A new Li-ion battery charger with charge mode selection based on 0.18 um CMOS for phone applications

Fouad Farah1, Mustapha El Alaoui1, Abdellali Elboutahiri1, Mounir Ouremchi1, Karim El Khadiri2, Ahmed Tahiri2, Hassan Qjidaa1

1,2,3,4,7Department of Physics FSDM, Sidi Mohamed Ben Abbellah University, Fez, Morocco
5,6Laboratory of Computer Science and Interdisciplinary Physics, ENS, Sidi Mohamed Ben Abdellah University, Fez, Morocco

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ABSTRACT

A new architecture of Li-Ion battery charger with charge mode selection is presented in this work. To ensure high efficiency, good accuracy and complete protection mode, we propose an architecture based on variable current source, temperature detector and power control. To avoid the risk of damage, the Li-Ion batteries charging process must change between three modes of current (trickle current (TC), constant current (CC), and constant voltage (CV)) in order to charge the battery with degrading current. However, the interest of this study is to develop a fast battery charger with high accuracy that is able to switch between charging modes without reducing its power efficiency, and to guarantee a complete protection mode. The proposed charger circuit is designed to control the charging process in three modes using the charging mode selection. The obtained results show that the Li-ion batteries can be successfully charged in a short time without reducing their efficiency. The proposed charger is implemented in 180 nm CMOS technology with a maximum charging current equal to 1 A and a maximum battery voltage equal to 4.22 V, (with input range 2.7-4.5 V). The chip area is 1.5 mm² and the power efficiency is 90.09 %.

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Corresponding Author:
Fouad Farah
Department of Physics FSDM
Sidi Mohamed Ben Abbellah University
Fez, 30050, Morocco
Email: fouad.farah@usmba.ac.ma

1. INTRODUCTION

Currently, the batteries production has encountered a revolution regarding its design, especially after the appearance of lithium-ion batteries. These batteries present a favourable choice for several devices such as phones, EDAS and electric vehicles. This is due to many reasons: weight (Lithium-ion batteries are three times lighter than lead batteries for the same stored energy), high efficiency, the lithium batteries have a performance close to 100%, Life cycle over 1000 cycles, output voltage (ranges 2.5-4.2 V), environmental impact and cost of stored energy [1].

To this day, many Li-Ion battery charger architectures have been published in the literature using CMOS technology [2-14]. As already stated, with these high performances, li-ion battery chargers became the most used for mobile applications. Thereafter, there are two architectures of battery chargers, one based on the linear regulator and the other on the switching regulator. The battery charger is implemented with CMOS technology and is integrated in a System on Chip to reduce the effect of noise and ripple. The linear
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The architecture of the Li-Ion battery charger system consists mainly of two blocks: The charging block and the Power supply block. For the conventional Li-Ion battery chargers, the power supply block is an AC-DC converter, which is independent of load circuitry, usually the SC or LDO. The efficiency of the conventional Li-Ion battery charger is presented in (1) [20]:

$$\eta_1 \approx \frac{V_{BAT}I_{CH}}{V_{DD}\left(I_q + I_{CH}\right)} \approx \frac{V_{BAT}}{V_{DD}}$$ (1)

However, if we compare the quiescent current ($I_q$) and the charging current ($I_{CH}$), we can distinguish that $I_q$ is much smaller than $I_{CH}$. Consequently, the efficiency is equal to $V_{BAT}$, $V_{DD}$ ratio. The η1 is quite weak in the initial process ($V_{DD}$ constant), which represents a major disadvantage. However, the variable current source circuit shown in Figure 2 can produce an adaptive reference voltage in order to retain the charger at high power throughout the charging process. The energy efficiency of the variable current source battery charger is shown in (2), it is optimized using variable current source While $V_{DC}$ follows the $V_{BAT}$ with a fixed voltage. The proposed charger can also work in constant-voltage and constant-current modes for charging a Li-Ion battery [21, 22].

$$\eta_1 \approx \frac{V_{BAT}I_{CH}}{V_{DC}\left(I_q + I_{CH}\right)} \approx \frac{V_{BAT}}{V_{DC} + 0.3}$$ (2)

The dissipated power plays an important role in the performance of the battery charger. This power can be calculated by subtracting the power output and the input power is shown in (3):

$$P_{\text{diss}} = (P_{DC} - P_{BAT}) + P_q = (V_{DC} - V_{BAT}) \ast I_{CH} + P_q$$ (3)

