Smart $LiFePO_4$ battery modules in a fast charge application for local public transportation

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***Abstract*—This paper describes the research effort jointly carried out by the University of Pisa and ENEA on electrochemical energy storage systems based on Lithium-ion batteries, particularly the Lithium-Iron-Phosphate cells. In more detail, the paper first illustrates the design and experimental characterization of a family of 12 V modules, each of them provided with an electronic management system, to be used for electric traction. Then, the sizing of the energy storage system for an electric bus providing a service with "fast and frequent" charge phases is described.**

***Keywords*—Lithium-ion batteries; electric propulsion; battery management systems; Life cycle assessment**

I. INTRODUCTION

The market of the electric energy storage systems based on traditional lead-acid batteries provides a large choice of options and configurations for both the battery sizes available and the manufacturers of cells and systems. Instead, there are many manufacturers of cells based on the Lithium-ion chemistry but only a few producers of modules or entire systems. If the largest players of the automobile market (first in Japan and then in Germany) have tackled the problem by means of direct agreements with the manufacturers, the small and medium enterprise suffers the lack of a mature market for the Lithium-ion storage systems. This is particularly true for the Italian scenario [1].

The availability of standard modules provided with electronic monitoring and managing capabilities would allow the manufacturers of market-niche vehicles, such as the electric minibuses for the local public transportation, but also many other off-road vehicles (e.g. agricultural machines, fork-lifts and other industrial electrical vehicles), to use the last generation of battery technology without acquiring the know-how necessary for the in-house design of the battery system. These manufacturers can benefit of the modular approach, by building batteries of various sizes for the different applications by using the same modules, with obvious advantages in terms of production volumes and cost reductions [2]-[4].

ENEA and the University of Pisa are carrying out a joint research effort in the framework of the Program Agreement "Ricerca di Sistema Elettrico", funded by the Italian Ministry of Economic Development. During the last years they have developed 12 V standard modules with capacity values spanning from 30 Ah to 100 Ah, which are provided with an advanced battery management system [5]. The seamless connection of these modules may allow the producer of market-niche electric vehicles to implement the required energy storage in an effective way.

This paper first describes the design and the experimental characterization of the above mentioned modules. Then, it shows an interesting use of the modules to implement the battery suitable for the energy storage of a public transportation electric bus characterized by a service profile where the charge phases are frequent and fast. This application is rather demanding for the energy storage system, as it requires frequent fast charges for the entire duration of the daily service, *i.e.*, around 16 h.

II. THE STANDARD MODULES

As mentioned above, the basic idea underlying this work is the development of a standard 12 V battery module to be used in many applications for electric traction and more in general for automotive applications [4]. The initial investigation has led to the identification of the most suited type of chemistry. The Lithium-Iron-Phosphate (LFP) cells seem to be the best alternative to lead-acid ones for electric traction, because of the voltage range and the good intrinsic safety features that this chemistry provides. TABLE I. shows the voltage ranges of several Lithium-ion cells as a function of the specific chemistry, together with the possible voltage ranges of a series-connected 4-cell module. It stands that the module built with LFP cells provides the voltage range most similar to that found in lead-acid batteries.

There are many different kinds of electric traction vehicles, starting from the "purely electric" to the "hybrid" ones, where the traction is due to the joint action of an electric motor and

TABLE I. CHARACTERISTICS OF VARIOUS LITHIUM-ION CHEMISTRIES [6]

Chemistry	***Cell voltage (min, nom, max)* (V)**	***# of cells***	***Battery voltage (min, nom, max)* (V)**
LCO	2.7–3.7–4.2	4	10.8–14.8–16.8
LMO	2.75–3.7–4.2	4	11–14.8–16.8
NMC	2.7–3.6–4.2	4	10.8–14.4–16.8
NCA	2.7–3.6–4.2	4	10.8–14.4–16.8
LFP	2.5–3.2–3.65	4	10–12.8–14.6

an internal combustion engine. As far as the hybrid vehicles are concerned, the large spreading of different topologies, e.g. parallel, series, plug-in rechargeable, charge sustaining, charge depleting, etc., does not allow the rise of a widely accepted standard, capable of representing all the different alternatives. In addition, the development complexity of a hybrid vehicle tends to narrow its application only to the large and medium size enterprises, which have the power to establish direct agreements with the battery producers. Besides the usual meaning of vehicles as road and off-road transportation means, the electric energy storage is gaining more importance also in the marine applications. New battery generations are expected to be used in boats and vessels for the electric propulsion in protected areas, for maneuvering in the harbors and for powering the auxiliary electric appliances, particularly when anchored.

