$Implementation of a Coulomb Counting Algorithm for SOC estimation of Li-Ion Battery for Multimedia Applications

Conference Paper · March 2015

DOI: 10.1109/SSD.2015.7348255

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2015 12th International Multi-Conference on Systems, Signals & Devices

$Implementation of a Coulomb Counting Algorithm for SOC estimation of Li-Ion Battery for Multimedia Applications

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***Abstract*— Lithium-Ion based batteries are quite popular thanks to their good electrical characteristics but they risk to be damaged when they are overcharged or deeply discharged. In order to avoid these problems, Lithium-Ion batteries require an accurate state of charge determination to extend their lifetime and hence protect the equipment they supply. In this paper we propose a solution based on an enhanced Coulomb counting method which we have implemented on a hardware platform based on the PIC18F MCU Family. The results are promising. The proposed system is supported by IntelliBatteries and integrated on its products.**

***Keywords*— Li-Ion Battery, State of charge, Monitoring, Coulomb Counting, Hardware Implementation**

I. INTRODUCTION

With technological advances, electronic systems become widely used in most applications especially in multimedia ones. These systems require to be powered permanently. To ensure that energy supply, there are specific power systems which are rechargeable batteries. Indeed they are different types of rechargeable batteries, which differ from each other by several characteristics, such as the chemical compositions, the energy density and their lifetime [1,2]. Besides these portable electronic devices tend to be more and more compact and lighter. Batteries based on Lithium-Ion (Li-Ion) technology seem to be the more adequate thanks to their good characteristics like high energy density, high voltage, important number of charge/discharge cycles and security. Table.I summarizes the characteristics of different types of rechargeable batteries [1].

Table.I. Some rechargeable Batteries Characteristics

	Lead Pb	Ni Cd	NiMH	Li-Ion
Specific energy (wh/kg)	30-40	40-60	60-120	120-200
Energy Density (Wh/l)	60-75	50-150	140 -300	250-620
Self-discharge rate (%)	5	10-20	30	5
Nominal voltage (v)	2	1.2	1.2	3.6
Cycles number	50-500	2000	500-1200	500-3000

Li-Ion Batteries requires a specific charge method which consists on the constant current-constant voltage (cc-cv) charging algorithm illustrated in Fig.1 [3]. Also these batteries type have specific behaviors such as the different discharge gaits under different currents shown in Fig.2 and the self-discharge characteristic. So battery monitoring is one of the most important challenges facing Li-Ion batteries in order to monitor these behaviors. State-of-charge (SOC) estimation is the crucial task in battery monitoring.

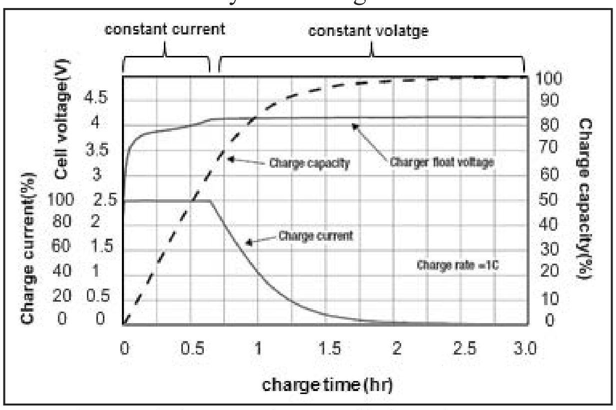

Fig.1. Typical CC-CV charge profile for a Li-Ion Battery

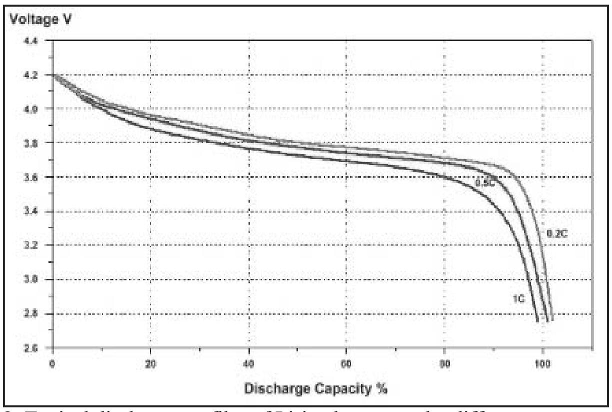

Fig.2. Typical discharge profiles of Li-ion battery under different currents

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Accuracy in SOC knowledge can avert batteries from coming in over-charge and deep-discharge and these states may cause irreversible damage to the battery's internal structure [4].

