

# Preparation and characterization of a lithium iron phosphate battery bank for an electric vehicle

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**Abstract-** Electric vehicles are expected to be a major contribution to sustainable mobility. The energy storage capacity issues and related costs are still being the main obstacles to overcome but significant progresses are being done in this area, namely with the advent of lithium based batteries. This paper deals with the preparation and characterization of a lithium iron phosphate,  $\text{LiFePO}_4$ , battery bank for an electric vehicle. The precautions to have in the first charge and discharge, a simple system to monitor and to ensure that the tight voltage limits are respected and a LabVIEW© system to measure the voltages, currents and to calculate the battery pack effective capacity and charge/discharge efficiency for different charge/discharge rates are presented. The efficiency and harmonic contents of the used chargers are also calculated. The installation of a commercial battery management system, BMS, and the impact on the previous results is also discussed.

## I. INTRODUCTION

There is currently an intense activity in the world around electric vehicles (EVs). Scientists, engineers and vehicle manufacturers are working hard to solve issues concerning the technology involved creating standards to allow a worldwide EVs dissemination and some governments are giving incentives to foster the daily use of the EVs. There is now a wide colligation of players with the same goal, but to reach it, it is absolutely necessary to overcome some issues. One of the main problems to be solved is the maximum range of an electric vehicle with a single charge. New forms of energy storage and electric charging stations strategically well placed are some of the most studied and sought possibilities.

In order to supply a small but high-performance EV and to deepen the knowledge [1]-[4] on the subject of charging systems for electric vehicles, the authors, at the Polytechnic Institute of Coimbra/Engineering Institute of Coimbra, IPC/ISEC, have prepared a Lithium Iron Phosphate,  $\text{LiFePO}_4$ , battery bank and developed a study around it to make its characterization.

In this paper, the technical specifications of the cells, battery pack and chargers are firstly presented. Then, the preparation of the batteries for utilization, including the first charge and discharge cycles, with over voltage and deep discharge under voltage protection is described. It follows the description of the system and tests for battery pack and chargers characterization, including the calculation of the instantaneous power, the energies involved and performing energy quality analysis. Finally, a real time battery management system installation is presented along with some conclusions.

## II. TECHNICAL SPECIFICATION OF THE CELLS, BATTERY PACK AND CHARGERS

### A. Used Cells

The study develops around the TS-LFP90AHA [5] cells from Thunder Sky (recently Winston Battery Limited), a Chinese manufacturer, specialized in high energy lithium ion batteries. The model TS-LFP90AHA is one of the many models produced by Thunder Sky, with  $\text{LiFePO}_4$  cathode, nominal voltage 3.0-3.3 V and 90Ah capacity, C (Fig. 1). Other important characteristics are:

- Standard Charge/discharge current: 0.3 C;
- Maximum charge current: 270A (3 C);
- Maximum discharge current: 270A (3 C) constant; impulse  $\leq 10$  C;
- Maximum charge voltage: 4.25 V (normal temper.);
- Minimum discharge voltage: 2.5 V;
- Charge nominal duration: approximately 3h;
- Cycle life:  $\geq 2000$  (80% DOD),  $\geq 3000$  (70% DOD);
- Weight: 3 kg  $\pm$  0.1 kg.

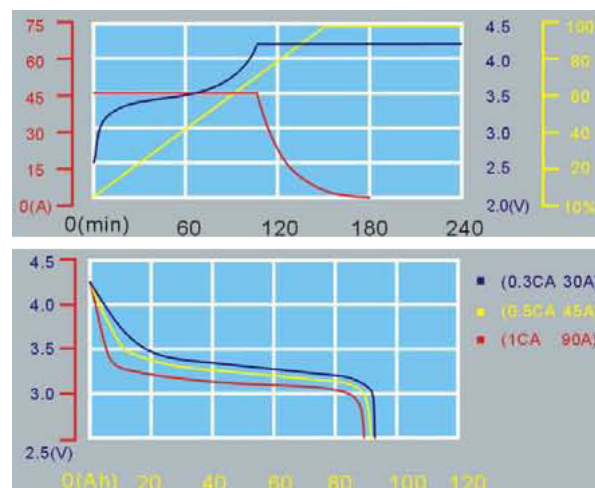


Fig. 1 – Charge and discharge characteristics of a TS-LFP90AHA cell from manufacturer manual [5].

