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An Ultra-Compact and Efficient Li-ion Battery Charger Circuit for Biomedical Applications

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Abstract—This paper describes an ultra-compact analog lithium-ion (Li-ion) battery charger for wirelessly powered implantable medical devices. The charger presented here takes advantage of the tanh output current profile of an operational transconductance amplifier (OTA) to smoothly transition between constant current (CC) and constant voltage (CV) charging regimes without the need for additional area- and power-consuming control circuitry. The proposed design eliminates the need for sense resistors in either the charging path or control loop by utilizing a current comparator to detect end-of-charge. The power management chip was fabricated in an AMI 0.5 µm CMOS process, consuming 0.15 mm² of area. This figure represents an order of magnitude reduction in area from previous designs. An initial proof-of-concept design achieved 75% power efficiency and charging voltage accuracy of 99.8% relative to the target 4.2 V.

I. INTRODUCTION

In this paper we present a novel, all-analog Li-ion battery charging circuit intended for operation in a wirelessly rechargeable medical implant. Lithium-ion (Li-ion) batteries are a popular choice for implants due to their ability to provide relatively high performance in both energy and power densities, of 158 Wh/Kg and 1300 W/Kg, respectively [1].

Previous Li-ion charger designs, however, often suffer from two significant problems. First, unnecessarily complex control circuitry [2], [3] is often employed to manage battery charging at the expense of circuit area and power consumption. Additionally, many circuits require a sense resistor in order to detect end-of-charge [4], [5]. This latter point is especially problematic for battery longevity due to the challenges of precision on-chip resistor fabrication, as undercharging the battery can drastically reduce its capacity [6].

The circuit presented here addresses both of these issues. By utilizing the tanh output current profile of an OTA, the circuit naturally transitions between constant current (CC) and constant voltage (CV) charging regions without the need for complex control circuitry. As a result, this circuit is an order of magnitude smaller than previous designs, while achieving an efficiency of greater than 75% in this proof-of-concept design. This design does not require sense resistors to determine end-of-charge, as our control circuitry operates in the current domain. Upon startup the device is capable of monitoring battery voltage levels and providing charging current during periods of power coupling, as in the case of a wireless power link. This design represents a simple, analog, power- and area-efficient version of previous, more complicated and power-hungry designs.

II. BACKGROUND

Battery longevity is a primary concern in implanted medical devices due to the significant cost and risk of resurgery. Battery longevity, in turn, is highly sensitive to the accuracy of the final charging voltage on the battery. Previous reports indicate that undercharging a Li-ion battery by 1.2% of the 4.2 V target value results in a 9% reduction in capacity [6]. Conversely if the Li-ion battery is overcharged, dangerous thermal runaway can occur. During discharge, deeply discharging the Li-ion battery below 3 V can permanently reduce the cell’s capacity. [7]
The charging profile of a Li-ion battery can be divided into four distinct regions as illustrated by Fig. 1: trickle-charge, constant current, constant voltage, and end-of-charge. Trickle charging is required only if the battery is deeply discharged (voltage is less than 3 V). During trickle-charge, the battery is charged with a small amount of current, typically no more than 0.1 times the rated capacity of the battery, or (0.1C) [6]. C represents the battery capacity expressed in terms of ampere-hours (Ah). Charging currents greater than 0.1C may be hazardous as the battery has a high internal impedance at these low voltages. Above 3.0 V, the battery may be charged at higher currents; this is the constant current region. As the battery voltage approaches 4.2 V, the charging profile enters the constant voltage region. In this region, the charging current should be progressively decreased as the battery voltage approaches 4.2 V. The constant voltage region is required in order to compensate for internal battery voltage drop; as the charging current decreases, the battery output voltage also decreases due to lower voltage drop across its internal impedance. Charging current should be decreased until a certain threshold is met, which is usually about 2% of the rated battery capacity [6]. Once this charging current is reached, the charger enters the end-of-charge region.

III. CIRCUIT DESCRIPTION

The simplified block diagram of our circuit topology is illustrated in Fig. 2. The circuit consists of four major blocks: a 4.2 V reference, OTA, current gain stage, and end-of-charge detector. The 4.2 V reference was designed using a bandgap reference followed by a non-inverting op-amp to produce a stable output voltage over a range of temperatures. This design is intended to be used in an implantable device, so the expected temperature variation is limited. Nevertheless, the design presented here is robust enough for charging applications where temperature varies significantly.

The OTA compares the battery voltage to the 4.2 V bandgap reference in order to determine the charging current. For battery voltages less than approximately 4.1 V, the OTA output is saturated. As the battery voltage reaches 4.1 V, the difference in input terminal voltages becomes small enough that the OTA enters the linear region and the output current begins to decrease. The OTA was designed to operate in sub-threshold to save power and also to reduce its linear range. In order to account for the trickle-charge region the OTA topology was slightly modified. Fig. 3 shows the schematic of the OTA with the trickle-charge modification, which is the addition of transistors M1 and M2. If the battery voltage is less than 3 V, the Trickle Charge Flag is low enabling M1. In this case, transistor M2 conducts some current, which reduces the OTA output via current stealing of the bias current. The reduction in charging current during trickle-charge is proportional to the ratio of W/L of M2 to the W/L of M6. Once the battery voltage crosses the 3 V threshold, the Trickle Charge Flag goes high disabling the current path through M1 and M2. As a result, the current output of the OTA is increased to its maximum value.

