

EVS29 Symposium
Montréal, Québec, Canada, June 19-22, 2016

Effects of fast charge on a lithium-ion battery system

F. Vellucci¹, G. Pedè¹, F. Baronti², R. Di Rienzo², F. Cignini²

¹*ENEA, Laboratorio Sistemi e tecnologie per la mobilità e l'accumulo, Santa Maria di Galeria (Roma), Italy,*
francesco.vellucci@enea.it

²*Università di Pisa, Dipartimento di Ingegneria dell'Informazione, Pisa, Italy,*
federico.baronti@iet.unipi.it

³*Università "La Sapienza", Centro di ricerca per il trasporto e la logistica – Officina della mobilità, Roma, Italy,*
fabio.cignini@uniroma1.it

Summary

The paper is related to a study that analyzes the effects of fast charge on a lithium-ion storage system at its different architectural levels: cell, battery module, complete battery system. A first set of tests was executed on a lithium-iron-phosphate cell subjected to a test profile which simulates the real working profile requested to the batteries to perform a particular service of local public transportation. This test profile includes a fast charge step at current rate 3C. More than 2000 cycles were executed and the cell did not show a significant reduction of performances. This encouraging result suggested to move up a grade in the architectural level, so a second set of tests was executed on a battery module made by 4 lithium-iron-phosphate cells series connected, submitted to the aforesaid test profile conveniently adapted to module level: before succeeding to perform the test profile, it was necessary to overcome different problems mainly due to the unbalancing of the cells which is particularly emphasized by the fast charge. These problems are typical of the battery packs, where more cells are connected together. The battery and thermal management systems housed inside the module made possible an optimization of the performances: more than 1600 cycles were executed with good results and the test is still in progress till to reach the end of life condition. The final grade of the experiment will be the test of 24 modules connected together to build a complete battery system installed on board a real minibus working according the mission above defined. The description of the problems encountered and test results related in the paper tries to give a good information about the impact on the performances and life of a storage system submitted to fast charge.

Keywords: BMS (Battery Management System), charge equalization, cycle life, fast charge, lithium battery

1 INTRODUCTION

The electric vehicles limited range is an important factor affecting their diffusion in the market, therefore fast charge is one of the most significant topics to investigate. ENEA (Italian National Agency for New Technologies, Energy and Sustainable Economic Development) started researches on life cycle tests of

battery systems for electric vehicles many years ago [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 charge.

Literature offers a lot of data about characterization, life cycles or ageing testing, and modeling of lithium-ions cells [3]÷[7]. But, on the other side, 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 TEST PROFILE AND RESULTS AT CELL LEVEL

A lithium-iron-phosphate cell 3.2 V – 60 Ah was submitted to a life cycle test based on the following profile:

- discharge at 2/3C for 1200 s,
- rest for 60 s,
- fast charge at current rate 3C for 300 s
- rest for 60 s.

The quantity of electric charge drawn from the cell during the discharge step is the same of the one stored in the charge step, Fig. 1.

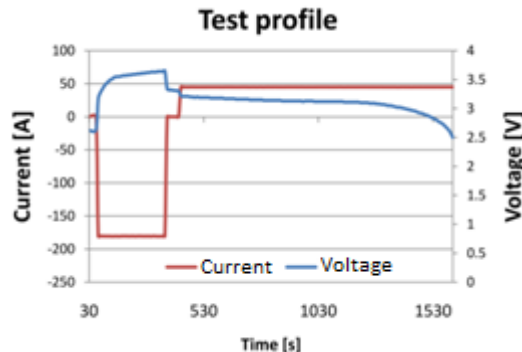


Figure 1: Test profile for cell (*current > 0* discharge, *current < 0* charge)

The maximum charge current rate recommended by the manufacturer is 1C, while the test profile submits the cell at 3C during the fast charge step: for this reason, the cell is a good example to emphasize the effects of fast charge. The physical quantities assumed to investigate the behavior of the cell during the execution of the life cycle test are the temperature and the capability to complete the charge and discharge steps depending on the value of the state of charge. Performances are checked periodically by the execution of a complete discharge at constant current $C/2$ (standard discharge) from the state of battery completely charged, followed by a complete charge type constant current/constant voltage at $I_{\max} C/3$ (standard charge, as suggested by the manufacturer of the cells): this sequence is used for the calculation of the capacity drawn in the complete discharge and the efficiency in the cycle of complete discharge/charge.

More than 2000 cycles were executed and the cell did not show a significant reduction of performances as shown in Fig. 2. No deformation occurred.

