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Fast charge life cycle test on a lithium-ion battery module

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Summary

The paper analyzes the effects of fast charge on a lithium-ion battery module made by 4 lithium-iron-phosphate cells series connected, submitted to a test profile which includes a fast charge step at current rate 3C. This test profile simulates the real working profile requested to the batteries of a electric bus to perform a particular service of local public transportation with recharge of the batteries at the end of line. More than 3,000 shallow cycles were performed: the battery module did not show a significant reduction of performances in terms of capacity and energy, but, on the other side, a relevant increase of the inner resistance was observed. As an effect of this, the autonomy of the electric bus is reduced correspondingly. Fixing a minimum value for the autonomy, a life estimate of the battery module was made. Finally, on the base of this result, a cost estimate and comparison between slow and fast charge was made, under the same service conditions and all through the vehicle life, for a real case of a minibus equipped with a battery system sized for fast charge at the end of line and a larger battery system sized for slow charge at the end of a working day. This comparison proved that, in the case study considered, the solution with fast charge is cheaper and the fast charge can be a valid instrument to solve the problem of short autonomy of electric vehicles.

Keywords: battery, cycle life, fast charge, life cycle cost, public transport

1 Introduction

The autonomy of electric vehicles is an important factor affecting their diffusion in the market, so fast charge is one of the most significant topics to investigate. ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) has been doing researches on life tests of battery systems for electric vehicles for different years [1,2] and in the last years it is increasing the experimental activities in the sector of life cycle testing of lithium batteries for fast charging.

Literature offers a lot of data about characterization, life cycles or ageing testing, and modeling of lithium-ions cells [3]÷[7]. Otherwise, a few results are available about testing with real working profiles and/or experiences with complete battery systems on board of electric vehicles [8] ÷ [10].

2 Battery module

The battery module is 12.8 V – 60 Ah. It was developed and realized by ENEA in collaboration with the University of Pisa, Department of Information Engineering, under the founding of the Italian Ministry of Economic Development in the framework of the Program Agreement for the Research on National Electric System. It is made of 4 lithium-iron-phosphate cells series connected and it is equipped with a battery management system (BMS), Figure 1 and Table 1.

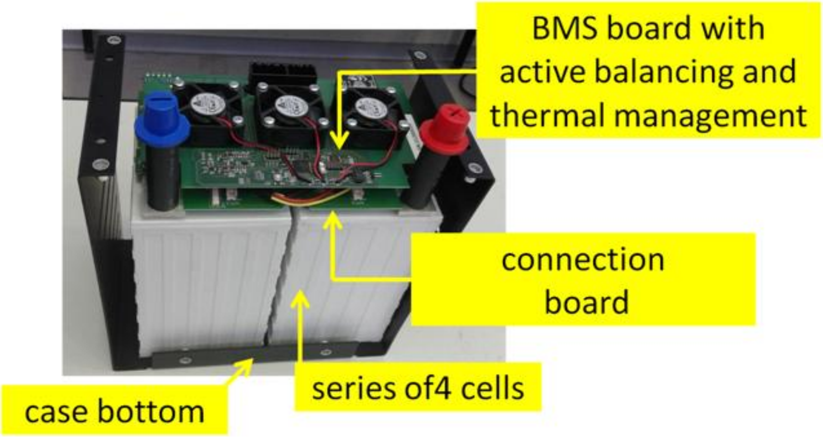

Figure 1: Battery module under test

Table 1: Main characteristics of the battery module

Cells	Type	Lithium-ion
	Cathode	LFP
	Anode	Graphite
	Number	4
	Connection	Series
Capacity		60 Ah
Dimensions		297x166x236 mm
Weight		12.3 kg
Voltage	Nominal	12.80 V
	Minimum	10.00 V
	Maximum	14.60 V
Max continuative current	Discharge	180 A (3C)
	Charge	60 A (1C)
Working temperature	Discharge	-20 ÷ +60°C
	Charge	0 ÷ +45°C
Balancing (operated by BMS)		Active
Cooling (managed by BMS)		3 x 12 V_{DC} 34.5 Nm^3/h – 75.5 Pa @ 7000 rpm fans

3 Test procedure

The test procedure is resumed in Table 2. It is consistent with a typical LPT (Local Public Transport) mission, where the battery system of the electric bus is recharged at the end of line.