Given the above considerations, we believe useful the development of a standard battery module for the electric traction of vehicle. Keeping in mind the possible applications, the minimum and maximum capacities are set to 30 Ah and 100 Ah, respectively, with an intermediate size of 60 Ah.

The first investigation step has been the experimental characterization of the various cell types, coming from different manufacturers, e.g. Thundersky, Kokam, Valence, HiPower, etc. The choice of the chemistry and the producer allowed us to define the preliminary specification of the control electronic needed to monitor and manage the battery module, the Battery Management System (BMS). Besides the monitoring and passive equalization functions, common to any BMS for vehicular applications, we also have investigated the key issues of the battery State-of-Charge (SoC) estimation, the active charge equalization of the series connected cells and the possible influence on the battery behavior of hysteresis phenomena, often found in LFP cells [7]-[9]. A comparative evaluation of commercial BMSs has also been carried out, in order to extract the information useful for the design and implementation of an advanced BMS for the module and for the entire battery (intended as a seamless connection of modules).

III. MODULE DESIGN AND CHARACTERIZATION

Three different modules have been realized [10]. Their electrical and physical characteristics are listed in TABLE II. and TABLE III. respectively. One of the aim of the research is to allow the realization of batteries of any size by simply interconnecting the elemental modules, without worrying of the thermal design of the battery or installing a dedicated cooling system. The solution adopted is based on a forced-air active cooling system consisting of very cheap fans like those used in consumer electronic applications.

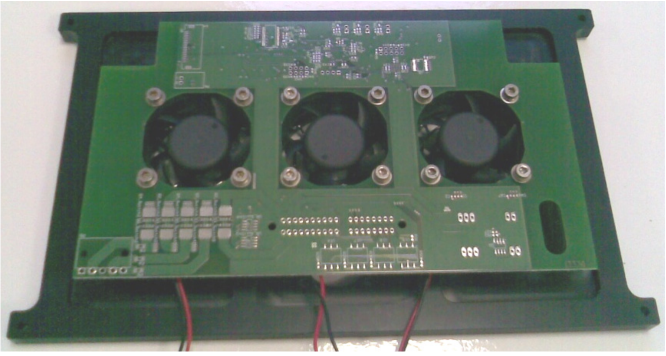

Fig. 1. Battery management system board with the cooling fans.

TABLE II. ELECTRICAL PARAMETERS OF THE MODULES

Size		Small	Medium	Large
Series connected cells		4	4	4
Nominal capacity (Ah)		30	60	100
Temperature (discharge) (°C)		−20÷+65	−20÷+65	−20÷+65
Temperature (charge) (°C)		0÷+45	0÷+45	0÷+45
Discharge @ +23°C	Max continuous current [A]	90	180	300
	Peak current @ 60 s (A)	150	300	500
	Cut-off voltage (V)	2.5	2.5	2.5
Charge @ +23°C	Charge method	CC/CV	CC/CV	CC/CV
	Max charge current (A)	30	60	100
	Max suggested cell voltage (V)	3.65	3.65	3.65
	Cell cut-off voltage (V)	3.85	3.85	3.85

TABLE III. MODULES PHYSICAL PARAMETERS

Module size	Length (mm)	Depth (mm)	Height (mm)	Volume (l)
30 Ah	251	160	220	8.83
60 Ah	277	166	256	11.77
100 Ah	279	198	337	18.62

In fact, each module is provided with three fans located on the cell container top cover, as it is shown in Fig. 1. The fans are $50 \times 50 \times 20\ \mathrm{mm}^3$ in size and are supplied by the 12 V module voltage with a current of 500 mA. The fans are activated by the BMS when the temperature sensors attached to the cells detect a value above +45°C. The fan load can be considered negligible if compared to the electric motor load, so that the benefit of the active battery temperature control is enjoyed with minimal penalty.