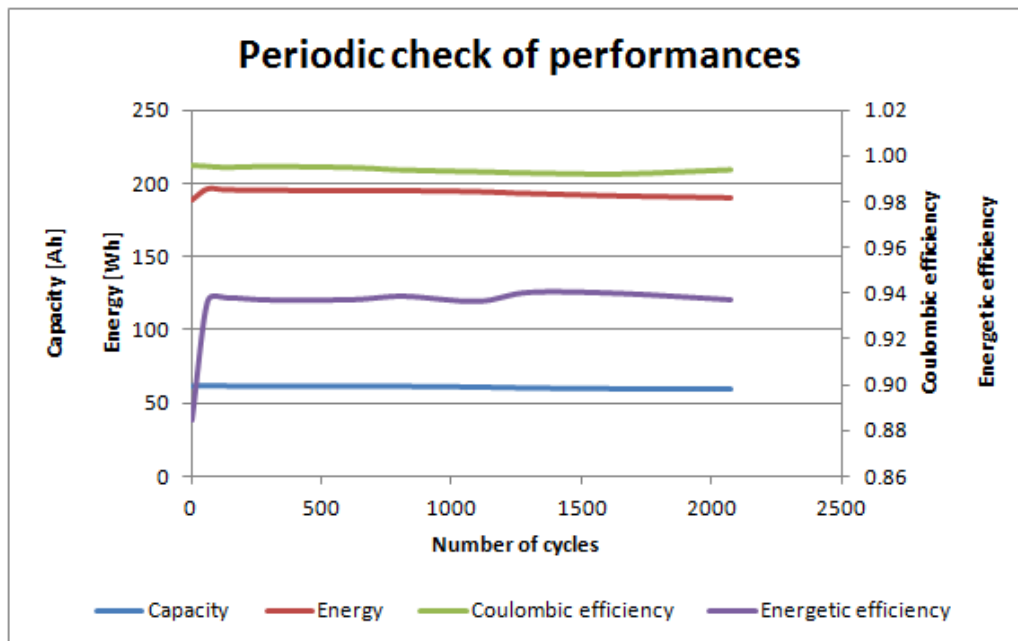


Figure 2: Periodic check of performances during the life cycle test at cell level

3 EFFECTS OF FAST CHARGE AT MODULE LEVEL

The encouraging result at cell level suggested to move up a grade in the architectural level, so a second set of tests was executed to investigate the effects of fast charge on a battery module 12.8 V – 60 Ah realized in ENEA by 4 lithium-iron-phosphate cells series connected. The battery module was equipped with a battery and thermal management system, Fig. 3.

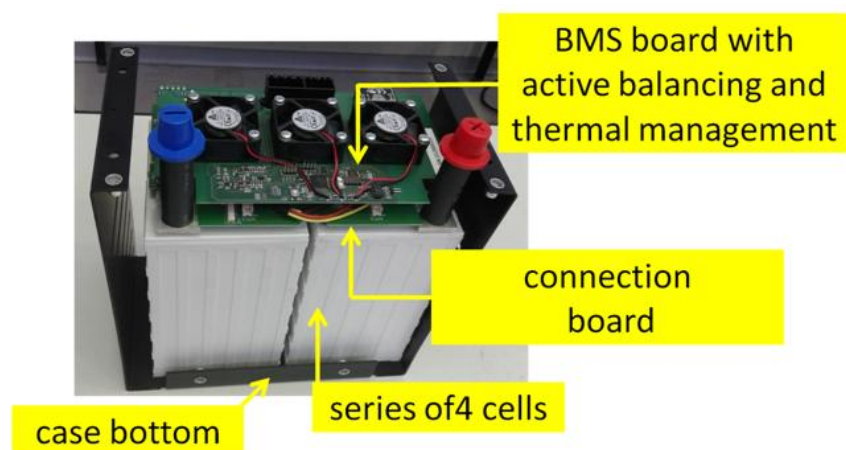


Figure 3: Battery module under test

The initial intent was to submit the battery module to a test profile including a fast charge at constant current 3C for 300 s.

Even if the cells of a pack are nominally all equal, they are really all different, because of manufacturing tolerances, variance in dimensions, internal resistance, self discharge, therefore, the battery module encountered different problems when the fast charge was applied: during the fast charge, the high current causes the cell voltage rises immediately and the working point moves towards the maximum cell voltage and it can happen that one or more cells goes over the limit and the alarm system stops the charge before completing the programmed charging time. This doesn't happen in the case of the single cell, because the charger manages precisely the cell voltage, while in the case of the battery module it manages the module voltage. This situation is emphasized by the unbalancing of cells: Fig. 4 shows how some cells in the module go over the threshold of maximum cell voltage.

If the cell voltage is not measured directly on the poles of the cells, but it is measured downstream the terminals or connection elements, also the contact resistance plays an important role in shifting upwards the working point.