In literature, many methods were proposed for the batteries SOC estimation [5-6]. In fact three main types of methods are identified: electrochemical methods, electrical methods and adaptive ones. The electrochemical methods in spite of their high accuracy are judged difficult to implement neither on software nor on hardware solution because of the need to access to the chemical structure of battery [7, 8]. Adaptive methods [9] require an equivalent model and a resolution algorithm such as neural network [10], Kalman filter [11], fuzzy logic algorithm [12] and state observers [13]. So accuracy of these methods depends on the efficiency of the battery model. Unlike previous methods, electrical ones require only parameters that are obtained by measurements such as terminal voltage, current and internal resistance. Among these electrical methods, coulomb counting based on current integration remains one of the most widely used method due to its implementation simplicity and low complexity [8, 7, 14,15].

In this paper the purpose is to propose an accurate monitoring solution for multimedia applications, which can provide an accurate SOC indication and provide insight on the battery health in order to ensure a best use of the Li-Ion battery during their lifetime. The overall project includes especially two steps. In the first one we implement a coulomb-counting algorithm for SOC estimation. In the second step we aim to propose a battery model and an adaptive algorithm to enhance the accuracy.

This paper suggests a SOC estimation method for Li-Ion batteries on the basis of coulomb counting algorithm. This method characterizes the operating states of a Li-Ion battery (charge, discharge, self-discharge) and tends to overcome the limitations of the classic coulomb counting method such as the cumulative errors, the aging and temperature effects on the accuracy of the battery state of charge estimation. The proposed algorithm has been implemented on an embedded platform based on the microcontroller PIC18F developed within IntelliBatteries Company as a demonstrator and validated by simulation and experimental tests.

In the next section we introduce the coulomb counting method and the basics of the different steps of the algorithm and we explain how we overcome the ageing and the temperature effects. In the third section we describe the implementation process on the hardware platform as well as the experimental tests. Finally, conclusions and perspectives are drawn in section IV.

II. PROPOSED COULOMB COUNTING ALGORITHM

Battery state of charge knowledge is so critical that an uncontrolled charge could lead to the destruction of the battery, that's why power management in embedded systems is so crucial.

Assuming that the initial value SOC (to) is known, instantaneous SOC is generally evaluated by integrating the battery current over time, as shown in equation (1)

$$SOC(t) = SOC(to) + \frac{\int_{to}^{t0+\tau} I_{bat}.d\tau}{Q_{rated}} \times 100\% \qquad (1)$$

SOC: State Of Charge
I_{bat}: battery current value
Q_{rated}: rated capacity (nominal capacity)

The coulomb counting method consists on exploiting the relation (1) by quantifying the charge delivered by the battery through sensing its input and output current [8, 14]. However there are some inefficiencies when using this method; first of all, the access to the initial SOC which is not guaranteed, secondly self-discharge may distort the real SOC value after a long storage period and finally the reference capacity Q_{rated} which must be updated in terms of aging battery degradation. Enhanced coulomb counting method takes into account self-discharge losses and requires a recalibration at fully and empty stages in order to determine initial SOC and update the reference capacity to have a 100% maximal SOC value.

The flowchart given in Fig.3 explains the algorithm used to manage the battery monitoring by switching from a battery operating mode to another in accordance with the transitions conditions.

