A Novel Universal Battery Charger for NiCd, NiMH, Li-Ion and Li-Polymer

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Abstract

A universal monolithic battery charger is presented, capable of automatically detecting the number and type of battery cells, NiCd, NiMH, Li-Ion and Li-Polymer. Different charging modes are supported from constant-current voltage-limited to constant-voltage current-limited with a wide range of charging rates, current or voltage limitations. A novel control using continuous and switched loops regulates the current and voltage concurrently during the various phases of the charging process. In addition, various end-of-charge detections are available, namely the detection of residual charging current for Lithium batteries, peak voltage for Nickel batteries, and safety detections including under and over voltage and temperature, and time-out detection.

The charger IC is implemented in a 5V, 0.5μm triple-metal standard CMOS process, requiring 8 pins and a total silicon area of 3mm^2. Three external resistors and a charging transistor complete the charger.

1. Introduction

As portability of electrical appliances becomes more widespread, portable power management systems, such as battery chargers, are finding their way into most battery-operated devices. Today's portable appliances range from simple applications such as toys and pocket lights to highly sophisticated appliances including mobile telephones and PDAs. These enormous differences in applications are also highlighted by the number and type of batteries used by these devices. Such diversification results in a wide range of demands on battery chargers. Nevertheless, all appliances place some basic but equally important demands on their battery charger, namely minimum charge-time, reliability, size, weight and cost. These are considered the five golden rules in the integration of battery chargers into portable applications.

The customer expects batteries to be charged fast but reliably in order to avoid damaging the battery or reduce its lifetime. These requirements call for efficient algorithms that optimise the charging process while preventing the charge current and voltage as well as battery temperature and charging time to exceed the narrowly allowed ranges of today's batteries. Some of these operating ranges are summarized in [1].

In order to accommodate these stringent requirements, today's battery chargers must be equipped with extensive charging flows with multiple control loops and a wide range of safety detection mechanisms and end-of-charge criteria. This makes battery chargers ideal candidates to be integrated into mixed-signal analogue-digital monolithic circuits. This trend, although seldom published, has been observed recently [2], [3], [4].

This paper describes an extremely small and versatile battery charger capable of supporting battery chemistries of NiCd, NiMH, Li-Ion and Li-Polymer. The charger is fully integrated except for the power PMOS transistor, two resistors to set the type of battery chemistry and a sense resistor to regulate the charge current, as shown in Fig.1. An additional LED and resistor may be added to indicate the charging state.

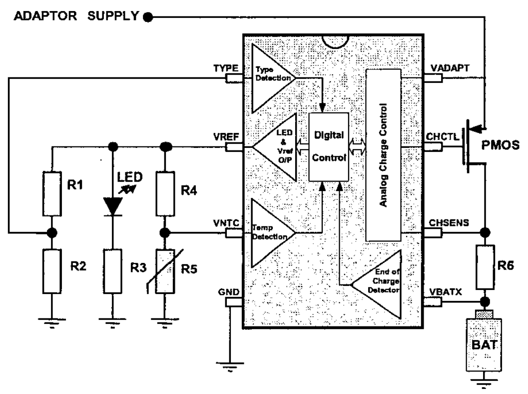

Figure 1. Battery Charger typical application

Two algorithms, described in section 2, define the charge flow of the four battery chemistries. The charging process is controlled by two novel loops that regulate the charging current and the battery voltage. These loops are described in section 3. End-of-charge detection is equally critical for a successful charging process and is presented in section 4. A die photograph and measurement results are presented and discussed in section 5 with conclusions drawn in section 6.

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2. Charge flow

The charge flow for batteries is strongly dependent on the chemistry of the battery. Although the charge flow differs significantly between the Nickel and Lithium based batteries, the flow for NiCd and NiMH batteries may be the same. Similarly one flow may be applied to Li-Ion and Li-Polymer batteries.

Fig.2 illustrates the flow used to charge Nickel batteries. After an initial Power-On Reset, if the battery voltage and temperature is not too low, the charger preconditions the battery with a fast charge during 3% of the time-out period. Subsequently, the number of cells is detected, the maximum allowed voltage is calculated and the time out period is set. Fast charge is initiated until the battery voltage starts to drop or time-out is reached. Top-off charging completes the charging process. A trickle current remains to keep the battery fully charged. Charging is done at constant current while the maximum voltage is not reached. During the whole process, the battery voltage and temperature are monitored and, if necessary, the charging process interrupted forcing the charger into initial protection, inhibit or cut-off modes.