### B. Battery Pack

32 cells were grouped to build the used battery pack. Considering 3 V for the cell nominal voltages, the pack has 96 V nominal voltage and C=90 Ah, i.e. 8640 Wh. It should, however be noted that the cell voltage varies both during charge and discharge, as can be seen in Fig. 1.

### C. Used Chargers

The chargers play an important role in the integration of electric vehicles since they will be responsible for recharging the batteries. The chargers must be adequate to the battery chemistry, the levels of voltage and type of

charge. In this study it was used the single phase supplied model POW48V30A from GWL/Power company, prepared to work with lithium-ion batteries. This model has intelligent control that calculates the battery pack state of charge (SOC), depending on its voltage, and adjusts the current. For example, when the battery pack SOC reaches 70%, there is an abrupt diminution of the current from 30 A to 22 A. However, these chargers can only charge 16 cells and should not be used with fewer cells. Consequently, two of these chargers were used (except for the first charges), and the battery pack had to be divided in 2 groups of 16 cells during the charging. The nominal voltage is 48 V and maximum voltage 64 V.

### III. FIRST CHARGE AND DISCHARGE

Even though if the manufacturer's manual allowed higher currents, the first cycle of charge and discharge were full cycles with a low current (3 A). The objective of these first cycles were to carefully check the individual cells behavior and balance the cells, reducing their voltage and charge disequilibrium and put them in same initial condition. For the pack first cells, the first charge was made individually, cell by cell, using laboratory power supply sources, with a set 3 A charge current. However, this was very time consuming and to accelerate the process it was done by groups of 4 cells or even 8 cells (Fig. 2). During these tasks, precautions were taken to prevent the damage of the cells. That was ensured through a monitoring and interruption system based on commercial electronic devices, the *CellLog 8S* [6] shown in Fig. 3.



Fig. 2 – Lithium iron phosphate battery bank preparation (2x8 cells), with the *CellLog 8S* cables in the cells terminals.

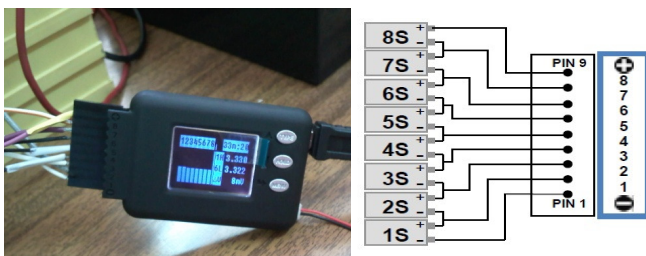


Fig. 3 – One *CellLog 8S* and connection diagram for 8 cells.

#### A. The *CellLog 8S* and the Security Interruption System

Using only 9 wires, each *CellLog 8S* can monitor up to 8 lithium ion cells in series (43 V maximum). It can measure, store and transmit in real time to a computer the cells voltages using an USB connection. This device possesses a system of adjustable alarms for maximum and minimum voltages levels, a time alarm and even an alarm for voltage

difference between cells. When an alarm situation is detected, a solid state relay contact changes its state. The user can select which alarms wants actives and configure them for the desired values. Making used of the alarm feature of the *CellLog 8S* devices, an interruption circuit was built using relays, push buttons, and the *CellLog* alarm connector. This system opens the power contactor, when one alarm of any of the *CellLogs* triggers, interrupting the charge or discharge process, and that can only be restarted manually. However, special care as to be taken, as the *CellLog* alarm solid state relay contact is not galvanic isolated from the *CellLog* inputs. Consequently, the alarms outputs of the four used *CellLogs* cannot be directly connected in series, but have to be connected through auxiliary electromechanical relays. This system is further described elsewhere [7]. One has also to be very careful as the USB connector ground of each of the *CellLogs* is also directly connected to its cells lower voltage (pin 1, in Fig. 3); more than one *CellLog* cannot be connected to the same computer at the same time, and even if different computers are used, one for each *CellLog*, special care has to be taken to avoid short circuits trough the different computers USB connectors ground.