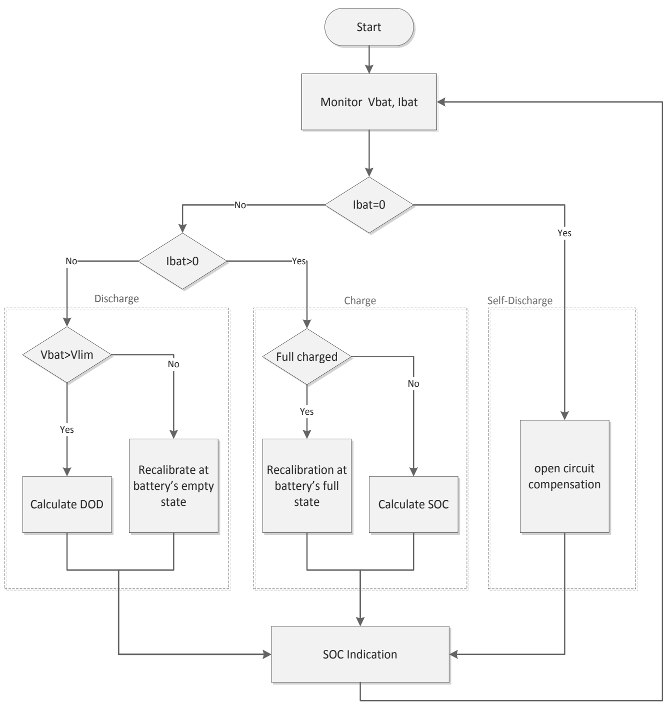

Fig.3. The flowchart of coulomb counting method

The estimation of the SOC of a Li-Ion battery in this method is based on monitoring both the voltage V_{bat} and the current I_{bat}. The operation mode of the battery is recognized by the direction of current through the battery system.

When the battery is in open circuit mode, $I_{bat} = 0$ and compensation of self-discharge losses will be taken into account as explained in sub-section C.

The information needed to carry monitoring are the measurement of the battery voltage, the current flowing through it and the operating temperature. Coulomb counter ΔQ is used to track the SOC when the battery is charged or discharged.

The amount of charges ΔQ in an operating period τ is obtained by a temporal integration of a measured charging/discharging current I_{bat} like expressed in (2):

$$\Delta Q = \int_t^{t+\tau} I_{bat} \, dt \quad (2)$$

This variance ΔQ that will be used in the following equations is negative if the battery is in discharge, positive if in charge.

A. Charge Mode

In this mode, the coulomb counter is presented by Q_{gained} as expressed in (3), which represents the quantity of charges accumulated during τ .

$$Q_{gained}(t+\tau) = Q_{gained}(t) + \Delta Q \quad (3)$$

So the variation of the state of charge gained in this same operating period is obtained by the relation (4)

$$\Delta SOC\,(t+\tau) = \frac{Q_{gained}(t+\tau)}{Q_{rated}} * 100\% \quad (4)$$

By cumulating the previous state of charge indication and the obtained one we can have the instantaneous value of SOC:

$$SOC\,(t+\tau) = SOC(t) + \Delta SOC\,(t+\tau) \quad (5)$$

Knowing the relationship indicated in relation (6) the value of depth of discharge DOD is updated in every charging operation in order to get it back every switching to discharging mode.

$$SOC(t) + DOD(t) = 100\% \quad (6)$$

B. Discharge Mode

In the discharging mode the coulomb counter is presented by Q_{lost}, which represents the amount of charges losses in the operating period τ by equation (7):

$$Q_{lost}(t+\tau) = Q_{lost}(t) + \Delta Q \quad (7)$$

The depth of discharge variation is calculated according to (8) and used in (9) to calculate the value of DOD .

$$\Delta DOD\,(t+\tau) = \frac{Q_{lost}(t+\tau)}{Q_{rated}} * 100\% \quad (8)$$

$$DOD\,(t+\tau) = DOD(t) + \Delta DOD\,(t+\tau) \quad (9)$$

The SOC indication then is done by applying the equation (6).

C. Self-Discharge Mode

At the battery storage periods, the percentage of monthly self-discharge is converted to amount discharged per hour; this amount is designed by the constant $q_{per/hour}$. Considering a 5% rate of self-discharge per month $q_{per/hour}$ is approximated to 0.0016 Ah. So the quantity of charges dissipated in the open circuit period Q_{oc} is calculated by the equation (10) representing the accumulative losses during the storage hours.

$$Q_{oc}(h+1) = Q_{oc}(h) + q_{per/hour} \quad (10)$$

h : Hour of storage

This value will be added to the amount of charge lost Q_{lost} during discharge mode and subtracted from the amount of charge accumulated Q_{gained} in charge mode as expressed in relations (11) and (12). This compensation of self-discharging loss is made at each open circuit period and before switching to another operating battery's mode.