The temperature control of the battery is very important as the thermography of the LFP cell subjected to a discharge of 3C (three times the battery capacity expressed in ampere) shows an average temperature of 40°C, with hot spots where the temperature locally reaches the quite high value of 70°C. The thermal imaging of a 100 Ah LFP cell taken during the experiment is shown in Fig. 2 [11]. It is worth noting that the temperature is not uniformly distributed and shows one hot spot below the positive terminal of the cell.

IV. BMS ARCHITECTURE AND TESTING

Every battery composed of Lithium-ion cells must be accompanied by the BMS, an electronic control circuit that provides the monitoring/management functions that allow the cells to remain in their safety operation area [12]. The main innovative feature of the BMS developed for the modules described in this paper is the active equalization of the cell charges, realized according to the pack-to-cell topology [9], [13]. The peculiar feature is the presence of a circular balancing bus shared between the cells and the modules that allows the intra-module but also the inter-module equalization [15]. Charge balancing is achieved by transferring energy from the more charged cells/modules to the less charged cell, avoiding the energy dissipation that occurs in passive

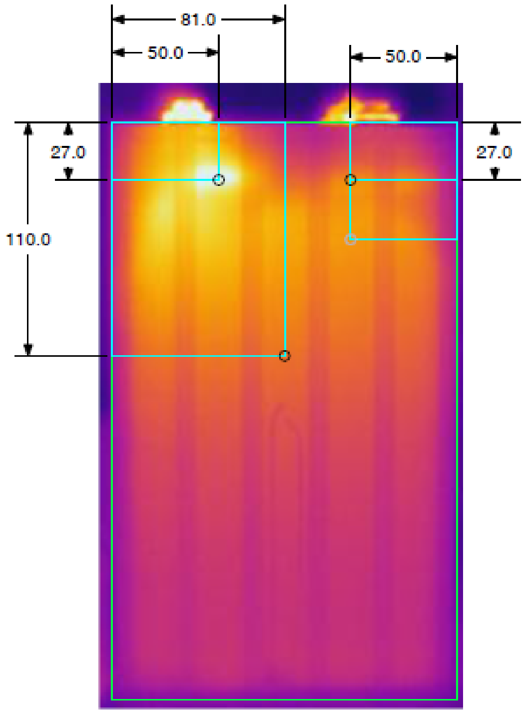

Fig. 2. Thermal imaging of a 100 Ah LFP cell showing a hot spot at 70°C. Dimensions are expressed in mm.

balancing, where the charge in excess is dissipated and not transferred.

Each module is provided with a BMS board that manages 4 cells. The BMS functions of the entire battery are jointly carried out by the electronic boards belonging to each module that are connected in daisy chain. The boards are identical to each other to standardize their production, but each one may be configured as “master” or “slave” in the daisy chain connection. Configuring a board means properly configuring the firmware on the inner microcontroller. Since the firmware is designed with a modular and parameterized structure, the cell capacity is one of the parameters that are configured. Thus, the BMS board is always the same, regardless of both the module function inside the chain and the module size.

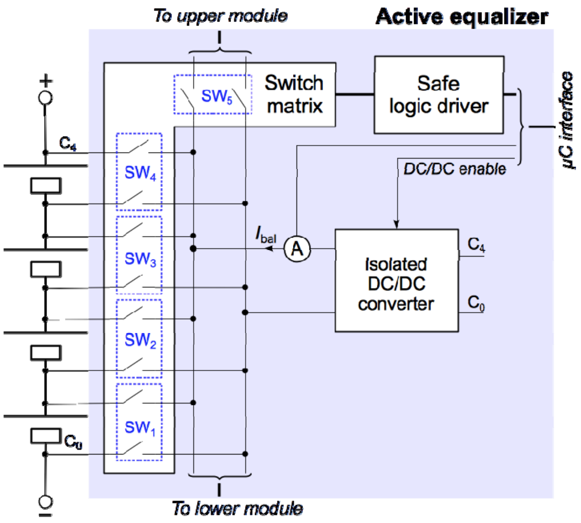

Fig. 3. BMS active balancing circuit. The switch matrix to select a particular cell and the DC/DC converter to recharge it are shown.