The individual cells voltages, the total and its time evolution can be visualized using the *LogView* software [8]. During the first charges, one important verified feature was that above 3.4-3.5 V (Fig. 4 and Fig. 15) the voltage on the cells increases very fast, even with a 3 A charge taking just a few minutes to reach the maximum 4.0-4.25 V limit. Also when discharging, below ~3.1 V the voltage drops very fast (cf. Fig. 15). For example, in Fig. 4, the 3 A charge was interrupted twice around minute 40 as the maximum voltage difference between the cells alarm was set to 150 mV. The first discharge was also done at 3 A, in order to gain knowledge on the battery behavior.

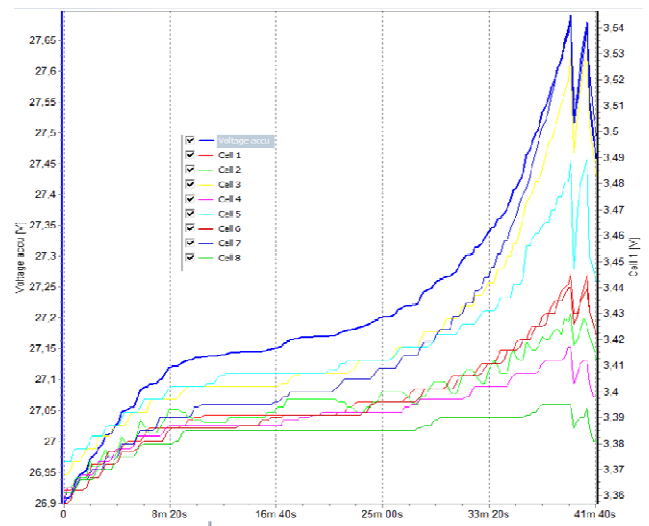


Fig. 4 – Voltage evolution of cells 25 to 32 during charge, as measured by one *CellLog 8S* and visualized using *LogView*.

### IV. SYSTEM AND TESTS METHODOLOGY FOR BATTERY PACK AND CHARGERS CHARACTERIZATION

After the first charge and discharge cycles, to characterize the battery bank it was necessary to develop systems that allow monitoring and calculate the chosen parameters. Thus a program was created in *LabVIEW*© platform using an acquisition board, that measures currents,

voltages and calculate power, energy, harmonic distortion rates, showing and recording their values.

#### A. Monitoring System with LabVIEW®

The *LabVIEW*® system was built using the acquisition board *PCI-MIO-16E-4* of *National Instruments* with the I/O connector block *SCB-68* that enables the use of 16 non-differential channels or 8 differentials. The channels are connected to insulated current and differential voltage probes [7].

The battery pack efficiency is determined dividing the energy provided during its discharge by the energy absorbed in the charge. The charger efficiency is calculated dividing the energy supplied to the batteries during a charge operation by the energy it absorbs from the network. The charger instantaneous efficiency is determined dividing the instantaneous power absorbed by the batteries by the instantaneous power absorbed through the network. The total current harmonic distortion, THDi, of the current chargers is calculated instantaneously. The input power,  $P$ , (1) and the input energy,  $E$ , (3) absorbed by the charger are calculated by:

$$P = V_{rms} I_{rms} FP \quad (1)$$

where  $FP$  is the power factor and in non-sinusoidal system can be calculated by (2) [9-11].

$$FP = \frac{\cos \phi_1}{\sqrt{(1 + THD_i^2)}} \quad (2)$$

$$E = \int_0^t P dt \quad (3)$$

As mentioned before, the bank configuration is different for the charge (a series of two groups with a series of 16 cells) and the discharge (32 cells in series). Therefore, there was need to develop two monitoring programs, one for charge (Fig.5) and one for discharge [7]. Its visual interface has several scopes (graphic displays) for the registry of the parameters evolution in time and numeric indicators for the instantaneous values.