$$Q_{lost} = Q_{lost} + Q_{oc} \quad (11)$$

$$Q_{tot} = Q_{tot} - Q_{oc} \quad (12)$$

D. Temperature effect

The temperature variation affects considerably the state of charge of the Li-Ion battery [16]. In order to improve accuracy of the battery state of charge, a temperature coefficient α is introduced and multiplied by the value of the calculated SOC [17]. This coefficient varies depending on the operating temperature according to the intervals variations (13).

$$\alpha = \begin{cases} 0.5, & T < -20° \\ 1, & -20° \leq T \leq 40° \\ 0.8, & T > 40° \end{cases} \quad (13)$$

E. Recalibration

When the loaded voltage V_{bat} drop under a limit voltage V_{lim}(3V), during the discharging mode the battery is considered totally discharged. When it's empty, the battery can no longer be used and should be recharged. So after a cycle of charge/discharge a recalibration should be made of Q_{max} which represents the maximum capacity that can be released by the battery. This recalibration allows rectifying the indication of SOC by replacing Q_{rated} by Q_{max} in relation (4). Also we recalibrate the State-of-Health (SOH) of the battery SOH defined is relation (14) as:

$$SOH(nc) = \frac{Q_{max}(nc)}{Q_{rated}} * 100\% \quad (14)$$

nc= number of cycles

Moreover, the battery is fully charged. Then SOH should be updated by assigning the quantity of charges releasable from the battery to Q_{max}. The SOH indeed represents the ageing degree of the battery; in fact it's at 100% maximum value when the battery is new. When the battery is getting old and Q_{max} became more and more inferior than Q_{rated} , SOH value drops to indicate the health degradation of the battery.

III. IMPLEMENTATION

The adopted coulomb counting algorithm for SOC estimation was implemented on hardware platform. Monitoring functions include the measurement of the battery voltage, the current flowing through it and the operating temperature by the 10 bits Analog to Digital Converter (PIC18F).

A. Measurement

Battery parameters detection is one of the most important issues in control and management of a battery management system [5]. It includes cell voltage measurement, current detection and temperature detection. Estimation of SOC and other battery states imposes high requirements on cell voltage precision [5]. In order to measure the voltage and the current with which the battery is charged or discharged, a resistor is placed in series with the battery. The voltage value is obtained by a measure of the voltage across the battery, and a difference between the voltages at the two terminals of the resistor will derive the current value, knowing the value of the resistance.

This resistance, which allows the current sensing in the battery gauge, should not be too high in order to avoid power dissipation during the charging at a constant current of 1A, but it should be still enough so that the analog/digital converter in the microcontroller can detect a voltage variation across it, which corresponds eventually to a 10 mA current, in order to detect the end of charging. In our case, a 10-bit converter is used to detect a voltage variation of 1mV. A 0.1 Ohms resistance would detect a current of 10mA (U = 1mV) and does not dissipate too much power while charging the maximum current value (P = 100mW).

The external temperature is measured using a negative temperature coefficient resistor R_{NTC}. The diagram presented in fig.4 includes different modules connection to the data acquisition system.

The transmission of battery electrical parameters is ensured by a USB connection between the multimedia application (Smartphone, PC…) and the MCU (PIC18F).

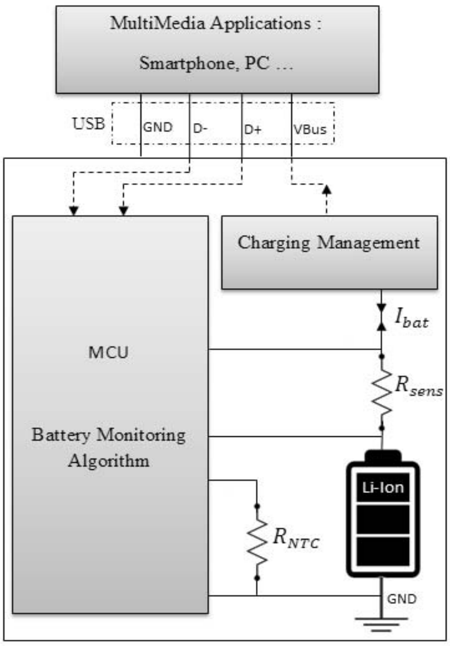

Fig.4. The basic circuit developed

To show the mesurement a graphical interface is used as shown in Fig.5 that includes electrical parameters of the battery : battery voltage Vbat, Voltage across Rsens Vpack+, current through the battery Ibat, and charging voltage Vbus.