Table 2: Test procedure

Step number	Step type	Step characteristics	Step end conditions	Comment	Correspondence with LPT mission
01	Rest		60 s	Life cycle profile with fast charge	Stop at end of line. Disconnection from charging station
02	Discharge	CC @ 1C	900 s or V_{min}		Travel
03	Rest		60 s		Stop at end of line. Connection to charging station
04	Charge	CC/CV I_{max} = 3C	300 s		Stop at end of line. Fast charge
05		Go to step 1 and do the loop from step 1 to step 4 for 48 times		Loop	Operation for 16 h without interruption
06	Rest		7200 s	Slow charge	Slow charge and balancing during night at the garage
07	Charge	CC/CV I_{max} = C/3	Complete charge		
08	Rest	Rest while the BMS provides the balancing function		Balancing	

The ENEA's battery module is equipped with a battery management system which realizes the thermal control, so it was possible to run it in charge at rate 3C, even if the maximum rate in charge recommended by the cells manufacturer is 1C, and the temperature remained in the normal working range. This was appositely chosen to better highlight the effects of fast charge. Further, the BMS provides an active balancing of the state of charge of the cells by means of a converter that takes energy from the overall module and supplies the most discharged cell in the module through a switch matrix. To avoid unbalancing, a slow charge with balancing was introduced in the test procedure every night, before starting the test sequence the day after. An example of the repetitive execution of the test profile, from step 01 to step 04, is shown in Figure 2 (current in red, module voltage in blue).

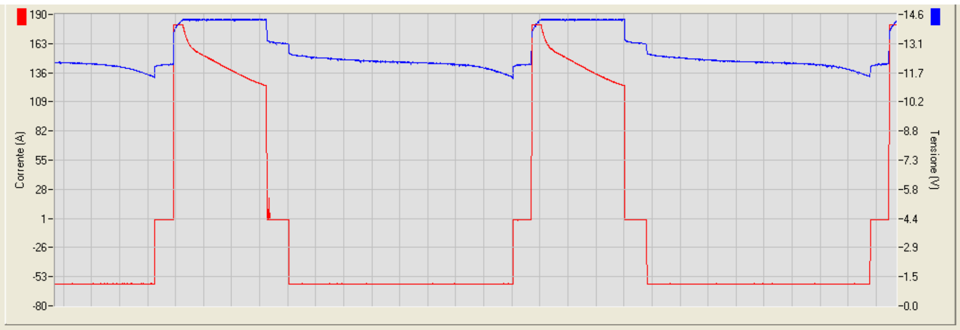

Figure 2: Test profile

The test procedure was performed by one of the bidirectional AC/DC converters (cyclers) belonging to the equipments of the ENEA's "Systems and Technologies for Mobility and Storage" Laboratory.

The cycler is an electronic equipment able to run charge and discharge of the storage system according to planned and controlled conditions: it is possible to set the way of charge/discharge, the current/power value, warning and alarm conditions for each step of the test procedure. It works as a power supply during charge and as a load during discharge. The energy drawn from the storage system during discharge is given to the grid (regenerative function).

The cycler produces a test result in form of a .csv file where the values (measured and registered) of the physical characteristics are reported in a table, see Table 3.

During the test configuration, it is possible to set the data sampling rate, up to the minimum value 0.1 s[a]. It is possible to set different values of the data sampling rate in the different steps of the same testing procedure.

The tests were performed at +25 °C, guaranteed by the air conditioning system of the test room (no climatic chamber was used).