The BMS boards communicate to each other by means of an isolated CAN bus. The CAN bus is available outside the battery to allow the connection of an external PC for supervision, diagnostic and logging functions. Each BMS board is attached to the module cells by means of another printed circuit board, by which the power connections from cell to cell and the sense connections to each cell terminal are realized. This solution dramatically simplifies the module assembly, as any connection cable to be manually wired is missing. Should a mass production start, the assembly would completely be automated.

As stated above, the cell balancing is realized according to the pack to cell topology, in which a DC/DC converter fed by the module voltage provides some recharging current to a particular cell selected by means of a switch matrix consisting of MOS switches. Fig. 3shows the active balancing circuit, in which the balancing current to the less charged cell may reach the value of 2 A.

The upper switch reported in Fig. 3 allows the charge balancing between different modules, when activated. As the balancing bus structure is circular, the DC/DC current from one module can reach a cell selected in another module realizing the inter-module balancing. Furthermore, the balancing currents coming from different modules may join into a single cell, to increase the current value up to 6 A and shorten the balancing time. Each of the module cells is provided with a temperature sensor for independent temperature readings. An isolated Hall-based current sensor interfaced to the BMS board acting as master of the battery measures the battery current.

V. CELL AND MODULE PRELIMINARY LIFE TESTS

The proposed approach for the implementation of a generic battery needs an evaluation that also takes the economical aspects into account. To this end, one of the most important factors is the expected lifetime of the cells when exposed to deep and intense charge/discharge cycles that may overcome the rated values. As preliminary experimental test, we have subjected a 60 Ah cell to the cycle shown in Fig. 4.

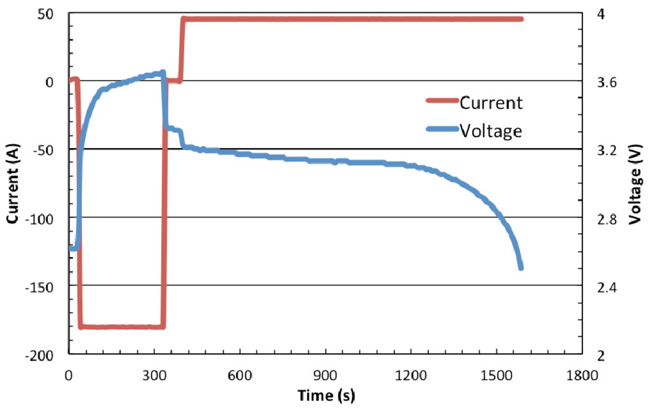

Fig. 4. Experimental fast charge/discharge cycle as life test of the battery.

The application in which the cell is used is an urban transportation minibus and the cycle represents a scenario in which the battery is subjected to fast, brief and repeated recharges.

The cycle consists of a balanced sequence corresponding to an expected path of 5 km followed by 5 min of fast recharge at 3C, corresponding to the stop at the end of the route. It is worth noting that 3C is 3 times (fast charge) the value of the maximum recharge current for a complete recharge and could be dangerous for the battery life. At the same time, the recharge lasts only 5 min (brief charge). Up to now, the cell has been subjected to tests lasting more than 1,000 h, for more than 2,000 charge/discharge cycles, without any observable degradation of the performance. This corresponds to a mission of more than 13,000 km.

VI. CASE STUDY: THE "GULLIVER" REPOWERING

The minibus Gulliver produced by Tecnobus is a small bus for urban public transportation rather spread in small/medium cities of the country. The range autonomy requested in the application described above is achieved by substituting the whole battery pack at midday, with a new fully charged one. A traditional lead-acid battery with the capacity sufficient to complete the daily mission without intermediate recharging stops would result in excessive weight and size of the battery itself. However, the solution doubles the costs, as it requires the availability of two batteries per each minibus: one of them is under recharge at the deposit while the other is operational on the bus. Fig. 5 shows the Gulliver minibus during the battery replacement. The operation is not straightforward but it is quicker that a full battery recharge.

As proposed above, a fast and partial recharge (5-10 min) any time the bus stops at the first stop of the daily route would allow an alternative way of managing the battery energy during the day. In such a framework, the design of the energy storage is based on a route of a few kilometers and leads to a battery of "minimum size", provided that the policy of frequent and fast recharges is applied to the battery.