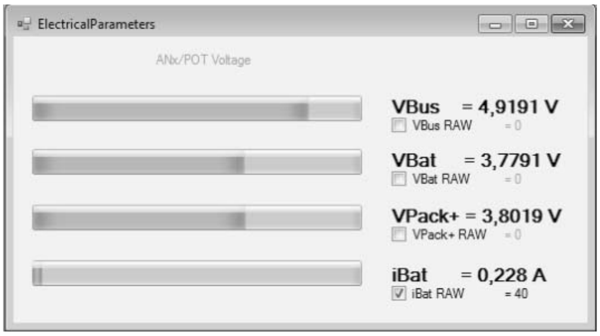

Fig.5. The Measurement Interface

B. Application

In order to validate the developed algorithm, the tests were achieved using a test card developed in IntelliBatteries, it consists of five main parts which is shown in Fig.6:

- The charging management that ensures the battery charging with the cv-cc procedure.

- The MCU that contains the programmable card PIC18F.

- The NTC resistor that measures the local temperature of the battery.

- The protection module that protects the battery against overload, voltage drops, power surges.

- USB connection that ensure both charging process and data transmission from the multimedia application to the MCU.

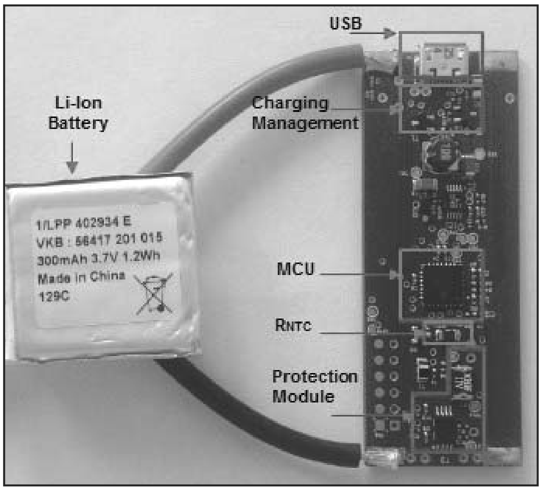

Fig.6. The test card

The monitoring algorithm is then implemented with embedded C language on the MCU using MPLAB®X IDE. Diagram presented in Fig.7 includes a callgraph generated by the MPLAB®X software. It lists the functions used in monitoring the state of charge of the battery.

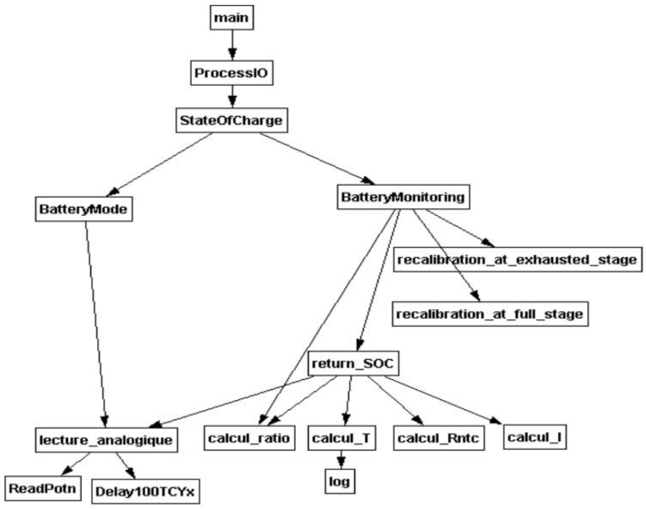

Fig.7.The Callgraph of the implemented coulomb counting algorithm

C. *Results and Exprimentations*

Once the integration of the monitoring algorithm was completed, we achieve some tests and comparisons to validate the effectiveness of the developed system.

<u>*Test 1*</u>:

The first test based on comparison between the coulomb counting algorithm simulated by Matlab and the algorithm embedded on the MCU. This test was effectuated during charging mode of two Li-ion batteries connected in parallel with a total nominal capacity of 4400 mAh.

In the Fig.8 the blue curve represents the cumulated capacity obtained by the Matlab simulation while the green one is the result of the same algorithm embedded on the hardware platform. Despite the difference detected between the two curves for the same algorithm with the same data which is due to that Matlab is a high-precision calculator while the MCU has an ADC of only a resolution of 10 bits, this illustration proves the reliability of the developed system since the two curves are nearly superposed.