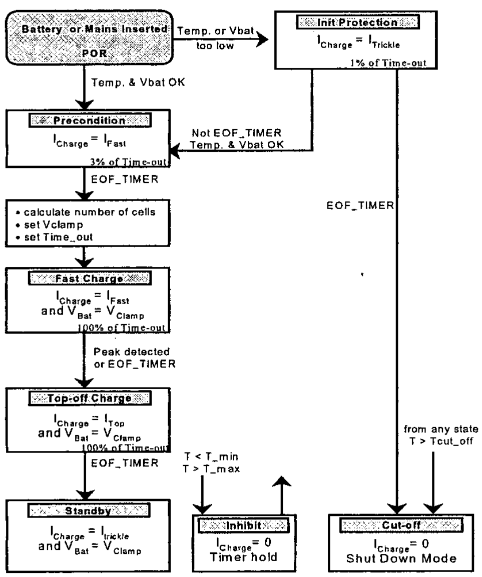

Figure 2. Charge flow for NiCd and NiMH

Fig.3 illustrates the flow used to charge Lithium batteries. Again, after an initial POR, time-out is set and fast charge follows with constant current while the battery voltage remains below its maximum level. When the maximum voltage is reached, the current is reduced until it reaches a minimum value, beyond which charging is terminated. Similarly to the Nickel batteries, the battery voltage and temperature are frequently monitored and, if necessary, the process is interrupted forcing the charger into initial protection, inhibit or cut-off modes.

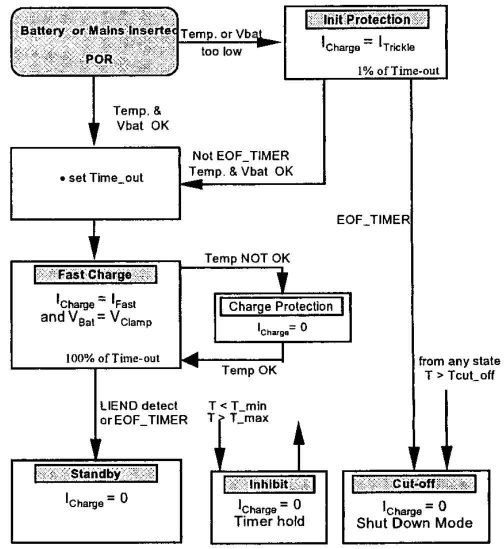

Figure 3. Charge flow for Li-Ion and Li-Polymer

3. Novel current and voltage control loops

Current and voltage control is the most important although the most difficult aspect of any efficient battery charger. The novel approach permits constant-current and constant-voltage charging by allowing both loops to operate concurrently where one loop smoothly takes over the control from the other without interrupting or destabilizing the charge process. Each of these control loops is presented separately and subsequently integrated as one.

3.1. Current control loop

The current control loop consists of a differential amplifier sensing the current flowing through a resistor in series with the battery, as shown in Fig.4. The difference amplifier drives the gate of an external power PMOS which in turn forces the charge current through the sense resistor into the battery. The charge current is defined by an internal voltage of 110mV and by the external sense resistor, R_{SENSE}.

$$I_{FAST\text{-}CHARGE} = \frac{110mV}{R_{SENSE}}$$

A dominant pole in the gate of the PMOS transistor, τ, defines the bandwidth and the stability of the loop. Assuming that the battery is an ideal voltage source, the bandwidth and open loop gain are defined by the amplifier gain, $A(s) = Ao/(1+j\omega.\tau)$, the transconductance of the PMOS, Gm, and the sense resistor.

Consequently,

$$GAIN_{Open\ Loop} = G_m \cdot R_{SENSE} \cdot A(s)$$
$$= G_m \cdot R_{SENSE} \cdot \frac{Ao}{(1+j\omega.\tau)}$$

In this design, the unity gain-bandwidth of this loop is approximately 100kHz.