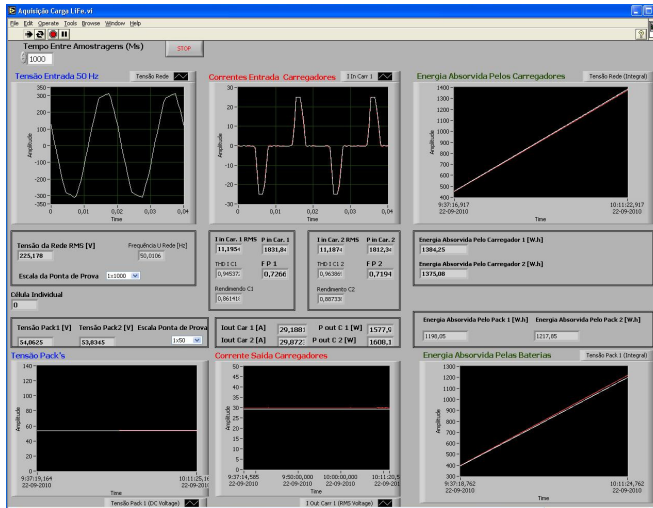


Fig. 5 - LabVIEW Monitoring Program Visual Interface during a charge.

#### B. Tests Description and Methodology

The battery and chargers tests were based on cycles of charge followed by a discharge. The charge current starts at 30 A, lowering by steps with the SOC increase. The discharge current was different depending on the test: 15 A, 30 A and 60 A. However, it should be noted that the current

was not really constant since the discharge resistance was constant and the voltage decreases with the discharge. Due the laboratory limitations, the maximum continuous discharge current was 60 A.

A charge or a discharge ends when at least one cell reaches the limit voltage values defined in the *CellLog* alarm. The same limits were set for all *CellLog* 8S devices in all tests: 4.2 V for maximum voltage, 2.7 V for minimum voltage and  $\Delta V \leq 0.5$  V between cells.

#### V. CHARGERS EXPERIMENTAL TESTS

Following are shown the tests results for one charge. As showed in Fig. 6, the charge current is constant, approximately 30A, until the change of stage by the charger, when the current has an abrupt decrease. The charge powers (Fig. 7) have the same behavior that the current, showing a small difference at the charge end, where it seems to increase faster. This is due to the behavior presented by the cells voltage at the end of the charges, as will be shown in Fig. 15.

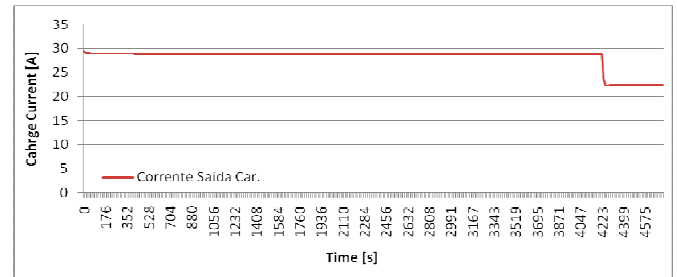


Fig. 6 - Charger Output Current

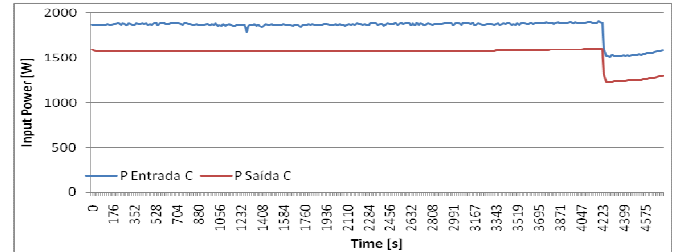


Fig. 7 - Charger Input Power (blue) and Charger Output Power (red)

The evolution of the THDi and charger efficiency, in Fig. 8, is in accordance with the expected results. At the moment of transition of stage, both THDi and efficiency show a variation.

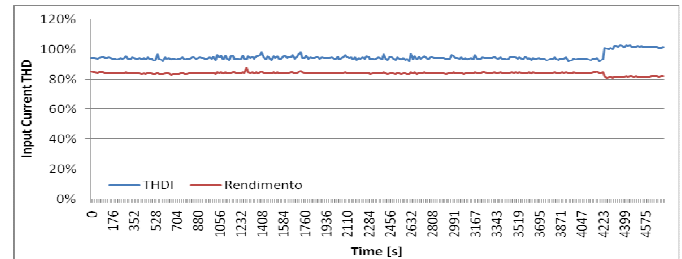


Fig. 8 - Current THD (blue) and Charger Efficiency (red)

The increase of the THDi is due that mostly the high frequency harmonics assume a bigger influence when compared with the fundamental frequency wave in the lower load level. The efficiency decrease on the other hand is due to the increase of the harmonics influence. The charger global efficiency depends on the difference of the energy



absorbed by the charger and the energy absorbed by the batteries (Fig. 9).

