

# A Real-Time Smart Charge Controller to efficiency charge processes of LiFePO4 batteries

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**Abstract** – This paper aims to describe an embedded Real Time measurement and control system, based on an innovative, dynamic circuital model for LiFePO4 batteries, which allows to improve the overall efficiency of charge processes and to extend battery life. In applications such as electric traction and stationary storage, where the battery performances are critical, it is essential to have a smart management of the energy flows to improve the Quality of Service and to reduce costs. The smart charge controller proposed in this paper uses a dynamical 2<sup>nd</sup> order circuital model to simulate the battery behavior during charge processes: the algorithm analyzes the relative error between the expected and the measured data and adapt the I-V setpoint dynamically to keep the relative error in a certain window. This lets to reduce the effects of the harmful higher order phenomena, such as gassing, so leading to an improvement in battery efficiency and lifetime.

## I. STATE OF THE ART

Energy Storage systems are nowadays widespread in many applications. For their high energy density versus weight (140-180 Wh/kg) [1], Lithium-ion and Lithium ion polymers batteries have become a standard de facto for high technology and for electric traction. One of the main disadvantages of Lithium-ion technology is unsafety, since these batteries tolerate very little overcharge and over-discharge. These operating conditions may lead to instability and risk of venting with flames or even explosion. Lithium ion polymers, which have solid electrolyte are in general more stable then the standard lithium ion and can tolerate better little overcharges and over-discharges. The LiFePO4 technology exhibits the highest stability, and for this reason is appropriate for transportation applications such HEV and purely electric traction [2].

### A. Standard charge process for Lithium Ion batteries

An accurate multi-stage battery charger is necessary to charge properly Lithium cells, since they do not tolerate even little overcharges.

A typical Lithium ion cell has a nominal open circuit

voltage in the range 3.6 – 3.8 V/cell, depending on the materials, but the phosphate-based lithium-ion (LiFePO<sub>4</sub>) has a nominal cell voltage of 3.20 V and 3.30 V; lithium-titanate is 2.40V. This voltage difference makes these chemistries incompatible with regular Li-ion in terms of cell count and charging algorithm [3]. In this paragraph will be discussed the charge process for a battery of 3.2V LiFePO<sub>4</sub> cells, the same considerations can be made for the other ones, by adapting the voltage levels.

Li-ion batteries are charged at a constant current (first stage) in range 0.5 – 1C, anyway manufacturers advise to not exceed 0.8C for an optimal charge. When the voltage reaches the threshold of 3,65 V/cell (or the value specified by the manufacturer), the battery charger must keep it constant until the current drops below 3% of the rated current, or it will no longer fall. Lithium cells, unlike the lead acid ones, do not need to be fully charged, indeed keeping the voltage at the maximum threshold reduces their useful life. A full charge on the other hand has some advantages in terms of battery capacity at the expense of service life. Figure 1 shows a typical charge profile of a Li-ion cell.

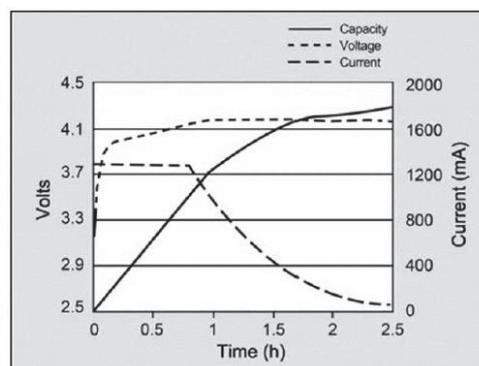


Fig. 1. Charge profile of a typical Lithium ion cell [4].

### B. Battery modeling and charge control systems

Lithium-ion and lithium ion polymers batteries for safety concerns should always be equipped with an electronic control circuit (BMS – Battery Management System), which has the task to monitor in real time at

least the voltage drop on each cell of the battery pack, the battery current and temperature. The BMS monitors the charge process and has to intervene promptly if the functioning parameters exceed the limits [5]. Moreover advanced battery management systems implement algorithms to enhance battery efficiency and lifetime. Many models and algorithms for stochastic processes [6-11] are used to estimate the battery behavior. Models are mainly of two types: mathematical [12, 13] and circuital impedance based [14]. Mathematical models are in general more accurate and complex [15, 16]. Circuital models are often less complex and more understandable from an electrical point of view. Obviously the higher is the order of the circuit, the more it is accurate and complex. A good trade-off between accuracy and complexity is reachable with a 2<sup>nd</sup> order circuital model [17, 18]. It approximates well the battery behavior far from the end of charge condition, but near to these operating condition, higher order phenomena, like gassing become relevant and the model is no more able to approximate well the battery behavior. This is because the battery begins to refuse further charge and converts the energy received in heat, affecting negatively efficiency of the charge process and battery life [19, 20]. In this paper we propose a smart charge controller based on a 2<sup>nd</sup> order circuital model. which dynamically adapts the I-V setpoint in order to reduce the higher order phenomena.