The current gain stage is simply composed of current mirrors to increase the current output of the OTA, from a few hundred nano-amps to whatever charging current is required in the design. In our application, we were constrained to 10 mW of power consumption so the charging current was limited to 2 mA. All current mirrors in this design including those in the OTA are of the Wilson Current Mirror type in order to reduce channel length modulation error.

Figure 2. Simplified battery charger block diagram

Figure 3. OTA and trickle-charge circuit schematic
The end-of-charge is detected by comparing the output of the OTA to a reference current; this reference current is proportional to the reference current used to bias the OTA in order to minimize error. Fig. 4(a) shows the schematic of the current comparator [8]. The End-of-charge Output signal goes low when the OTA output is higher than $I_{REF}$, otherwise it equals $V_{DD}$. When the End-of-charge Output signal is high, the last stage of current mirrors in the current gain block is disabled, reducing the charge current to zero.

In order to determine when the battery reaches the 3 V threshold for the trickle-charge region, we designed a simple low-power detector circuit, shown in Fig. 4(b). This circuit is used to detect critically low battery voltage, in order to prevent any damage to the battery due to deep discharge; when critical threshold is reached, the detector circuit cuts off power to the load. As the battery voltage decreases, the voltage at the node $V_x$ between transistors M2 and M3 decreases. The relationship between the voltage at this node and the battery is linear, so the current flowing through transistor M5 reduces quadratically when M2 and M3 are in saturation and exponentially when they enter sub-threshold. The current output of M5 goes through another current comparator similar to the one shown in Fig. 4(a), in order to detect when the battery voltage falls below 3 V. Transistors M1 through M4 were designed with large widths and lengths in order to minimize process variation. This strategy also minimizes power consumption such that the threshold detector may be run off the battery voltage directly for constant protection against deep discharge. The designed threshold detector consumes only 3 µW when the battery voltage is approximately equal to 3.7 V.

IV. RESULTS

The battery management chip was fabricated in an AMI 0.5 µm CMOS process, consuming 0.15 mm² of chip area. Fig. 5 shows the die micrograph of the test chip.

Fig. 6(a) shows the measured results of the battery management IC charging a 25 mAh battery during trickle-charge and a portion of the constant current region. The battery was charged with 1.5 mA and 2.2 mA during trickle-charge and constant current, respectively. Although trickle-charge is not strictly needed in this case since the constant current charging rate is already less than 0.1C for the 25 mAh battery, we included it here to demonstrate circuit functionality. Further, while the proof of concept circuit was limited to about 2 mA maximum charging current, the design can easily be modified if a higher charging current is required by adjusting the current gain in the last stage of current mirrors.

Fig. 6(b) shows the remaining regions of the charging profile: constant current, constant voltage, and end-of-charge. The constant voltage region begins when the battery reaches approximately 4.1 V. The transition between constant current and constant voltage is continuous since the control loop is based on a simple tanh function. According to Fig. 6(b) the charging current decreases as the battery voltage goes from 4.1 V to 4.2 V, reaching the end of charge when the current is approximately 0.26 mA. At the end of charge the battery voltage is 4.21 V, providing an accuracy of 99.8%. In this test with a 25 mAh battery the total charging time was about 800 minutes. This long charging time is purely due to the maximum charge current of 0.1C, which was determined by the power consumption requirement of 10 mW. If the current mirrors are adjusted to provide 1C during constant current, a charging time of a few hours can be attained with this 25 mAh cell.

We obtained a power efficiency of approximately 75% during constant current mode. The limiting factor in efficiency is the fact that the test circuit was designed for a 5 V supply. One can easily design for a lower supply voltage, increasing the overall power efficiency of the system. By simply reducing the supply voltage from 5 V to 4.5 V, the efficiency of this circuit can be increased to approximately 83%. In our chip we were not able to reduce the supply voltage to 4.5 V because of the Wilson current mirrors in the OTA. Nevertheless, if these mirrors are replaced with current mirrors that require less voltage headroom, the supply voltage can be easily reduced to 4.5 V.

Table I compares this design with previous Li-ion charger circuits in the literature. While the design presented here has yet to be optimized for supply voltage, it nevertheless achieves competitive power efficiency while consuming at least an order of magnitude less area than other designs.
Most of the literature uses the maximum power efficiency during charging as a figure of merit for battery chargers. However, power efficiency is not constant during a charge, as the battery voltage varies from 3 V to 4.2 V. Rather, we believe a better figure of merit is the total energy delivered to the battery divided by the total energy consumed. Using this figure of merit, the design presented achieves energy efficiency close to 70%.

V. CONCLUSION

A novel design for a Li-ion battery charger that simplifies the control circuit by using the tanh output current profile of an OTA has been presented and experimentally verified. This design does not require the use of sense resistors to determine the end-of-charge point, reducing layout area and charging errors due to resistor variability. The layout area required for this chip is more than an order of magnitude smaller than previous designs, as Table I illustrates. Without optimization, the proof of concept design achieved a power efficiency of 75%, which is comparable to previous designs. This efficiency can be further improved if one designs the circuit to operate with a lower supply voltage or with an adaptive supply that varies with battery voltage. If the supply voltage is reduced to 4.5 V, a power efficiency close to 83% can be obtained. To our knowledge, the circuit presented here achieves excellent energy efficiency with potential for further improvement, and consumes the smallest layout area of any design thus far.

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REFERENCES