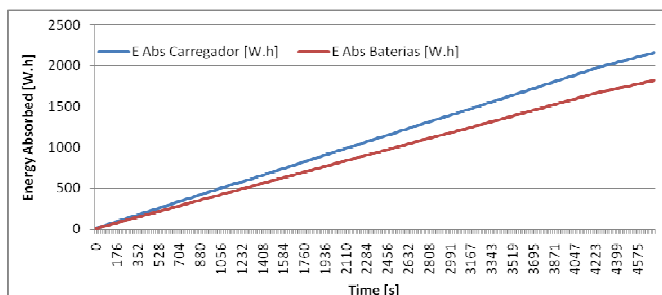


Fig. 9 - Energy Absorbed by the Charger (blue) and Energy Absorbed by the Batteries (red)

The chargers global results can be summarized as:

- THDi min:  $\approx 95\%$  THDi max:  $\approx 110\%$
- Instantaneous Efficiency:  $\approx 85\%$
- Global Efficiency:  $1820.4/2161.2 = 0.842 \Rightarrow 84.2\%$

## VI. CHARACTERIZATION OF LiFePO<sub>4</sub> BATTERY PACK

For each test of charge or discharge, the energy absorbed or supplied by the batteries was calculated by the developed system from the measured currents and voltages, as well as the efficiency for each discharge current. Fig. 10 shows an example of the pack 1 (first 16 cells) charge voltage and the chargers output currents, and in Fig. 11 the input and output powers of both chargers are presented.

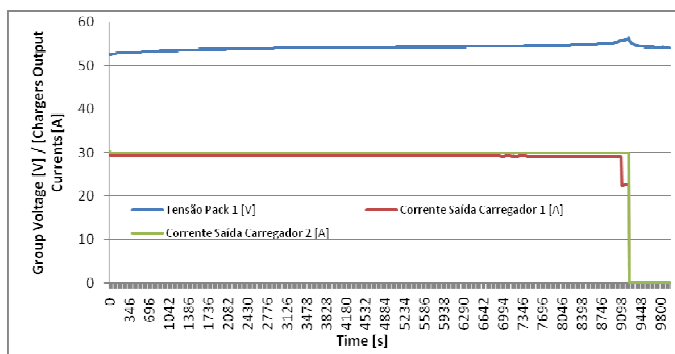


Fig. 10 - 16 Cells Group Voltage (blue); Charger 1 Output Current (red) and Charger 2 Output Current (green)

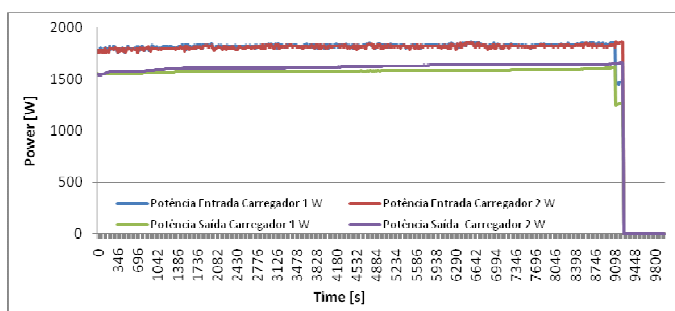


Fig. 11 - Charger 1 Input Power (blue); Charger 1 Output Power (green); Charger 2 Input Power (red); Charger 2 Output Power (purple)

After each charge, the battery pack was prepared for the discharge test, with the 32 cells in series, as in Fig. 12.

The results in Fig. 13 and Fig. 14 are for a 15 A discharge current.

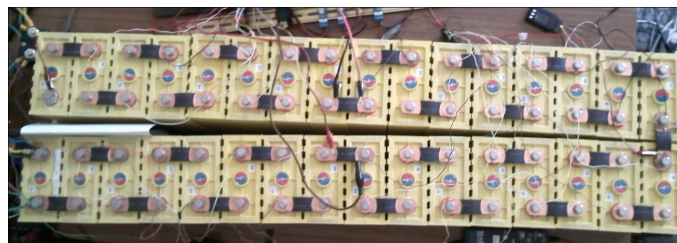


Fig. 12 - Battery bank connected for discharge test (32 cells in series).