Table 3: Row of the data registered by the cycler

Date hour	Cycle number	Step number	Mycro cycle number	Step time	BS Voltage	Current	Step capacity	Step energy	Total capacity on charge	Total energy on charge	Total capacity on discharge	Total energy on discharge	Temperature (K)	Temperature (Pt100)
				[s]	[V]	[A]	[Ah]	[Wh]	[Ah]	[Wh]	[Ah]	[Wh]	[°C]	[°C]

The cycler is equipped with a temperature sensor K type and a temperature sensor Pt100 type: the temperature sensor K type was positioned inside the battery module (between two cells, in the middle) while the temperature sensor Pt100 was positioned outside the battery module, nearby it, to register the room temperature.

The temperature of the cells was measured by NTC sensor applied on the cells, one sensor on each cell. The values measured by these sensors are sent to the BMS, which register and manage them to verify that the temperature of the cells remains in the normal working conditions and, if necessary, the cooling system is activated or the battery is disconnected (final safety action).

4 Test results

During performing the test procedure, all the electric and thermal quantities always remained in the normal working conditions.

The test procedure was periodically interrupted to check the performances of the battery module. The check consists in a capacity and energy measure, taken during a standard cycle of charge and discharge according to the current rate recommended by the cells manufacturer, and a measure of the inner resistance. More than 3,000 cycles were executed without registering a significant reduction of performance in terms of capacity, energy and efficiency, as shown in Figure 3.

The evaluation of the inner resistance is shown in Figure 4: a relevant increase (around twice as many the initial values) was registered in the parametric checks executed after 1000÷2000 repetitions of the test procedure.

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[a] Data related to the cycler used to perform this test procedure. The best performance available from the cyclers in the Lab is 0.01 s (100 Hz).