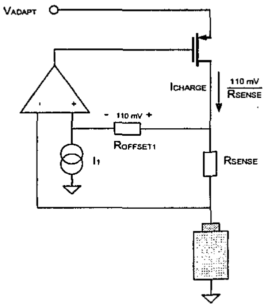

Figure 4. Charge current control loop

3.2. Voltage control loop

While charging the battery, both its charge and voltage increase. The voltage however is limited by a chemistry dependent maximum. The purpose of the control loop is to maintain maximal charging current while obeying the voltage limitation. This is achieved with a voltage control in parallel with the current control loop. The dimensioning of this loop has two constraints:

1. A very high gain in order to limit the battery voltage with the precision of a few milli-volts.
2. A gain-bandwidth much smaller than that of the current control loop in order to avoid instability when both loops are active simultaneously.

A switched-sampled feedback loop is an ideal candidate to achieve a very small unity gain-bandwidth while maintaining a very large gain. Fig.5 illustrates the implementation of this loop. The maximum battery voltage, V_{BATMAX}, is defined by the external resistors R1 and R2 in Fig.1 and applied to the loop via a 4-bit DAC. While V_{BAT} is lower than V_{BATMAX}, the output of the comparator selects V_{UP} and the capacitor C1 charges C2 at every clock cycle with a time constant:

$$\tau_V = C2/C1.T_{CLK}$$

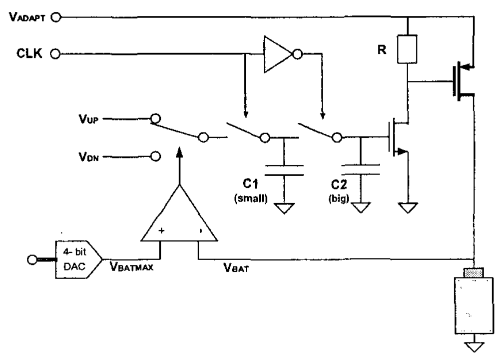

Figure 5. Switched-sampled voltage control loop

Because C1 is approximately 100 times smaller than C2, the time constant is very long achieving a unity gain bandwidth of approximately 100Hz. When V_{BAT} exceeds V_{BATMAX}, the output of the comparator selects V_{DOWN} and C1 discharges C2 with the same time constant. C2 drives a current source which in turn drives the gate of the power PMOS. The PMOS drives the charge current into the battery. The DC gain of the loop is virtually infinite as this switched-sampled system approximates an ideal integrator.

3.3. Combined current-voltage control loop

As mentioned above, both loops must operate concurrently. Fig.6 shows the integration of both loops. The current control loop remains unaltered as presented above, while the voltage control loop is slightly altered. The current source, I_2, in the voltage control loop flows through a resistor, $R_{OFFSET2}$, to create a voltage difference at the input of amplifier. This voltage "fools" the amplifier to think that it is sensing too much voltage across the sense resistor with the consequence that the amplifier will reduce the current flowing through R_{SENSE}.

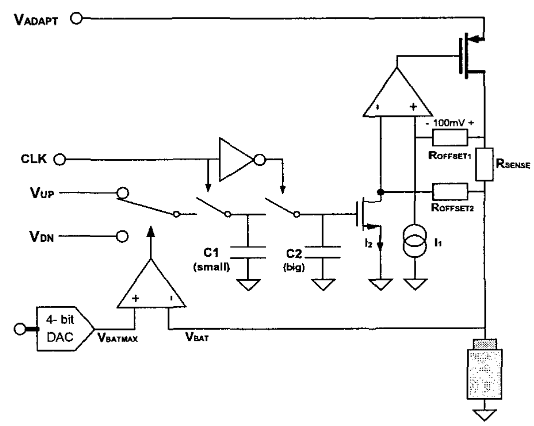

Figure 6. Current-Voltage charging control loop

Fig.7 shows a simulation result of the charge current and voltage on a Li-Ion battery. After an initial pre-conditioning (not shown) the charge current is constant until V_{BAT} approaches V_{BATMAX} at approximately 0.82 hours. Beyond this point the current reduces exponentially until it reaches a minimum charge current of 5.5mA at approximately 1.9 hours. At this point, the battery is considered full and charging is terminated.