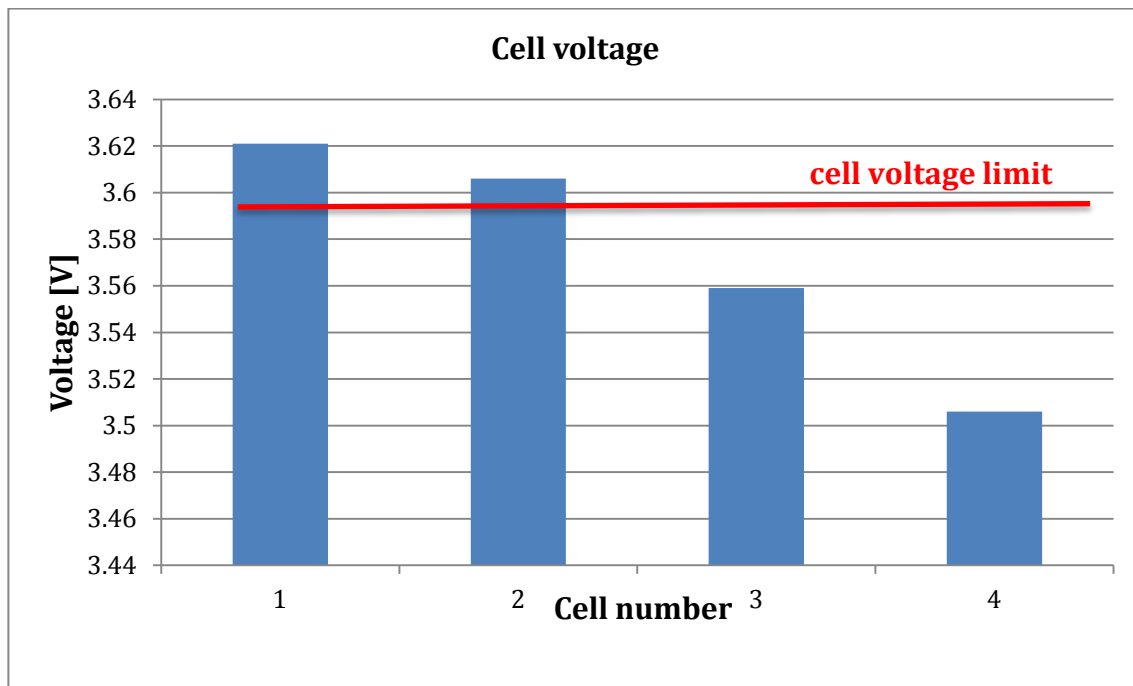


Figure 4: Cell voltage during fast charge

The attempt to supply the fast charge was repeated at different SOC levels: 75%, 50%, 25%. The behavior mentioned above was observed at all these SOC values. Obviously, the negative effect of fast charge is as bigger as the SOC is higher.

To help the battery module in accepting the fast charge, it was decided to change the type of charge from CC (constant current) to CC/CV (constant current until the voltage reaches the maximum value allowed for the module and then reduce progressively the current value so to maintain the voltage value). Fig. 5 shows the comparison between the two type of charge.

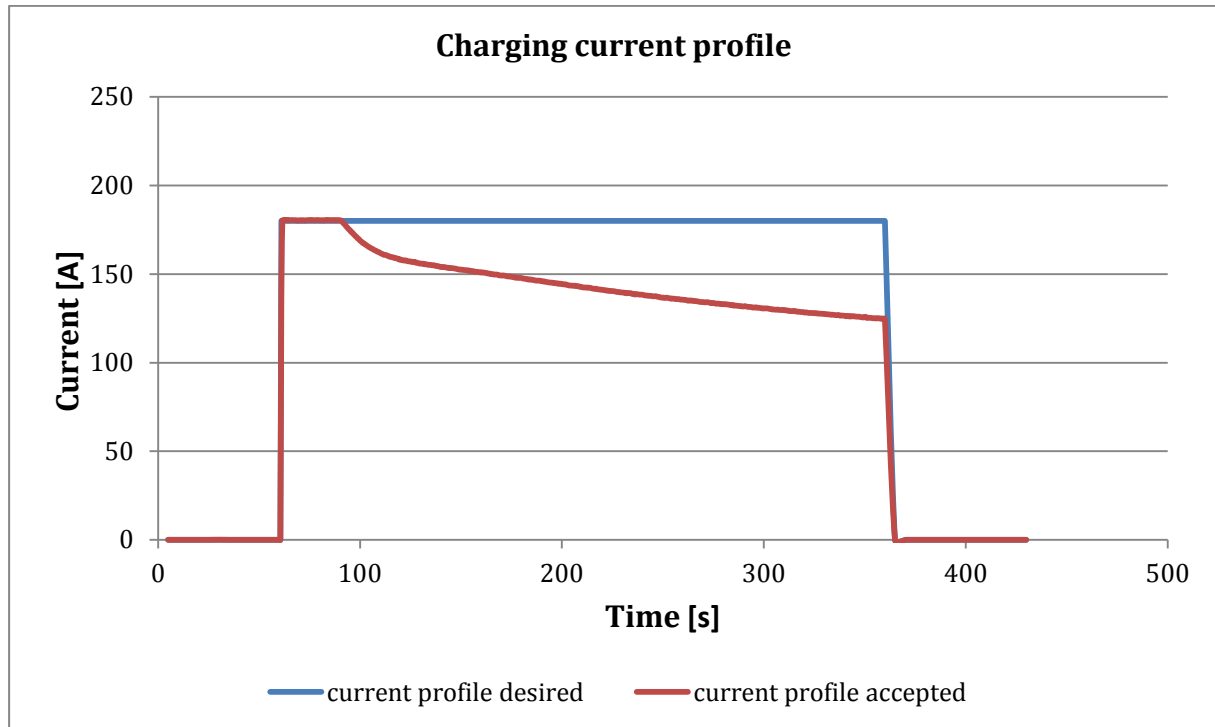


Figure 5: Charging current profile

This allowed the acceptance of the charge without interruption operated by the alarm system. The following conditions were observed:

- when the SOC value is high, the charger immediately regulates the current to not go over the maximum voltage limit so the maximum C-rate is less than 3C;
- when the SOC is lower, the charger reaches the C-rate 3C and maintains this current value until the module voltage reaches the maximum voltage limit and then it reduces progressively the current value in order to maintain the voltage value until the end of the programmed charging time. The duration of the part at 3C is as longer as the SOC value is lower.

This behavior will be shown in details in the section relating to the test profile used for the battery module.

4 TEST PROFILE AND RESULTS AT MODULE LEVEL

4.1 Test procedure

After the considerations above mentioned, the life cycle test on the battery module was realized changing the fast charge from CC to CC/CV: this is to help the cell voltage to remain under the limit. The fast charge is followed by a discharge at constant current 1C for 900 s. The execution of the test profile is shown in Fig 6, directly drawn from the computer associated to the cyclers used to perform the life cycle test.