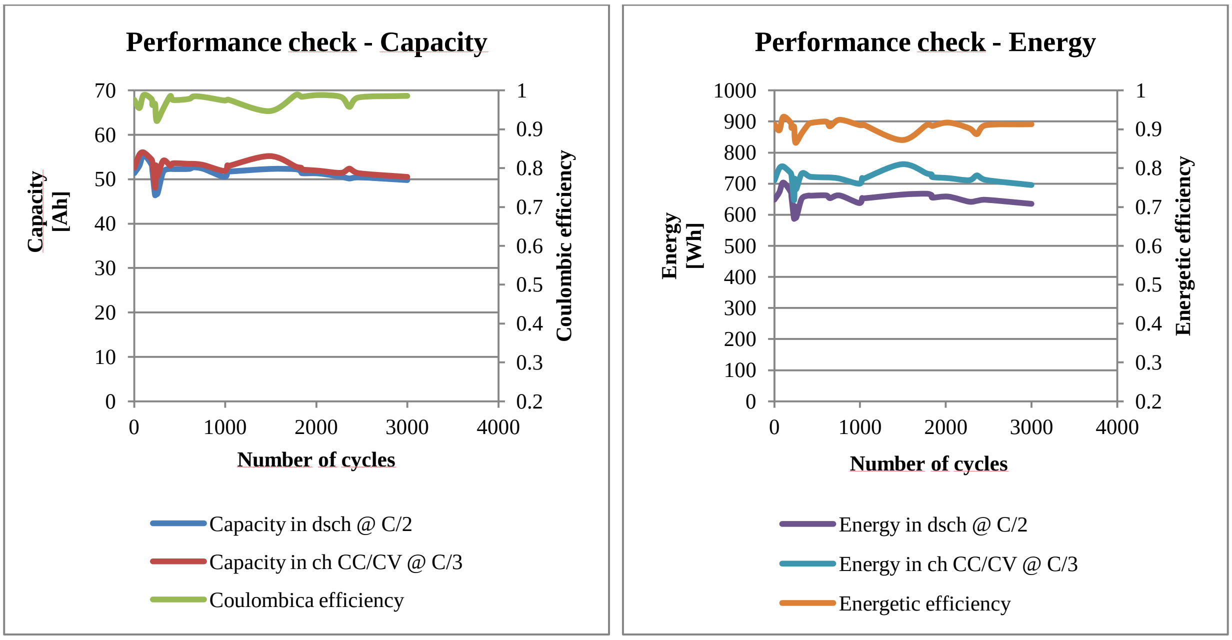

Figure 3: Capacity and energy of the battery module in the parametric check

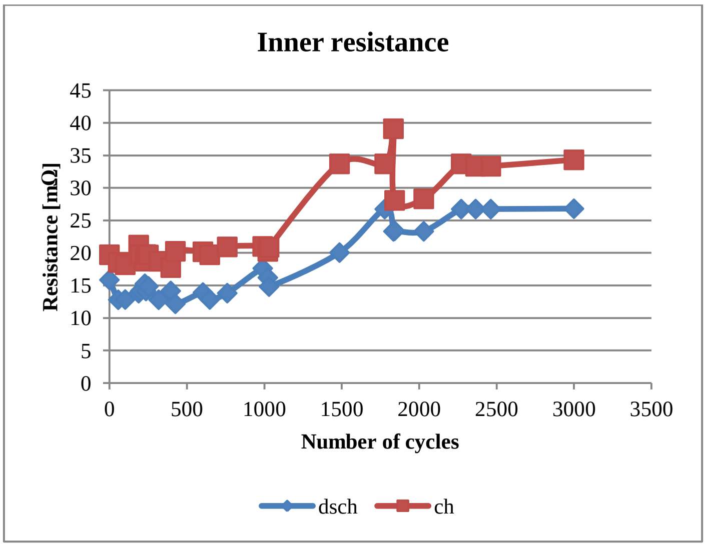

Figure 4: Inner resistance of the battery module

5 Life estimate of the battery module

Due to the increase of the inner resistance, both in charge and discharge, the length of the step 02 (discharge)/04 (charge) in the test procedure progressively reduces during the ageing because the minimum/maximum voltage is more quickly reached. Starting from the initial theoretical value 15 Ah, progressively the battery module reduces its capacity in the steps 02 (discharge) and 04 (charge) of the test procedure and correspondingly the electric bus, in the analogy with the LPT mission, reduces its autonomy. This situation is shown in Figure 5. For this reason it seems more realistic that the “end of life” condition is provoked by the increase of inner resistance rather than the capacity reduction measured in the parametric check (as the usual assumption for the battery systems in vehicular applications).

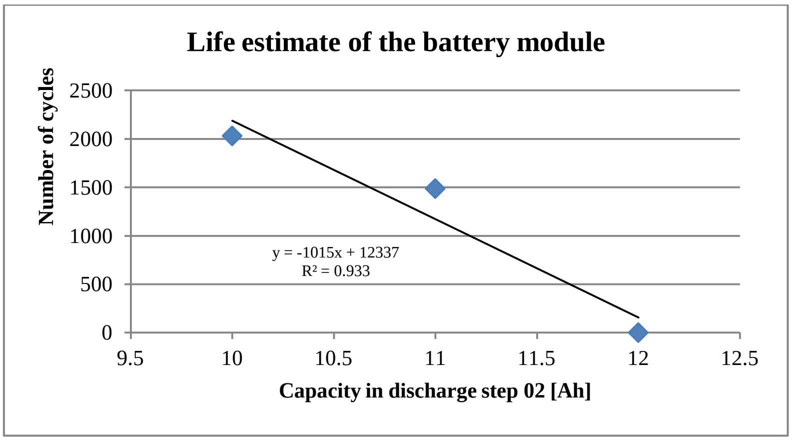

Figure 5: Life estimate of the battery module

Considering the real case of a minibus whose battery system is realized by 24 modules like the one used for the test, it was fixed 5 km as the minimum distance sufficient for a TPL mission and (using the correlation with the kilometric consumption) calculated the corresponding capacity necessary to cover such a distance. In these conditions, the minimum capacity required to the single battery module is 5.5 Ah. At this point, it is possible to estimate the life of the battery module using the trend line that better fits the experimental data relating to the capacity drawn in the discharge (step 02 of the procedure), see again Figure 5. The life expected is about 6,750 cycles.