3. ARCHITECTURE OF THE PROPOSED BATTERY CHARGER

3.1. The Proposed Charge Mode Selection

The charge mode selection is designed by a logic circuit, it is made by two analog comparators, logical ports such as NAND, OR, inverters and temperature detector circuit PTAT. First, the battery voltage is compared through comparators with the predefined references voltage ($V_L$, $V_H$), in order to generate three control signals ($V_{TC}$, $V_{CC}$ and $V_{CV}$); their main role is to provide currents ($I_{TC}$, $I_{LC}$ and $I_{CV}$) via the reference current generator as shown in Figure 3. $V_C$ represents the control signal that provides a charging current to each state of charge. The output of the port OR is used to stop the charge if the charging current is reduced to 0.05 C or if PTAT circuit detects 115 degrees. The charge mode-selection function is presented in Table 1.

$$P_{\text{diss}} = (P_{DC} - P_{BAT}) + P_q = (V_{DC} - V_{BAT}) \ast I_{CH} + P_q$$ (3)
3.2. Temperature detector PTAT

Generally, all the techniques used in literature focus on rapidity, efficiency and life cycle of the Li-Ion batteries during the charging process. However, the major missed safety factor is the risk that can occur because of temperature, i.e. transistors temperature reaches a level that can damage the entire circuit. Therefore, we proposed a temperature detector PTAT circuit shown in Figure 4 to control the charger temperature [23, 24].

![Figure 4. Schematic of the proposed temperature detector PTAT](image)

The proposed PTAT based on current mirror structure is designed to stop the charging in any mode of charging once the temperature reaches 115°C. The transistors M4 and M5 have a size ratio of 1: N, and for M1 and M2 the same size. The current through the transistors M4 and M5 is given by (4):

\[
I_D = 2\eta\mu C_ox \frac{W}{L} \exp \left[ \frac{V_{gs}-V_{th}}{\eta V_T} \right]
\]

(4)

where \( V_T \), \( V_{gs} \), and \( V_{th} \) represent the thermal voltage, gate–source voltage and threshold voltage respectively. \( W/L \) is the width and length ratio, \( C_ox \) represents the gate-oxide capacitance, \( \eta \) is the substrate factor and \( \mu \) is the carrier mobility. The PTAT voltage is the voltage over \( R_1 \) which can be copied to the output and is given by (5):

\[
\Delta V_{gs} = \frac{\eta K T}{q} \ln N
\]

(5)

3.3. Reference Current Generator

The reference current generator is represented in Figure 5. This circuit is composed of a current block and a voltage block.

a. Current block

This block is used to produce the CC charging mode reference currents and the charge end current. The amplifier OP, the resistor \( R_{REF} \) and the transistor M10 are used to generate a constant reference current \( I_{REF} \), which is given by:

\[
I_{REF} = \frac{V_{REF}}{R_{REF}}
\]

(6)
M1, M2, M3 and M4 represent the current mirror system in order to generate currents corresponding to each constant current ($I_{TC}$, $I_{LC}$ and $I_{OFF}$), which are proportional to $I_{REF}$ as follow (7-9):

$$I_{TC} = \left( \frac{W}{L} \right)_2 I_{REF}$$  \hspace{1cm} (7)

$$I_{LC} = \left( \frac{W}{L} \right)_3 I_{REF}$$  \hspace{1cm} (8)

$$I_{OFF} = \left( \frac{W}{L} \right)_4 I_{REF}$$  \hspace{1cm} (9)

b. Voltage block

The voltage block is used to produce the CV charge mode reference current. It is composed of current mirror (M5, M6) and a comparator, the charging current $I_{CV}$ is created as follows: As showing in Figure 5, when the battery voltage attains 4.2 V value, the current $I_{CV}$ is generated by the comparator in order to switch from $I_{LC}$ to $I_{OFF}$ (high level to low level). As already mentioned, each mode of charge has a corresponding current, which is generated by three transistors M9, M8 and M7 (controlled by $V_{TC}$, $V_{LC}$, $V_{CV}$).

![Figure 5. Schematic of reference current generator](image)

3.4. Charging current controller

The purpose of the operating of charge current controller show in Figure 6 is to provide a driving voltage $V_D$ of the current source to each charging mode. The output current $I_S$ is measured by the current sensor in order to be compared with the three charging currents ($I_{TC}$, $I_{LC}$ and $I_{CV}$) through the comparator M12-M15, the output voltage $V_D$ is changed with these input currents. In addition, it represents the lowest voltage level of the signal selector circuit (composed of the transistors M18 and M19).