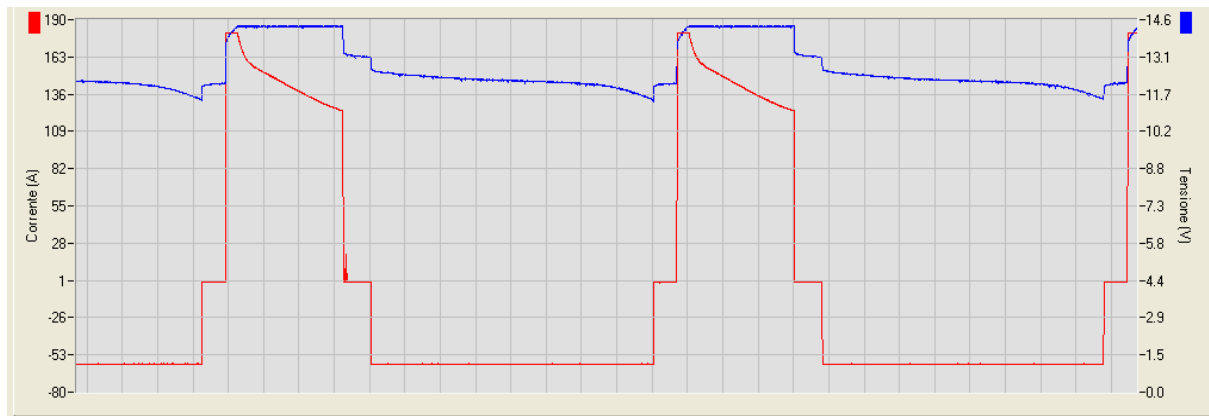


Figure 6: Life cycle profile used at module level

The current (considered positive in charge) is symbolized in red and the current axis is on the left side of the diagram, while the module voltage is in blue and its axis is on the right side of the diagram.

After 30 repetition of the charge/discharge profile reported in Fig. 6, it was introduced a slow charge followed by a balancing phase. In fact, the battery module built in ENEA is equipped with a battery management system (BMS), shown in Fig. 7, which realizes an active balancing of the state of charge of the cells by means of a converter that takes energy from the overall module and, in turn, supplies the most discharged cell in the module through a switch matrix. This equalization compensates the unbalancing accumulated during the execution of the life cycle profile and helps the cells to remain under the upper voltage limit during the fast charge.

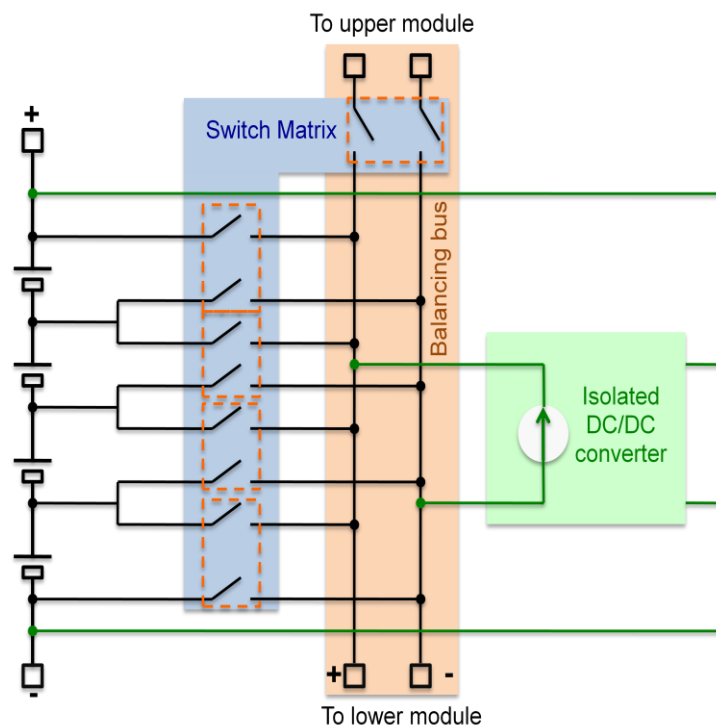


Figure 7: Schematic of BMS

The complete test procedure is reported in Table 1.

Table 1: Complete test procedure

Step number	Step type	Step characteristics	Step end conditions	Comment	Correspondence with TPL mission
01	Rest		60 s		Stop at end of line Disconnection from charging station
02	Discharge	CC @ 1C	900 s or $V_{\min}$	Life cycle profile with fast charge	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 30 times		Loop	Operation for 10 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 complete test procedure is consistent with a typical mission required by the local public transportation (TPL) for a minibus which, during the normal stop at the end of line, recharges the energy to cover the distance of its operational service by the means of a fast charge. This correspondence is shown in the last column of Table 1, at the right: the rest steps represent the connection/disconnection to/from the charging station, the fast charge represents the phase to store the energy necessary to cover the distance of the bus service which corresponds to the discharge. One loop of discharge and fast charge takes 1320 s, so 30 iterations correspond to 1 working day of 10 h of operation without interruption of the service or bus substitution. The behavior of the battery module in terms of electric quantities is shown in Fig. 8.

In the CC/CV type charge, the charger is set to charge at a constant current (CC phase) until the maximum voltage limit of the battery module is reached, then it maintains this voltage value (CV phase) reducing progressively the current value until the end of time of the charge phase (300 s, accordingly with Table 1). The current value in the CC phase is less or equal to 3C and it is decided by the charger in function of how much current the module battery is able to accept without going over the upper voltage limit. In the first cycles, the maximum charging rate 3C is not reached because the SOC value is high and the charger immediately regulates the current so to not go over the maximum voltage limit. Anyway, the maximum value of the charging current increases quickly with the number of cycles and after a few iterations it reaches 3C.