A battery as small as that of a hybrid vehicle needs in any case to fulfill the requirements in term of available power, both during the discharge and recharge phases. The Lithium-ion batteries are the perfect replacement for the lead-acid ones, because of their high specific power and the almost symmetric behavior.

Fig. 5. Battery replacement at midday stop for the Gulliver minibus.

TABLE IV. GULLIVER MINIBUS AND COURSE CHARACTERISTICS

Bus mass (1,200 kg of lead-acid cells)	6,000 kg
Average speed	20 km/h
Course length (circular)	5 km
Specific energy consumption (per km)	700 Wh/km
Energy for traction	3.5 kWh
Max available recharge power (380 V/64 A)	43 kW
Max energy recharged in 5 min	3.6 kWh

TABLE V. PARAMETERS OF THE BATTERY

Battery voltage	72 V
Module type	12 V/100 Ah
Max string recharge current (2C)	200 A
Number of strings in parallel	3
Total battery capacity	300 Ah
Max. available battery recharge current	600 A
Max. battery power during discharge	64.8 kW

A. Battery minimum sizing

The first activity has thus been carried out to verify the possibility of utilizing the previous described Lithium-ion modules to re-power the Gulliver bus. We chose the 100 Ah module as the elemental building block of the new battery. The modules may be discharged at 3C (the rated value) and recharged at 3C (for brief periods), as in the lifetime test described in Section V, without appreciable degradations. We chose to limit the recharge current to 2C, to reduce the possible stress of the cell. The characteristics of the Gulliver minibus and the expected daily route are reported in TABLE IV. These parameters are the basis for a correct sizing of the battery. All the other parts and characteristics of the bus are left unchanged, in order to end up with a transformation kit consisting only of the new battery and the relevant charger. A simple wired battery/charger connection through a Combo unified connector is the most straightforward way to implement the recharge. An appealing alternative solution consists of the Schunk pantograph depicted in Fig. 6. An inductive charger seems at the moment too expensive for the application and it will be left to further development of the research.

The main constraint in the battery design is the maximum recharge current that is limited to 2C. When this limit is fulfilled, the maximum rated discharge current of 3C seems to

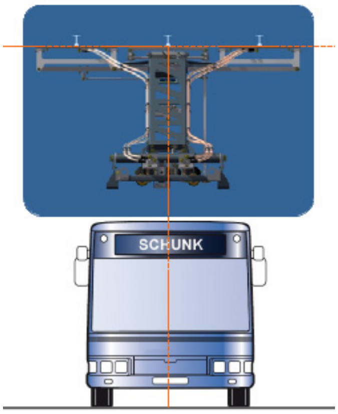

Fig. 6. Schunk recharge station (from www.schunk-sbi.com).

be sufficient for the bus drive. Therefore, the parameters of the battery, the size of which is sufficient for the application, are reported in TABLE V. It is worth noting that the battery voltage value of 72 V allows the utilization of a large kind of commercial chargers of sufficient power, which are rather cheap because of the series production.

Fig. 7 shows the energy stored in the battery during the simulation of a duty cycle of about 8 h, consisting of consecutive repetitions of the course, interleaved with fast (2C), brief (6 min) and frequent (every 21 min) recharges. The course is repeated several times up to a total length of 115 km. It is worth noting that more than 50% of the battery energy has been utilized after 8 h of duty, half of the expected daily operational time. Some additional recharge is thus needed to bring the battery back to the full state of charge, to cover the entire operational period. If the full recharge was not executed, the vehicle could operate for 200 km before the collapse of the battery state of charge below 10%. In any case, the full battery charge would guarantee 14 h of continuous operation.

