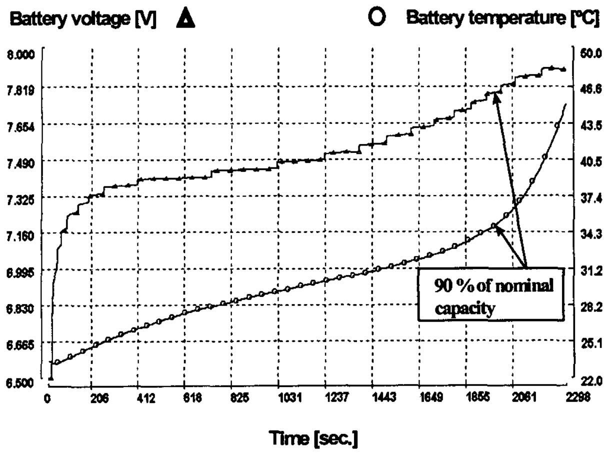

Fig. 13. Voltage and temperature evolution in a 6V NiMH battery during a "2C" charging at 23ºC of ambient temperature.

Fig. 13 shows the evolution of different parameters in a 6V NiMH battery during a "2C" charge a 23ºC of ambient temperature. The heavy increase of battery temperature from fast-charge starting, places the final battery temperature (when Ceffective ≅ 90%) about 35ºC. Therefore, if battery is repetitively charged on these conditions, battery cycle-life could be reduced.

If the ambient temperature is higher or lower than standard temperature (23ºC) the efficiency of charging process decreases. Thus, an effective ultra-fast charge (in less than one hour) without excessive gassing or heating is not possible.

Moreover, test results show that the use of:

- Pulsed current (see Fig. 14.a)
- The ReFLEX® method [8] (see Fig. 14.b). A pulsed current with high-current, short time discharging pulses.

do not improve enough the efficiency of charging process in both NiCd and NiMH batteries.

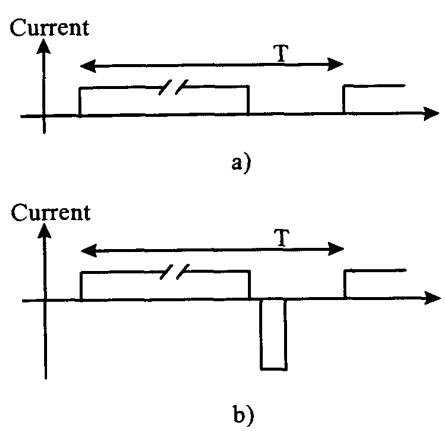

Fig.14. a) Pulsed current b) ReFLEX® method.

Thus, any type of charging current (constant current, pulsed current or the ReFLEX® method) can be chosen: a constant charge current would be the easiest solution.

A regulated charge current is necessary to maintain a continuous charge-voltage characteristic (this is essential to determine correctly the end of fast-charge). Moreover, a regulated current reduces the charge time and guarantees a safe fast-charge.

The discharge current must be also regulated to determine rightly the battery charge state, and to minimize full discharge time when the battery is initially half-charged (a "C" rate allow us to reduce the necessary discharging time).

As it can be seen in Fig. 9, 10, 12 and 13, battery voltage increases quickly above nominal voltage (1.2 V/cell) during fast-charging process. If charge rate increases, battery voltage during charging process increases also. This fact must be noted in order to design the right output parameters of charge power stage.

b) Instrumentation stage

Current measurement can be made by means of a series shunt. Due to obtained values can be positive or negative values (depending on type of process: charge or discharge) a previous adaptation to the right range is necessary: a simple rectifier-amplifier block becomes sufficient.

Battery voltage can be sensed through an amplifier block. Later, the measurement must be filtered (only an R-C filter) to limit the effect of voltage jumps caused by battery and/or external noise. (The fast-charge end method proposed in this paper avoids the necessity of making averages with voltage values.)

c) Control stage

Any inexpensive microprocessor can be used to control all charging process.

In portable applications, batteries with different capacities are used. Thus, the microprocessor must know the "C" parameter to select the right charge/discharge current values. One of possible solutions is the following:

Two digital inputs allow us to choose one of following capacities: 0.6 Ah, 0.9 Ah, 1.2 Ah or 2 Ah. With these four typical values a wide range of capacities can be charged in one hour or less. For example, the 800-1000 mAh range can be covered with a fixed 900 mAh charge current.