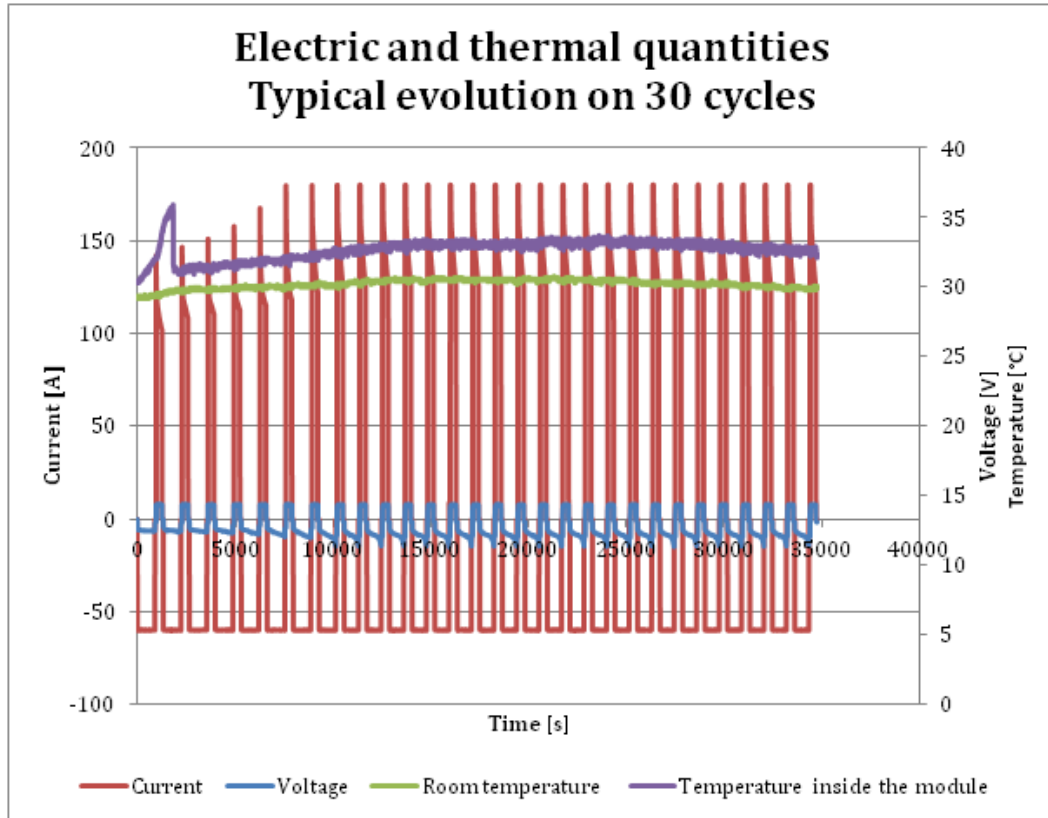


Figure 8: Typical evolution of the battery module's electric quantities during the life cycle profile (*current > 0 charge, current < 0 discharge*)

Correspondingly, the quantity of electric charge stored in the battery module during the charge phase increases with the number of cycles. As long as the electric charge stored in the charge phase is lower than the electric charge drawn in the discharge phase, the battery module generally discharges and the voltage value at the end of the discharge phase decreases until it reaches the minimum voltage and the discharge finishes before the programmed time of 900 s: correspondingly, the quantity of electric charge drawn in discharge decreases until it is equilibrated by the quantity of electric charge stored in charge. This equilibrium condition is reached after 8 ÷ 9 cycles, the SOC value (at the beginning of the cycle) is about 33% and the quantity of electric charge at the balance is 12 Ah, as shown in Fig. 9.

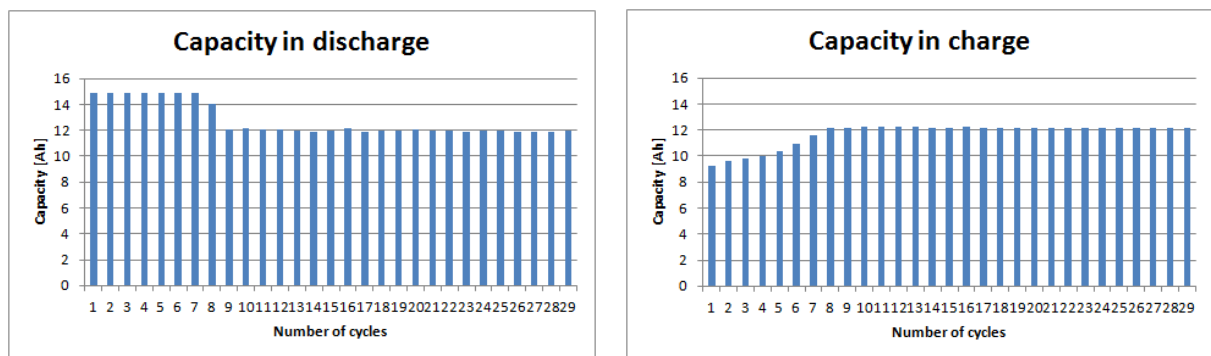


Figure 9: Typical evolution of the quantity of electric charge in charge/discharge during the life cycle profile

When this equilibrium condition is reached, the battery module can theoretically work indefinitely. For example, Fig. 10 shows the situation during the execution of the 24TH cycle: the battery module has supplied a quantity of electric charge that is bigger than 4 times the nominal value. In a service without the fast charge, this would have required 4 complete recharges at least, with interruption of the service or substitution of the bus. In the module, the temperature is controlled by 3 fans, 12 V_{DC} 34.5 Nm³/h – 75.5 Pa at 7000 rpm each one, managed by the BMS: the test was executed at room temperature +23 °C, the BMS switches on the fans (one or all together, if necessary) when one or more cells reach the temperature +33 °C and switch off when the temperature decreases at +30 °C. The working of the thermal management system is shown in Fig. 11. The temperatures of switch on/switch off the fans is settable when configuring the BMS before the battery module starts to work.