## II. THE MEASUREMENT-CONTROL ALGORITHM

The measurement and control algorithm is based on the comparison between the voltage measured at battery terminals and the voltage  $V_{\text{batt}}$  provided by the model showed in Figure 2, whose circuital parameters are obtained with the Extended FDIA algorithm in function of the State of Charge, State of Health, temperature and number of cells of the battery [21]:

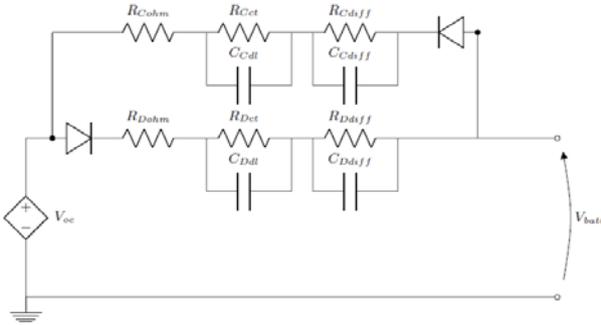


Fig. 2. Run-time 2<sup>nd</sup> order directional model.

The smart charge controller measures, in real time, the battery state of charge (SoC) with the *Coulomb Counting technique*, the ambient temperature, and, if the State of Health (SoH) is well known, it updates the values of the circuital parameters. At the same time the system

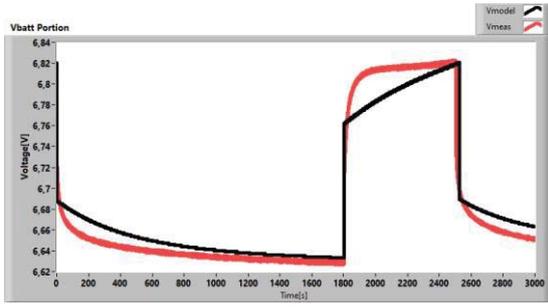
measures the battery current and stimulates the model with it. The voltage  $V_{\text{batt}}$  is the output of the model and represents the expected voltage at the battery terminals.

$$\begin{aligned}
 V_{oc}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m v_{ij}(SoH, n) * SoC^i * T^j \\
 R_{Dohm}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m a_{Dij}(SoH, n) * SoC^i * T^j \\
 R_{Cohm}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m a_{Cij}(SoH, n) * SoC^i * T^j \\
 R_{Det}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m b_{Dij}(SoH, n) * SoC^i * T^j \\
 R_{Cet}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m b_{Cij}(SoH, n) * SoC^i * T^j \\
 C_{Ddiff}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m c_{Dij}(SoH, n) * SoC^i * T^j \\
 C_{Cdiff}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m c_{Cij}(SoH, n) * SoC^i * T^j \\
 R_{Ddiff}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m d_{Dij}(SoH, n) * SoC^i * T^j \\
 R_{Cdiff}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m d_{Cij}(SoH, n) * SoC^i * T^j \\
 C_{Ddiff}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m e_{Dij}(SoH, n) * SoC^i * T^j \\
 C_{Cdiff}(SoC, SoH, T, n) &= \sum_{i=0}^m \sum_{j=0}^m e_{Cij}(SoH, n) * SoC^i * T^j
 \end{aligned} \tag{1}$$

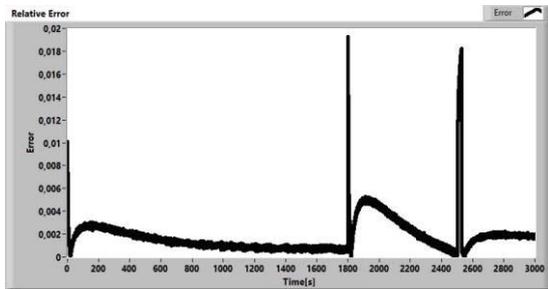
The parameters of the circuital model are calculated applying a polynomial best fitting technique with an approximation at the 5<sup>th</sup> order on a set of experimental data. To obtain the experimental data a test setup consisting in 30 pulsed charge and discharge profiles was performed on three different batteries at the target temperatures of 0°C, 25°C and 50°C. The batteries tested are made of two 2.3 Ah LiFePO4 cells in series.