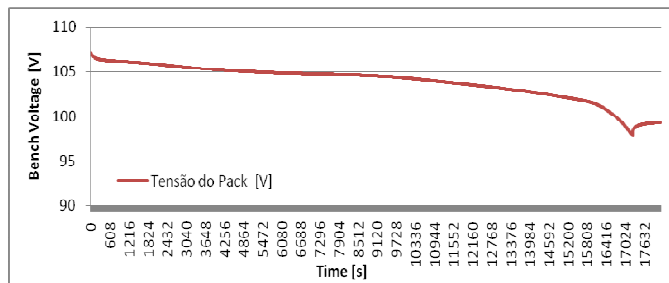


Fig. 13 - Battery bank voltage at 15 A discharge

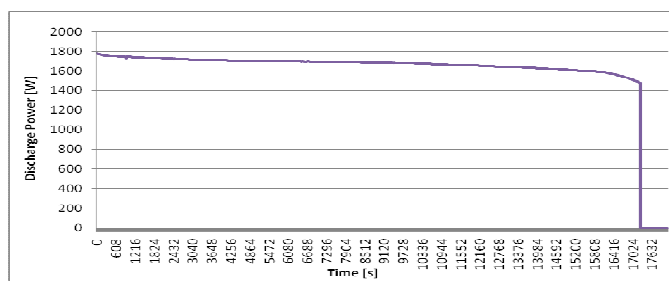


Fig. 14 - Discharge Power for 15 A

As expected from Fig. 1, at the beginning and at the end of both charge and discharge, the voltage variations are more pronounced. It has also been verified that this effect increases with the increase of the discharge current. In Fig. 15 it is presented the evolution of the individual cells and accumulated (blue, higher curve) voltages of the 8 cells monitored by one *CellLog* and shown in *LogView* during a charge followed by a discharge.

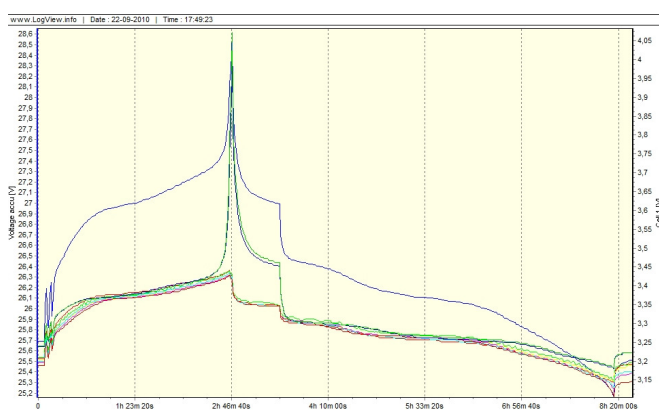


Fig. 15 - 8 cells voltage variation: individual and total voltages

In this figure the referred phenomenon is more clearly seen, particularly at the end of the charge, where some of the individual cells voltage suddenly increases very sharply, and decreases exponentially at the beginning and at the end of the discharge. Due to this variation, which do not occur in all the cells at the same time, is it mandatory the existence of an individual cells monitoring system with an interruption

system to avoid the damage of the cells by reaching very high or very low voltages.

The results for the different currents were:

*Cycle of 15 A discharge current:*

Energy Absorbed at charge: 7393.02 W.h \*  
 Energy Provided at discharge: 7226.25 W.h  
 Cycle Efficiency:  $7226.25 / 7393.02 = 0,9774$

*Cycle of 30 A discharge current:*

Energy Absorbed at charge: 7530.60 W.h\*  
 Energy Provided at discharge: 7284.16 W.h  
 Cycle Efficiency:  $7284.16 / 7530.60 = 0.9673$

*Cycle of 60 A discharge current:*

Energy Absorbed at charge: 7768.08 W.h\*  
 Energy Provided at discharge: 6814.76 W.h  
 Cycle Efficiency:  $6814.76 / 7768.08 = 0.878$

\*Sum of both groups of 16 cells.

From the above results, even though if the energy absorbed by the battery pack is not equal for all tests, it is clear that the energy provided at the discharge decreases with the increase of the discharge current. That is due to the fact that the increasing of the discharge current increases the losses at the wires, at the contacts and mainly the internal losses of the cells. Higher currents also increase the voltage variation taking to an earlier end of the discharge, preventing the maximization of the energy transferred at the process.