Figure 10: Print screen during the execution of the 24TH cycle

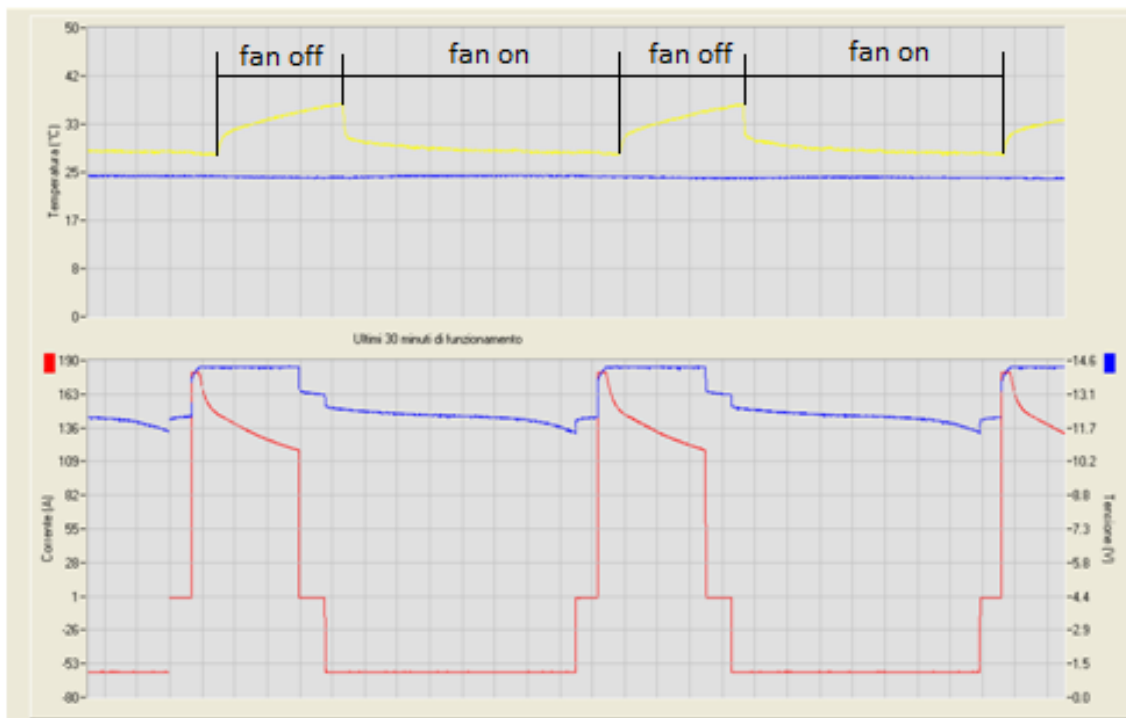


Figure 11: Control of temperature

4.2 Results

Performances are checked periodically by the execution of a complete discharge at constant current $C/2$ (standard discharge) from the state of battery completely charged, followed by a complete charge CC/CV at $I_{\max} C/3$ (standard charge, as suggested by the manufacturer of the cells): this sequence is used for the calculation of the capacity drawn in the complete discharge and the efficiency in the cycle of complete discharge/charge.

The test is still in progress: at the moment, more than 1600 cycles were executed without registering a significant reduction of performances. Fig. 12 shows the diagrams of capacity, energy and efficiency measured at the parameters checks during the life cycle test.

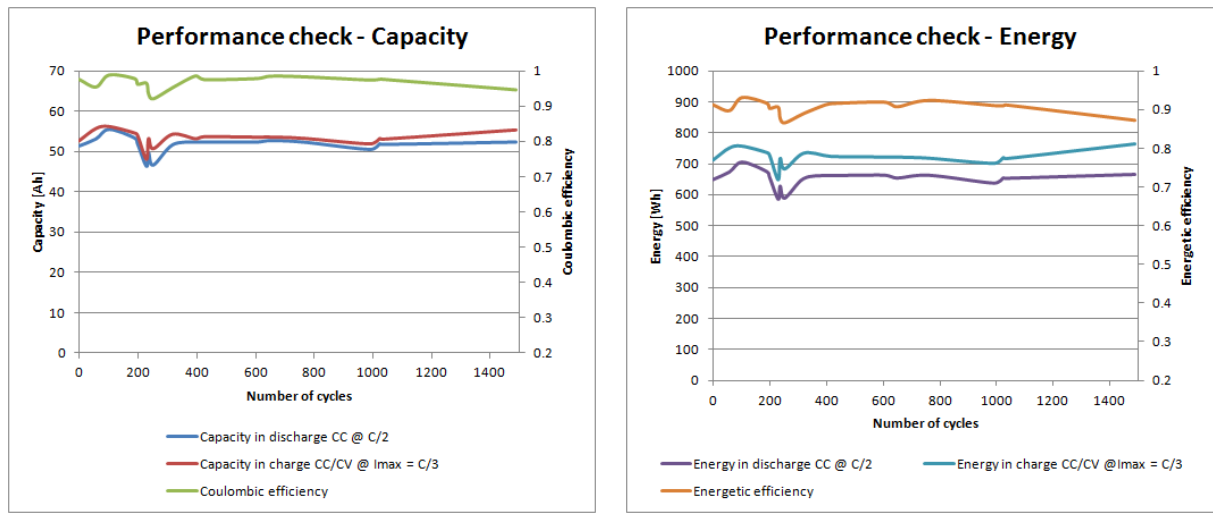


Figure 12: Performances of the battery module during the life cycle test

The life cycle test will be continued until the end of life condition corresponding to a capacity reduction of 20% in regard to the capacity value measured before starting the life cycle test. This criterion (residual capacity 80% in respect to the initial value) is the one universally used in the automotive field to declare the battery “out of service”.