Once the model was characterized new pulsed tests have been performed on new batteries to estimate the accuracy of the model. At 25°C with SoH=100%, figure 3 and 4 show the voltage measured and that provided by the model (a) and the relative error (b) for a Charge process respectively at a SoC between 68% and 78% (Figure 3) and between 88% and 98% (Figure 4).

As it can be seen the maximum relative error with a SoC between 68% and 78% is below 2%, while the mean relative error is 0.1%, then it increases when the battery is near to the end of charge condition. In fact the maximum relative error measured at a SoC between 88% and 98% is 2,5% and the mean relative error is 1%. This because the model cannot represent well higher order phenomena.

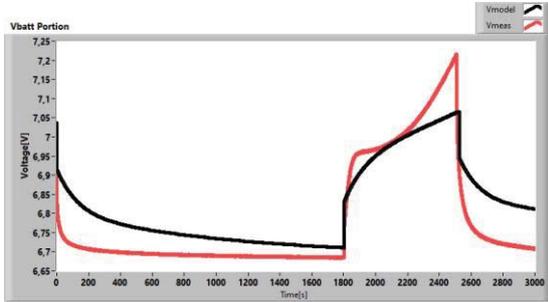


(a) Voltage Measured and Voltage provided by the model

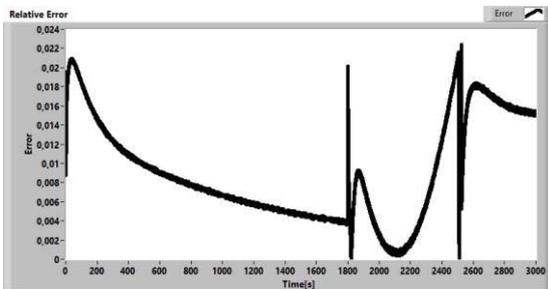


(b) Relative error

Fig. 3. Charge profile at SoC=68% T=25°C



(c) Voltage Measured and Voltage provided by the model



(d) Relative error

Fig. 4. Charge profile at SoC=88% T=25°C

The Smart Charge controller proposed implements a closed loop control on the battery current in order to minimize the relative error between the voltage measured at the battery terminals and that provided by the model, so reducing the effects of the higher order phenomena.

$$I(t + \Delta t) = I(t) - K(Er_V(t)) \quad (2)$$

Where K is a constant and  $Er_V(t)$  is the relative error at the time t:

$$Er_V(t) = \frac{V_{meas}(t) - V_{model}(t)}{V_{meas}(t)} \quad (3)$$

Actually, the measurement-control loop should result in a multi-stage charger, with a different voltage threshold for each stage, obtained from the model simulation. In fact if the voltage setpoint is continuously updated to minimize the relative error between the measurement and the model, the algorithm would fail. This because if there is a non-zero relative error, the control system implementing the equations (2) and (3) tries to adjust the charge current in order to minimize the relative error between the measured and expected voltage. Anyhow, being the new current also the input current to the model, it induces a proportional variation in the expected voltage  $V_{batt}$ . This can progressively reduce the current to zero, or even trigger instability, depending on the sign of the relative error. A multi stage charger with a number  $n$  of stages, each of which is characterized by a voltage threshold to be followed can represent a good trade off. The voltage threshold for each stage is determined by the model and kept constant for a certain time window. Since the parameters of the model change slowly during the charge process, until the end of charge condition, it is reasonable to update the voltage threshold  $V_{th}$  every increment of 5% in the State of Charge. Taking that as a baseline, the best  $n$  is still to be determined.

Each stage is then characterized by the equations (4) and (5):

$$V_{th}(t) = V_{batt}(t_0) \quad (4)$$

$$I(t + \Delta t) = I(t) - K(V(t) - V_{th}(t)) \quad (5)$$

Where K is dimensionally  $[1/\Omega]$  and its value is determined experimentally. A best trade-off between the stability of the system and the velocity of response was found for  $K=0,02 \Omega^{-1}$ .