The measured battery pack efficiency is shown in Fig. 16. As can be seen, the efficiency decreases with the growth of discharge current, and it is clearly shown why, according to the manufacturers data sheet, the standard discharge current is 0.3 C (27 A).

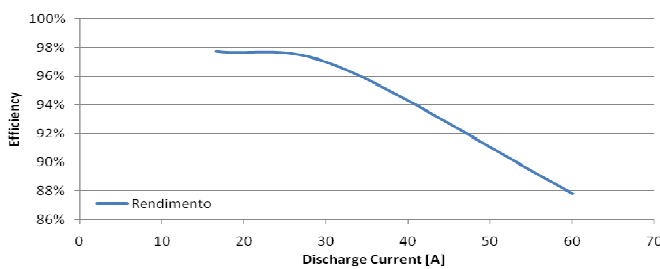


Fig. 16 - Batteries Efficiency as a function of the discharge current

## VII. BATTERY MANAGEMENT SYSTEM TESTS RESULTS

### A. Real Time Battery Management System

The *LabVIEW*© developed system allows to evaluate the charger and battery pack efficiency and power quality. Nevertheless, for a real EV utilization, an embedded system and with cell balancing capacity is need. To fulfill this purpose, it was used a *Real Time Battery Management System* (RT-BMS) from GWL/Power, which is a management system applicable to any kind of lithium battery. This acts during the charge and discharge of the batteries, controlling individually each cell through *Cell Balancing Units* (CBUs), as in Fig. 17, that communicate with a *Master Unit* (Fig. 18) through a flat cable FC-10.

The Master Unit can work standalone or connected to the computer, which through software, supplies all the

information about currents and voltages of each cell and of the battery bank. Its bigger advantage resides in that, unlike the *CellLog 8S*, beyond monitoring, also controls the processes. It is capable of balancing the voltage of each individual cell according to the definitions of the user previously stored into the *Master Unit* through the computer. When during the charge process one cell reaches a user defined voltage, its CBU starts deviating up to 5 A of the charge current allowing this cell to charge slower than the others and consequently to prevent its overcharge while the other cells are increasing their charge. The RT-BMS also possesses alarms for anomalies that can occur, such as errors, or lowering of the voltages for risky levels.

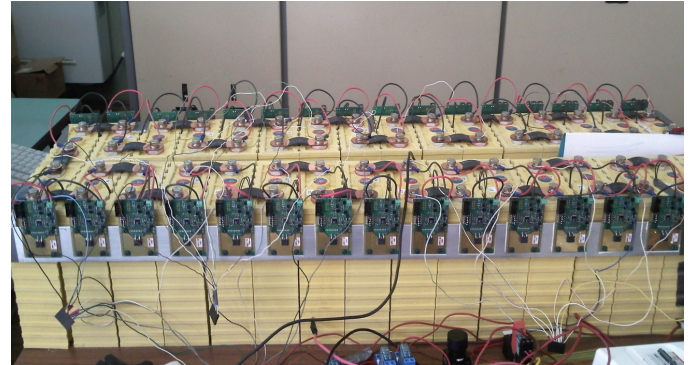


Fig. 17 – Battery bank with the CBUs installed

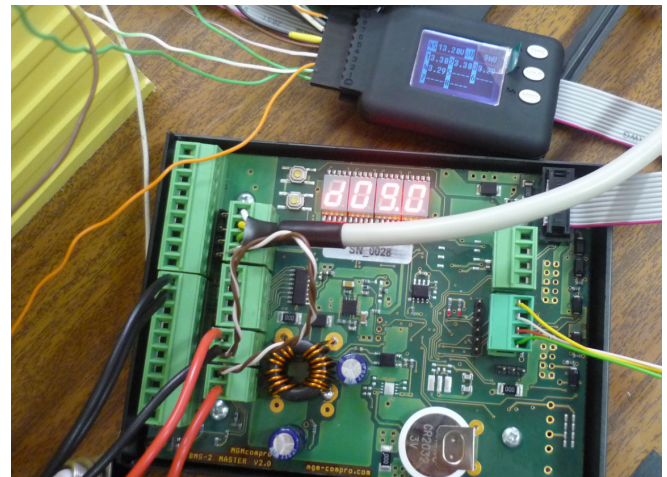


Fig. 18 – Master RT-BMS Control Unit (case open) with a CellLog 8S

Before starting the tests with the RT-BMS installed, a complete charge and discharge of the battery pack was done so that the cells are as balanced as possible. The balancing system works according the user settings. For these tests, the settings were:

- Cut-off voltage: 2.60V
- Low voltage: 2.75V
- Nominal voltage: 3.60V
- Charge voltage: 4.00V

Three cycles of charge and discharge were performed. In all cycles, the results for the cells voltages evolution, stored energy and efficiency, were identical to those obtained in the tests without the RT-BMS system, contrary to what was initially expected. After analyzing the situation it was concluded that with a 30 A or 22 A charge current, at least with the used heatsinks, the CBUs temperature rose significantly (Fig. 19) and they were not able to divert enough current to allow a much better cell charge balancing

than with *CellLog 8S*. I.e., when some cell(s) voltage starts to skyrocket, the overall pack charge will soon finish, as that cell will reach the voltage limit before the others are fully charged, and so the system shuts the charger down.

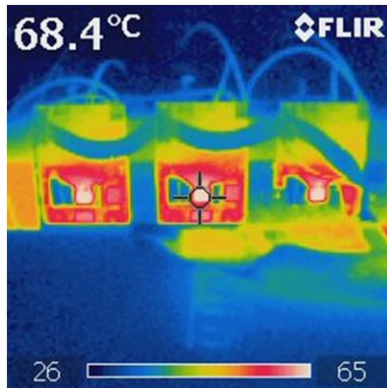


Fig. 19 – Thermographic image of 3 CBU's during cell balancing.

### VIII. CONCLUSIONS

A  $\text{LiFePO}_4$  battery pack was assembled and tested. From this study, the results led to the following main conclusions, concerning:

**The cells and the *CellLogs* based interrupt system -** During the charging, without a well adjusted RT-BMS, when the cells reach a certain level of charge the voltage starts to rise exponentially. This area of the curve is a very unstable zone, since the voltage changes very fast, requiring special care to not exceed the maximum recommended voltage for the cells. With recourse to *CellLog* devices and the interruption system, this problem can be prevented by taking an interruption when some cells reach the level of voltage near the maximum. After the interruption, the voltage level falls rapidly to a value much lower than it previously was. This value is not a fixed value, varies from cell to cell, but is close to 3.4 V.

**The chargers -** Assesses the level of battery SOC and adapt the charge currents. This kind of charge has the ability to maintain a constant current for SOC steps, thereby optimizing the load. In terms of energy quality, for smaller currents, this causes a harmonic distortion that is within the limits allowed, about 3% for the voltage THD and 111% for current THD. However, with such chargers generalization, some problems might arise in the distribution network. Regarding the efficiency, it is reasonable and corresponds to the manufacturer prediction, approximately 85%. The values of THDi and performance vary when varying the current, and when the THDi increases the efficiency decreases. This is because a current reduction causes a higher increase in the amplitude of the harmonics than in the fundamental frequency, raising their influence. Thus, in percentage terms, the harmonics increase in amplitude.

**The Battery Pack -** Without the balancing system, the charge and the discharge of batteries is not complete, and either one or the other process was terminated as soon as any cell enter the unstable zone and hit the voltage limit established. Thus, the energy absorbed and supplied by the batteries did not reach its maximum value. This is also reinforced as usually the cells only reach its maximum capacity after some cycles. In these tests, these values vary between 7200 Wh and 7700 Wh, resulting in a maximum

efficiency near of 98% and decreasing with the discharge current.

**The RT-BMS -** Concerning overcharge prevention, the RT-BMS operation is based on diverting part of the charge current entering the cell, as a kind of by-pass and, when necessary, will discharge the higher charged cells. That may lead to an increase of the energy consumption. In terms of energy results, it was quite identical to the tests without the balancing system, due to the lack of balancing power from the balancing system. This can be improved, for example, by a better CBUs heat removal.

As a final conclusion, the study done allowed to improve the authors' knowledge on the  $\text{LiFePO}_4$  batteries and prepare a battery bank for EV.

### IX. ACKNOWLEDGMENT

The authors want to thank the Miguel Ângelo Correia da Fonseca, BSc in Electrical Engineering, former ISEC student, for his collaboration in the preparation of the battery and some experimental tests.

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