5 IMPLEMENTATION ON A MINIBUS

The test profile used for the experiences above mentioned is consistent with a typical mission required by the local public transportation for a minibus (kilometric consumption 600 Wh/km) which covers a distance of 5 km in 900 s at 20 km/h and charges the battery (charging power 55 kW) at the end of line for 240 s. In fact, it is possible to write the following equations:

- the total time, as a sum of the driving time, T_d , and the stop time, T_s . Considering the driving time and the stop time as a per-cent fraction, the equation becomes:

$$T_d + T_s = 1 \quad (1)$$

- the traction energy, as a product of the stored (charged) energy in the battery system and the drive train efficiency, η . The traction energy can also be written as a product of the kilometric consumption, C , the medium speed during the travel, V , and the driving time. The energy charged in the battery system can be written as the product between the charging power, P , and the stop time. On the base of these considerations, the equation becomes:

$$C \times V \times T_d = P \times T_s \times \eta \quad (2)$$

Solving the two equations system in the two unknowns T_d and T_s , we obtain the following values:

$$T_s = 0.21; T_d = 0.79$$

These values, combined with the kilometric consumption, bring to Table 2, which shows the stop time, the driving time, and the length of the travel corresponding to how many times it has been chosen to run the travel in an hour (see first column).

Table 2. Possible TPL missions

Number of travels in an hour	Total time	Stop time	Driving time	Travel's length
1	3600 s	756 s	2844 s	15.73 km
2	1800 s	378 s	1422 s	7.87 km
3	1200 s	252 s	948 s	5.24 km
4	900 s	189 s	711 s	3.93 km

The third line of the Table 2, with 3 running in an hour on a travel distance of about 5 km, has a good compliance with the charge/discharge profile used in the life cycle test and it is a mission of real interest for the Local Public Transport, the so called “nodal transport” (transport around the nodes of a public transport net). The battery system manufactured in ENEA is made by 24 modules 12.8 V – 60 Ah, organized in 4 groups. Each group consists of 6 modules series connected, so to reach the working voltage of the drive train of the minibus, 72 V. The 4 groups are parallel connected, so that the complete battery system has 72 V – 240 Ah and it is well dimensioned to support also the mission in line 1 on Table 2, that is the heaviest of all. Charging at power 55 kW (typical value of DC charging stations) implies that each group, module, cell, works at maximum C-rate 3C. Such a battery system was realized in ENEA and installed on board a minibus type “Gulliver – Tecnobus”, originally equipped with lead batteries. As shown in Fig. 13, the new battery system is housed in the same box of the old battery system.



Figure 13: Design (left) realization (middle) and installation (right) of the battery system

ENEA is starting the tests with the aim of completing the experimentation made at cell and module level, enlarging it to the level of a complete battery system, so to give a good information about the impact on the performances and life of a real battery system submitted to fast charge in a real working profile on board a minibus for public transportation.

6 CONCLUSIONS

The execution of a testing procedure with fast charge on a battery module which is particularly suitable to emphasize its effects, makes possible to draw some conclusions.

The high charging current causes the voltage increases due to the product of the current and resistance values. The resistance value is determined by the inner resistance of the batteries and the contact resistances, so it is very important the contact between the poles of the cells and the elements used to connect the cells one each other or to realize the terminals of the module. The quality of the contact is a factor to not forget when working at high currents.

Due to the voltage increase, the working point of the battery moves upwards, so this voltage increase can be supported without going over the maximum voltage only if the state of charge is rather low.

In terms of charging type, it is not generally possible to apply the charge at constant current at all the states of charge, but it is necessary to modify it in the charge at constant current/constant voltage.

Another important characteristic that the fast charge requires to the storage system is the cells balancing so to limit the possibility that one cell exceeds the maximum voltage. Further, a low dispersion of the cell voltage values helps to increase the quantity of electric charge that it is possible to store in the battery because the cells reach all together the complete charge. In the opposite situation, one cell only would reach the maximum cell voltage (causing the end of charge for all the battery system) while the other cells would be able to accept charge yet.

Thanks to the adjustments and expedients related in the paper, more than 1600 cycles on the battery module were performed without causing a relevant reduction of the performances. So, at the moment, the test profile with fast charge seems not to affect in sensitive way the performances. The common opinion about fast charge is that, in general, the fast charge affects significantly the life of batteries. But this is not a contradiction and it is probably due to the particular kind of fast charge we refer to: in fact, the common opinion generally refers to charges with SOC ranges up to 80% while this study refers to a partial charge, corresponding to a maximum SOC range of 25%, spaced out with a complete slow charge. A particular help comes from the battery management system, which makes so that, during the execution of the test profile, the cell voltage and temperature remain within the limits of normal working. Further, it provides the balancing of cells in the rest after the complete slow charge. Tests are still in progress and will be

continued until the end of life condition, corresponding to a performances reduction of 20% relating to the initial values.