6 Cost estimate and comparison between slow and fast charge

On the base of the above result, a cost estimate and comparison between slow and fast charge was made, under the same service conditions and all through the vehicle life, for a real case of a minibus equipped with:

(i) a battery system sized for fast charge at the end of line,
(ii) a larger battery system sized for slow charge at the end of a working day.

The cost estimate is resumed in Table 4.

Table 4: Battery system cost estimate

	Fast charge (3C)	Slow charge
Service time	16 h	16 h
Commercial speed	12 km/h	12 km/h
Duty cycle	75 %	75%
BS capacity	240 Ah	1000 Ah
Distance covered in a day	144 km	144 km
BS weight	288 kg	1200 kg
Vehicle life	12 y	12 y
BS unitary cost	500 €/kWh	500 €/kWh
BS total cost	8˙640 €	36˙000 €
BS life	20 months	72 months

The comparison is based on a 16 h (two shifts, 8 h each one) service and a commercial speed of 12 km/h.

Considering a duty cycle 75% (15’ charge and 45’ travel in one hour of the service) the minibus of situation (i) (fast charge at the end of line) covers 144 km in a day. The same distance is assigned to the situation (ii) (slow charge).

The nominal capacity of the storage system in the situation (i) is 240 Ah. This data is relating to a battery system made by 24 modules like the one here shown, really realized and used by ENEA, in collaboration with the “Centro Ricerche per il Trasporto e la Logistica” of Rome’s University “La Sapienza”, to retrofit a minibus “Gulliver” from Tecnobus, originally equipped with lead batteries. For this minibus, in the configuration with lithium batteries, a kilometric consumption of 325 Wh/km on a specific route located into the ENEA’s “Casaccia” Research Centre was measured. The battery system is organized in 4 strings in parallel connections, each one of them is made by 6 modules series connected, to reach the working voltage (72 $V_{nominal}$) required by the drive train. In the situation (ii), a broadly estimate of the battery system’s size is possible as the multiplication of the kilometric consumption (assumed 500 Wh/km due to the bigger weight of the battery system itself) and the daily distance, the result to be divided for the nominal voltage.

The weight of the battery system is the multiplication of the weight of one battery module (12 kg) and the number of modules used to reach the working voltage and capacity of each use case.

According to the typical values coming from the specialized scientific literature, vehicle life is considered 12 years long.

In the use case (ii) (slow charge) the daily working cycle is similar to a standard cycle, where the vehicle covers all its daily distance using all the capacity installed on its storage system and charges slowly and completely during night. In a good accuracy, the life of the battery system can be estimated by the number of cycle (conveniently reduced) given by the cells manufacturer relating to the standard cycle. By using the distance covered in a day, the number of cycles (that is the life of BS) can be immediately converted in number of days or months.

In the use case (i) (fat charge) the result of the present life cycle test can be usedb: because the discharge (step 02 of the testing procedure) draws theoretically 15 Ah, that is ¼ of the battery module’s nominal capacity, it can be assumed that 4 cycles of the test procedure correspond with one complete discharge. So, with first accuracy, the number of equivalent cycles with deep discharge can be calculated as the number of cycles with partial discharge (from the test results) divided by 4. The number of cycles with deep discharge, equivalent to the real number of cycle with partial discharge, can be converted firstly in distance coveredc and then in number of day and monthsd.

The purchase cost of the BS can be calculated as the multiplication of the unitary cost, assumed 500 €/kWh (data coming from direct experience of recent purchases), and the nominal energy of the BS.