B. Battery Life Cycle Assessment and proposed sizing

A proper design of the battery must consider some safety margins that take into account the natural degradation of the cells parameters due to aging [14]. The battery design is thus devoted to achieve a long operational period of the vehicle. To replicate the same properties of the original lead-acid battery, the Lithium-ion battery should provide a capacity of 585 Ah. The idea is to design a battery with a size larger than the minimum value calculated in the above subsection. If we connect 6 strings of 72 V in parallel according to the scheme shown in Fig. 8, the volume of the new battery is almost the same of the lead-acid one to be replaced, but the vehicle mass decreases from 6,000 kg to 5,520 kg. An important consequence deriving from having doubled the minimum size battery is that the battery current is halved in term of C-rate, as well as the SoC interval of operation. The battery is significantly less stressed and it is thus foreseen that its life could increase of at least a factor 2, because the life of a battery not only depends on the capacity and power supplied to the load. In fact, the way and the depth of the discharge/recharge cycles affect the battery life. Manufacturers indicate that the life of a battery improves by reducing the depth of discharge. Life tests carried out in our laboratories on lead-acid batteries demonstrated that halving the current triplicates the battery life and that the relationship between aging and current is not linear, being the losses in the battery proportional to the current squared [16], [17]. A further advantage of the current reduction is the reduction of the battery temperature that in its turn leads to less stress.

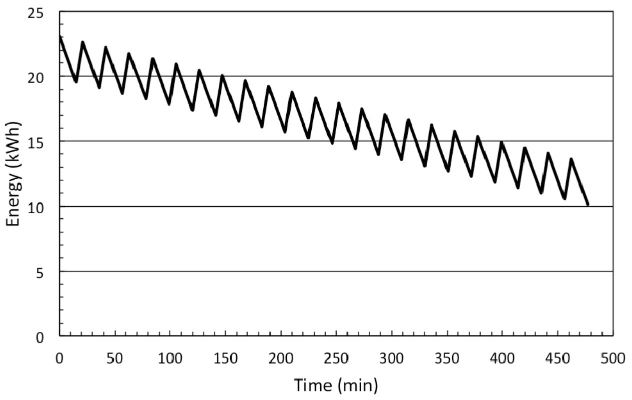

Fig. 7. Battery energy as a fucntion of time with fast recharges cycles.

As the life-tests described in Section V are still running, the end-of-life cost of the new battery is not available yet, and so the comparison between the costs of the “electric” and the “conventional” public transportation solutions is not possible. However, life tests carried out on other cells of similar chemistry show that a useful life expectation (calculated when the residual capacity reaches 80% of the initial value) of 100,000 km is a reasonable value. In addition, a vehicular battery might be used for a second life application in stationary storage systems after the above limit is reached.

As far as the module cost is concerned, only half of it is due to the cells. Therefore, a used module may be regenerated many times by substituting the cells only, with costs well below that of a new one. If we take the 100 Ah module as example, the cost of the cells (presently around 220 €/kWh), the two electronic boards, the fans and the container, we foresee a cost of 300÷400 €/kWh, with a production of 10,000 modules, corresponding to about 300 buses.

VII. CONCLUSIONS

The standard modules described in this paper are suitable for the public transportation application considered, even if consisting of LFP cells, cheaper and safer than the NMC ones. Standardizing the module in three sizes further allows cost reduction, as any battery size can be built with series/parallel combinations of modules.

The preliminary life-test experiments on the considered LFP cells show that the cells withstand fast charges without performance degradation and are thus suited to a public transportation application where a minibus is subjected to continuous brief cycles of fast charges, with the valuable advantage of halving the mass of the storage system.

The completion of the currently ongoing life tests is necessary to assess the economic advantage derived from the

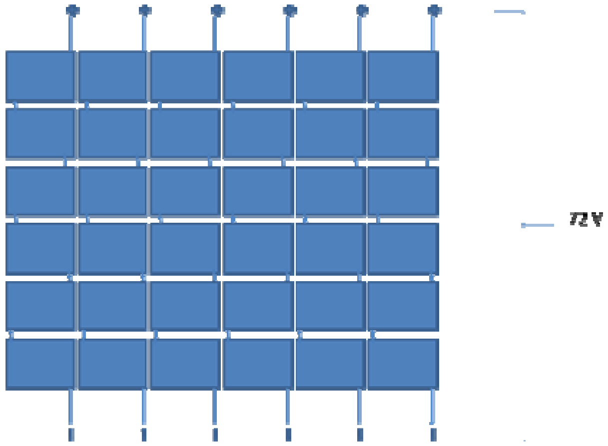

Fig. 8. Final battery layout with 6 paralled strings of modules.

replacement of the lead-acid with the new Lithium-ion battery. However, a very much longer life is expected as the battery is mostly exercised with less current and in the middle part of the SoC region.

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