<u>*Test 2:*</u>

The second test is performed on an Energizer battery whose characteristics are shown in the Table II.

The SOC indication obtained by the embeded coulomb counting algorithm was compared to the one obtained by using a linear approach which consists of a linear relation between the cumulated charge and the electrical parameters of the battery [4].

Fig.9.a and Fig.9.b show that in the same operating period equal to 100ms the linear approach presents a variation of 1% while the variation dropped to 3‰ by using the coulomb counting algorithm which proves the effectiveness and the accuracy of the proposed implementation of the coulomb counting algorithm.

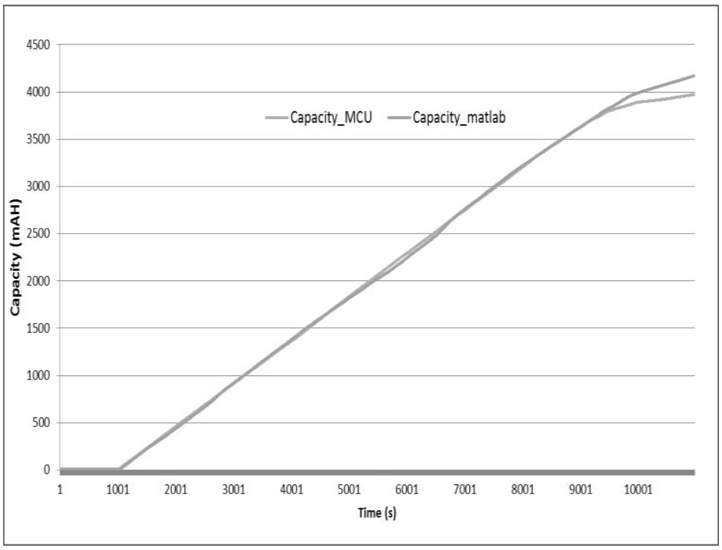

Fig.8.The variation curves of the instantaneous capacities obtained by both simulation and measurement

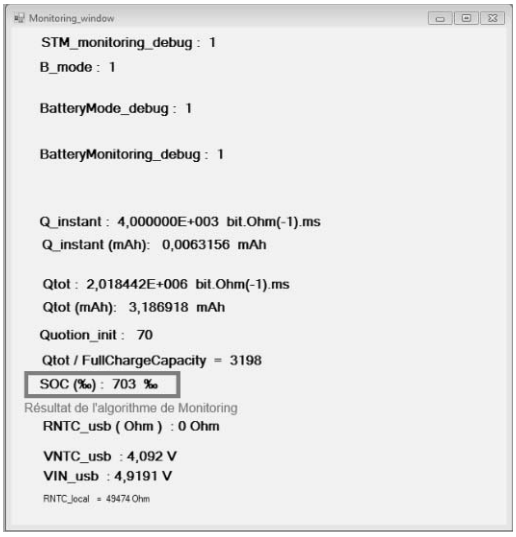

Fig. 9.a. SOC indication by coulomb counting approach

Fig.9.b. SOC indication by linear approach

Table II. Energizer battery characteristics

Energizer model	*CGAS007*
capacity	*3.7V , 1000mAh*
chemistry	*Li-Ion*
weight	*28g*
size	*37mm× 30mm ×12mm*

IV. Conclusion

In this paper, a coulomb counting method for state of charge estimation for lithium-ion batteries is detailed. This algorithm allows the system to operate in safe conditions by respecting the secure operating area of the lithium Ion battery to prevent over-charge and deep-discharge. To enhance the estimation accuracy, a recalibration at full and empty states is carried out and an evaluation of the state of health was considered. A hardware implementation of this algorithm was performed on an MCU (PIC18F) and validated by several tests.

This proposed system is supported by IntelliBatteries and integrated on its products. Presently we are developing a battery model that simulates the non-linear behaviors of Li-Ion batteries to enhance state of charge estimation accuracy and reliability.

Acknoldgement

THIS WORK IS PART OF A PHD THESIS SUPPORTED BY "PASRI-MOBIDOC" PROJECT, "INTELLIBATTERIES" COMPANY AND "SAGE" RESEARCH UNIT

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