Considering the battery system’s cost and duration, it is now possible to calculate the operational cost of the electric minibus’ battery system all through the vehicle life as a sum of the actualized purchase costs of the battery system and the charging costs (assumed average charge cost: 0.15 €/kWh). Figure 6 summarizes the results.

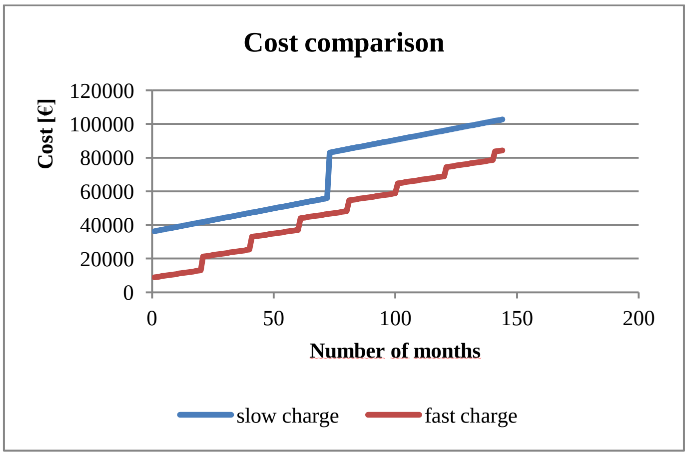

Figure 6: Cost comparison

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[b] Even if the commercial speed relating to the life cycle test is, theoretically, about 56 km/h.
[c] By using the nominal energy of the BS and the kilometric consumption.
[d] By using the daily distance.

7 Conclusions

The life cycle test had a prudential approach. In fact:

- the cells of the battery module have 1C as the maximum C-rate in charge;
- the battery module used for the life cycle test is not completely new, but it was previously used in characterization and short, not heavy, life cycle tests;
- the life cycle test was performed in heavier conditions compared with the ones strictly required from the corresponding TPL mission (5 km in 15', 20 km/h, about 20 A in discharge - step 02 of the test procedure – while this step was performed at 60 A all the test long)

This choice to perform a prudential test was specifically done on purpose to highlight the effects of fast charge on a battery system, even in the case of shallow cycles as the ones performed in this experience.

The test procedure is consistent with a typical mission required by the local public transportation for a minibus. The electric charge stored during the fast charge at the end of line is sufficient to cover the service distance so the minibus can work without interruption. In absence of fast charge, the service would be stopped periodically to charge the battery or the minibus should be equipped with a larger battery system. In fact, the fast charge allows to equip the minibus with the battery system which has the minimum size to make its transport mission.

Even if in a prudential approach, it was possible demonstrate that in an analysis where it is made the comparison between the life cycle cost of a battery system for a minibus, realized:

(i) with a minimum size, i.e. the electric charge stored during the fast charge at the end of line is exactly the one needed to cover the service distance so the minibus can work without interruption,
(ii) with a larger size, i.e., with the same daily service/distance of the use case above, the minibus only charges slowly and completely its battery system at the end of a working day,

it is more convenient to equip the minibus with the smaller battery system, using the fast charge at the end of line.

The case studied suggests that fast charge, thought not in absolute way, but in the proper combination/balance with the size of the battery system and the vehicle mission, can be a valid instrument to obtain a cost effective solution and solve the problem of short autonomy of electric vehicles. This is particularly true in the LPT field.

Nomenclature

BMS	battery management system
BS	battery system
C	nominal capacity value
CC	constant current
CC/CV	constant current/constant voltage
ch	charge
C/n	current rate stated as sub-multiple of the nominal capacity value
csv	comma separate values
dsch	discharge
I_{max}	maximum allowable value of current
LFP	lithium-iron-phosphate
LPT	local public transport
nC	current rate stated as multiple of the nominal capacity value
V_{min}	minimum allowable value of voltage

V_{max} maximum allowable value of voltage

$V_{nominal}$ nominal voltage

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