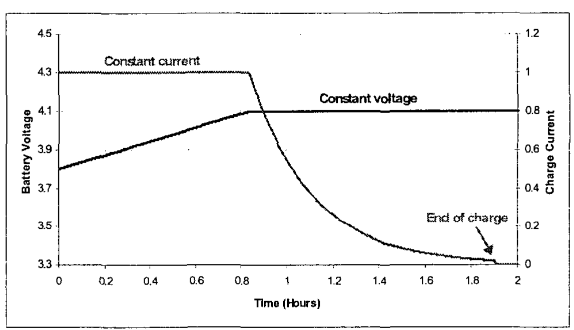

Figure 7. Simulation of Li-ion battery charging

4. End-of-charge detection

The end-of-charge mechanism and criteria depends on the chemistry of the battery. As indicated in Fig.2 and Fig.3, the criteria are very different between Nickel based and Lithium based batteries. For Nickel batteries, a high precision ADC is used to detect the peak voltage with a precision of 2mV or better. The voltage is measured multiple times and running averages are done. When the battery voltage starts to drop, the charger switches to top-off mode. In top-off mode a small current of 5.5mA is used to complete the charging process. Charging of Lithium batteries on the other hand, switches from constant current to constant voltage when the battery reaches a maximum voltage level. As described above, the voltage control loop reduces the charging current until the charging current reaches 5.5mA. At this point charging is terminated. Both battery types require time-out safety protection. Charging is terminated when the time-out is reached or when the battery temperature exceeds 60°C.

5. Measurement results

Fig.8 shows a microphotograph of the battery charger.

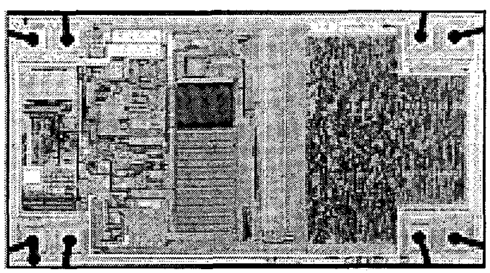

Figure 8. Die microphotograph

Fig.9 shows the charging of two NiCd batteries. After the initial preconditioning, charging is done at constant current until the battery voltage drops a few milli-volts around 3.6V. The current then switches to top-off, followed by trickle current for the duration of the time-out and finally turns off at approximately 3.5 hours.

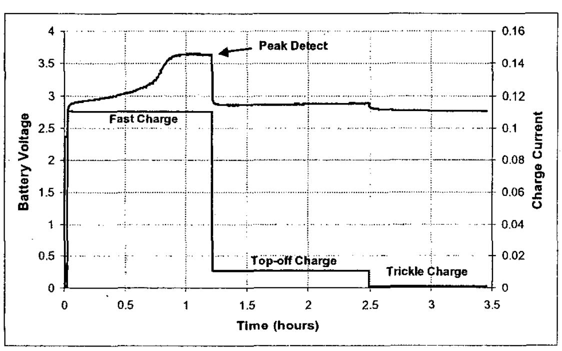

Figure 9. Charging Voltage and Current of NiCd

A zoom-in of the end-of-charge of a Li-ion battery at low charge current is shown in Fig.10. While the battery voltage is below 4.2V, charging is done with a constant current. Once 4.2V is reached, the current reduces exponentially until it reaches 5.5mA at which point charging is terminated. The smooth takeover and stability of the loops is clearly seen at the transitions between current and voltage control.

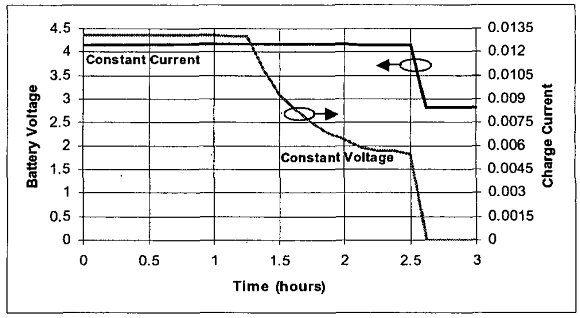

Figure 10. End of Charging I-V curves of Li-Ion

6. Summary

A very compact monolithic battery charger for NiCd, NiMH, Li-Ion and Li-Polymer was presented. A novel voltage-and-current control loop is demonstrated, resulting in a very efficient charging flow with a very accurate end-of-charge mechanism Measurement results show the accuracy and stability of the control loops. The battery charger is implemented in a triple metal 0.5μm standard CMOS process capable of supporting battery voltages up to 5.5V. The IC measures 3 mm^2. The battery charger is fully integrated, requiring only one external PMOS power device and 3 external resistors.

7. Acknowledgements

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