Moreover, if all key voltage values are memorized in volts per cell (V/cell) the fast-charger can be used independently of nominal battery voltage (only different resistors in the amplifier block that senses battery voltage would be necessary).

Finally, the block diagram proposed (one of possible solutions) to the fast-charger is shown in Fig. 15. As it can be seen, an effective (Fig. 16 and Fig. 17 show some experimental results obtained) and universal fast-charger can be implemented with few and inexpensive components.

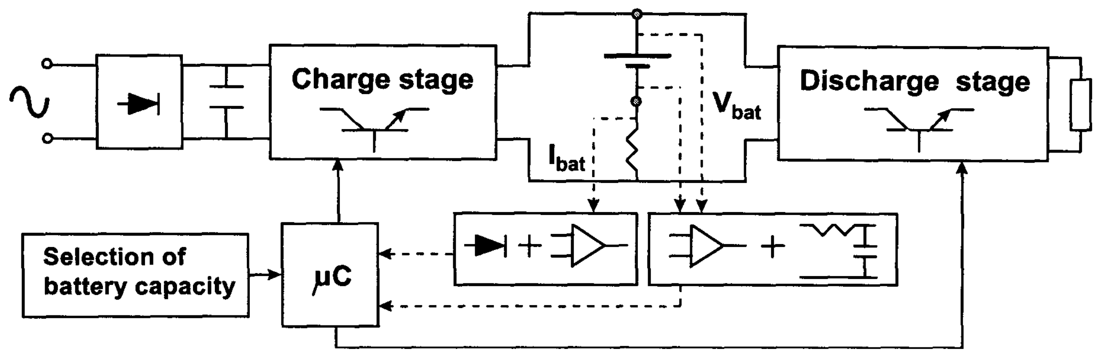

Fig. 15. Proposed structure (one of possible solutions) for the universal NiCd/NiMH fast-charger.

VI. CONCLUSIONS

The fast-charge method proposed in this paper detects deteriorated batteries, optimizes the charging time and guarantees a safe fast-charge without negative effects on battery life. This method is not dependent on the kind of charge and it is valid for both NiCd and NiMH batteries. Due to this method can be easily implemented, effective and universal battery fast-chargers can be obtained by using few and inexpensive components.

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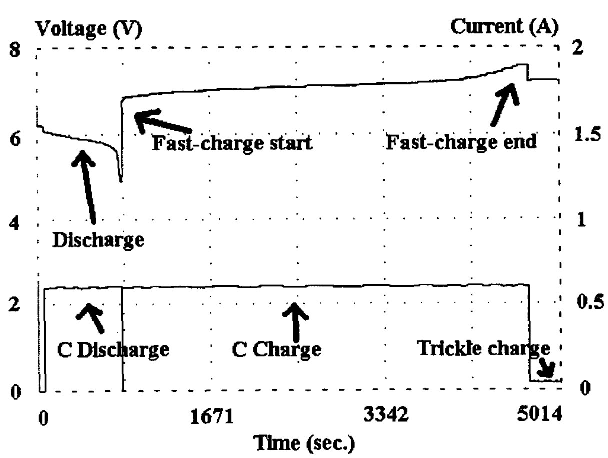

Fig. 16. Current and voltage evolution in a 6V, 0.6 Ah NiCd battery initially half-charged.

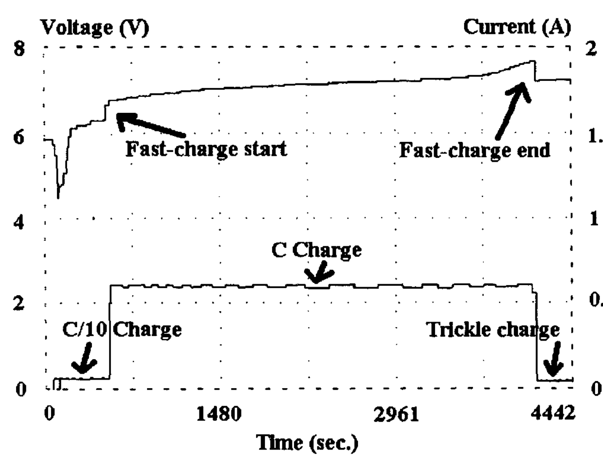

Fig.17. Current and voltage evolution in a 6V, 0.6 Ah NiCd battery initially full-discharged.