### III. IMPLEMENTATION

The Smart Charge Controller is implemented with a NI CompactRIO connected to the network with a fixed IP address. The task of the CompactRIO is to measure in

real time the voltage at battery terminals, the battery current and temperature, and to control the power instrumentation implementing the algorithm described in the previous section. A host application realized in LabVIEW, which includes a Multisim implementation of the circuit model, runs on a remote server and reads data acquired by the CompactRIO at a rate of 1 S/s. The host application, realized using the LabVIEW-Multisim Co-simulation (Fig. 5), stimulates the model with the current measured by the CompactRIO and returns the expected voltage of the model to the CompactRIO, which has the task to calculate the new I-V setpoint, implementing the algorithm described in the previous section, and to control the power instrumentation. The end of charge condition is reached when the charge current drops below the 3% of the rated current, like in the standard charge processes.

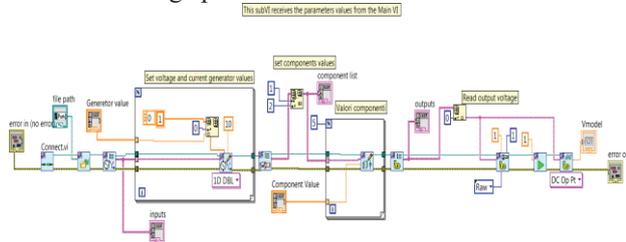


Fig. 5. LabVIEW-Multisim co-simulation for the simulation of the circuit model

The experimental setup consists of a Power Supply Ametek SGI 15/801, a Programmable Electronic Load Amrel PLA 10K-60-1500, a NI CompactRIO cRIO9082 with a voltage acquisition module NI 9223, a LEM CT-10 transducer and a thermistor for temperature measurements. The entire Block Diagram of the Charge Controller implemented is showed in Figure 6, while the flowcharts of the algorithm executed by the host application and the real-time application are showed in figure 7 and 8.