As mentioned in section II, the stop procedure is activated by two method:

a. By the comparison of output current $I_S$ and reference current $I_{OFF}$:

- If $I_S > I_{OFF}$ so $V_{END}$ is at the low level, which implies that the current voltage $V_C$ is at the high level.
- If $I_S < I_{OFF}$ than $V_{END}$ is at the higher level, which implies that the current voltage $V_C$ is at the low level.

Knowing that the driving voltage $V_D$ is ordered by $V_C$, the current source is deactivated and the charging stops.
b. By the temperature detected PTAT circuit:

The temperature of the charger is monitored throughout the charging period by a temperature detector. A reference voltage $V_{TEP}$ equivalent to 115 degrees is compared with the voltage of the state. The charging can be stopped in any state of charging according to the temperature of the circuit.

![Figure 6. Schematic of charge current controller](image)

3.5. The proposed battery charger

The proposed charging circuit with all blocks: Charging mode controller, reference current generator, charging current controller, temperature detector (PTAT) and finally current sensor circuit is represented in Figure 7. For the current sensor, the $M_S$ transistor plays the role of charging current sensor, and the current source represented by the power transistor $M_P$ which is used as a current source variable in order to generate a charge current to each charging mode.

![Figure 7. Circuit diagram of the proposed battery charger](image)

4. RESULTS AND DISCUSSIONS

The proposed battery charger LDO-based is implemented in 180 nm CMOS TSMC technology. In order to study characteristics of our proposed charger, a testbench is showing in Figure 7 with an equivalent model of Li-ion battery. Based on the Li-ion battery model, the transient simulation of LDO-based battery charger is simulated with 2.7-4.5 V input voltage. The measurement results of our battery charger are shown in Figure 8, where the maximum current is respectively 280.5 mA and 1A for trickle current mode and constant current mode. On the other hand, the maximum voltage is respectively 2.9 V and 4.22 V for trickle current mode and constant voltage mode.
Figure 8. Simulation results of outputs the battery voltage $V_{bat}$ and the charging current $I_{chg}$, respectively.

Figure 9 presents the output voltages of the proposed charge mode selection. However, three signals $V_{TC}$, $V_{LC}$ and $V_{CV}$ are provided to control respectively trickle current, large current and constant voltage mode. As already mentioned in section 3, to have a complete protection system, it is necessary to integrate a temperature detector in order to protect the charger from any temperature damage. Figure 10 presents the simulation results of the proposed temperature detector PTAT. The charging process is done normally, once PTAT detects 115°C value the charging stops.

Figure 9. The outputs voltage of the proposed charge mode selection

Figure 10. The simulation results of the proposed temperature detector PTAT

The power conversion efficiency of the proposed battery charger LDO-based is presented in Figure 11. The maximum efficiency of our charger is higher than the stated architectures [2, 3, 25]. As expected, the obtained results are much better compared to other works. However, the proposed techniques of charge modes-selection and temperature detector present excellent solutions:
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- To control the transition between the three modes of charge in order to reduce power dissipation and achieve high power efficiency (1A).
- To protect the battery from temperature damage.

Table 2 represents a performance comparison between our proposed work and others architecture of battery charger.

| Parameters                  | [2]    | [25]    | [3]    | This work |
|-----------------------------|--------|---------|--------|-----------|
| Technology (um)             | 0.18 CMOS | 0.35 CMOS | 0.35 CMOS | 0.18 CMOS |
| Power Supply (V)            | 4.8-5  | 4.4     | 4.5    | 2.7-4.5   |
| Output voltage (V)          | 4.2    | 4.1     | 4.2    | 4.2       |
| Maximum current (mA)        | 448    | 1000    | 700    | 1000      |
| Efficiency (%)              | 87     | 68.3    | 70.9   | 90.9      |

5. CONCLUSION

To conclude, the proposed architecture presents a good choice for phone applications as power management systems. Therefore, the proposed charger is able to switch from a charging mode to another without reducing its efficiency using the proposed charge selection, and also it can reach a high value of maximum charging current (1000 mA) in a short time, and with high power efficiency which can reach 90.9%. The result of simulation of the proposed battery charger LDO-based confirms the high performance and high power efficiency of our architecture. The proposed charger is designed in 0.18 μm CMOS TSMC technology, with a small area equal to 1.5mm2.

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