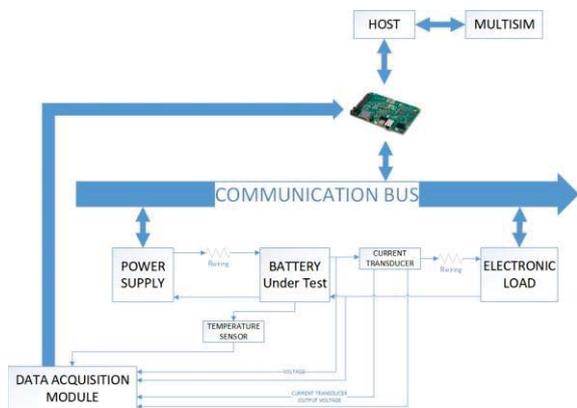


Fig. 6. Block diagram of the experimental setup

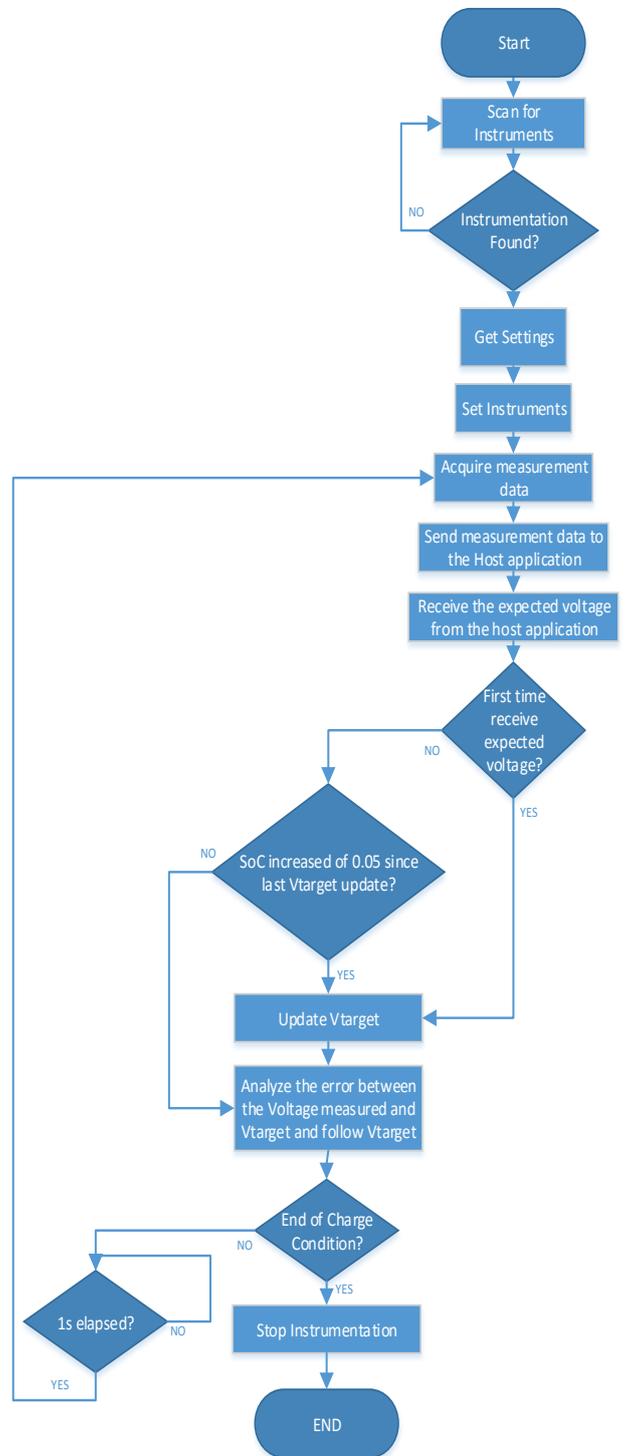


Fig. 7. Flowchart of the Real Time Application

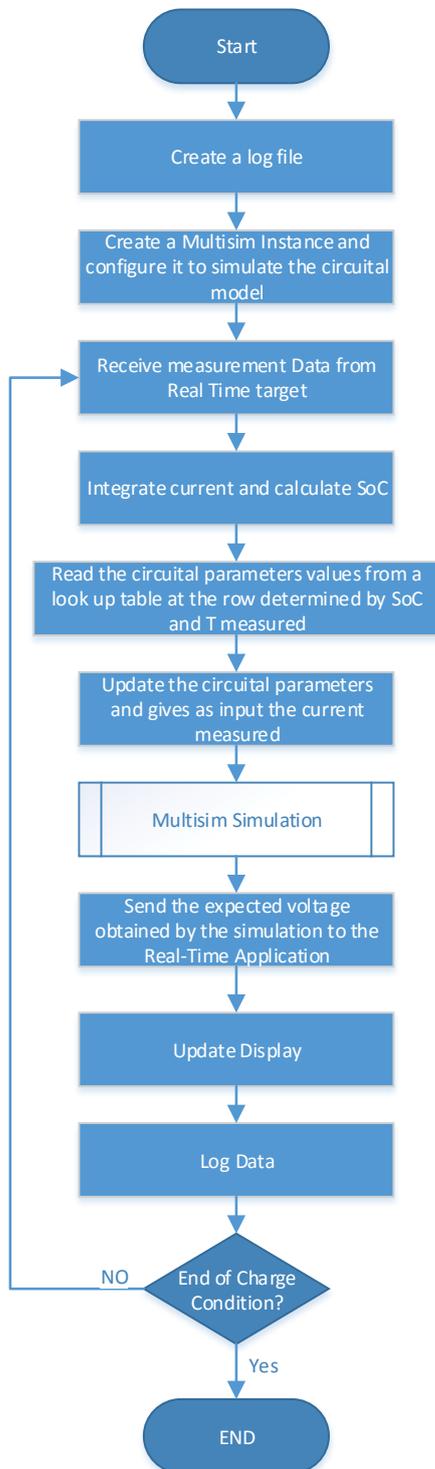


Fig. 8. Flowchart of the Host Application

#### IV. CONCLUSION

In this paper we proposed a new dynamic smart charge controller which implements a multi stage charging algorithm. Each stage is performed at a constant voltage, whose value is determined by the simulation of the circuitual model showed in Figure 2. The Smart Charge Controller has been implemented using a NI LabVIEW-Multisim co-simulation and a combined real time - host architecture. It is widely demonstrated in literature that slow charge profiles imply an increase in the efficiency of the process and an extension of the battery shelf life[22-25], while fast charge profiles are necessary in some applications to guarantee an acceptable quality of service. The final purpose of the smart charger proposed is to follow a dynamic I-V setpoint, which guarantees a best trade-off between the efficiency of the charge process and the quality of service granted. In the next future a significant statistical sample of LiFePO4 batteries will be tested using both the standard charge algorithm and the algorithm proposed in this paper, in order to quantify the efficiency improvement and the difference in the charge process duration.

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