On the other hand, this particular type of fast charge is really interesting for a mission of public local transport: in this case, the fast charge permits to perform the bus service without interruption. Also the battery system could be reduced in size, dimensioning it in function of the energy required by the mission. This study was designed with the aim of a fast charge which could have a return in real applications: speaking about fast charge, it seems more correct to speak about a fast charge correlated to the type of vehicle and its mission instead of fast charge in absolute meaning. Probably fast charge itself is not successful, but the right connection between “fast charge – battery system – vehicle- mission” is really successful. In this meaning, the fast charge results a valid instrument to solve the problem of the short autonomy of electric vehicles. With this aim ENEA is going to complete the tests on the battery module and starting the tests on a complete battery system onboard a minibus.

Acknowledgements

This work is supported by the Italian Ministry of Economic Development in the framework of the Program Agreement for the Research on Electric System.

References

- [1] “Assesment of high power lead-acid battery advancements by comparative benchmarking with a European test procedure”, G. Pede, V. Sglavo, M.Conte, ENEA, D.Macerata, CRF, Journal of Power Sources 111 (2003), 118-127
- [2] E. Rossi, C. Villante, “A hybrid car by ENEA for Urban Mobility”, EVS 25, Shenzen, China, Nov 5 ÷ 9, 2010
- [3] R. Arunachala, A. Jossen, J. Garche, K. Makinejad, S. Athlekar, “Cycle life characterization of large format lithium-ion cells”, EVS27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [4] J. Schmalstieg, S. Käbitz, M. Ecker, D. U. Sauer, “From accelerated ageing tests to a lifetime prediction model: analyzing lithium-ion batteries”, EVS27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [5] J. C. Viera, D. Ansean, M. Gonzalez Vega, V. M. García, J. C. Álvarez, J. L. Antuña, “High power LiFePO4 cell evaluation: fast charge, depth of discharge and fast discharge dependency”, EVS27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [6] A. Burke, M. Miller, “Life cycle testing of lithium batteries for fast charging and second-use applications”, EVS27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [7] E. Sarasketa Zabala, I. Laresgoiti, I. Alava, M. Rivas, I. Villareal, F. Blanco “Validation of the methodology for lithium-ion batteries lifetime prognosis”, EVS27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [8] M. De Gennaro, E. Paffumi, H. Scholz, G. Martini, “Analysis and assessment of the electrification of urban road transport based on real-life time mobility data” EVS27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [9] R. Baert, H. J. Kort, “Real world experience with operating electric vehicles in the Netherlands” EVS27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [10] M. Zolot, A. A. Pesaran, M. Mihalic, “Thermal evaluation of Toyota Prius battery pack” Hyatt Crystal City: Future Car Congress; 2002
- [11] A.F. Burke: ” Cycle Life Consideration for Batteries in Electric and Hybrid Vehicles”, SAE World Congress 1995, SP -1105

- [12] A.F. Burke, M. Miller: “Life cycle testing of lithium batteries for fast charging and second-use applications”, Electric Vehicle Symposium & Exhibition 27, Barcelona, Spain, Nov 17 ÷ 20, 2013
- [13] Omar, Noshin, Van Den Bossche, Peter, Hegazy, Omar, Coosemans, Thierry Clement, Van Mierlo, Joeri, Smekens, Jelle, Firouz, Yousef, Abdel Monem, Mohamed, Mulder, Grietus, Salminen, Justin, “Lithium Iron Phosphate Based Battery - Assessment of the Aging Parameters and Development of Cycle Life Model”, Energy, Vol. 113, 07.10.2013, p. 1575-1585
- [14] Mohamed Abdel Monema, Khiem Tradb, Noshin Omara, Omar Hegazya, Bart Mantelsb, Grietus Muldera, Peter Van den Bossche, Joeri Van Mierlo, “Lithium-ion batteries: Evaluation study of different charging methodologies based on aging process”, Applied Energy Volume 152, 15 August 2015, Pages 143–155

Authors



Francesco Vellucci has been working in the ENEA’s “Low Environmental Impact Vehicles” Laboratory, especially in the section relating to electrochemical batteries and supercapacitors. He graduated in mechanical engineering (with honors) at the Rome University “La Sapienza” (1999) and started working at ENEA in 2009. Previously he worked in the field of industrial combustion and electric traction, especially marine engines electrically propelled.



Giovanni Pede graduated in Mechanical Engineering, University “La Sapienza “ in Rome in 1978. Joined ENEA in 1984 after five years work in plant design and construction with an important industrial group. His experience in ENEA includes nuclear engineering, energy saving technologies and, since 1990, automotive engineering. Since 1990 he has worked in the field of automotive engineering. At the moment, he is the responsible of the ENEA testing laboratories for electric storage systems, vehicles and automotive components like motors, traction batteries, supercapacitors etc. He is author of more than 100 papers, about traction systems design and automotive components innovation, published on international congresses and journals.



Federico Baronti received the M.Sc. and Ph.D. degrees in electronic engineering from the University of Pisa, Pisa, Italy, in 2001 and 2005, respectively. Currently, he is an assistant professor at the Department of Information Engineering, University of Pisa. His research topics include the design of embedded electronic systems for biomedical, automotive, and marine applications. More recent activities concern Li-ion battery modelling and the development of novel battery monitoring and management systems. Other fields of interests involve the design of very-large-scale-integration integrated circuits for high-resolution and reliable time reference generation and the development of multichannel data acquisition and processing systems.



Roberto Di Rienzo was born in Avellino, Italy, in 1989. He received the M.Sc. degree in electronic engineering from the University of Pisa, Pisa, Italy, in 2014, where he is currently working toward the Ph.D. degree in electronic engineering. His research focuses on Li-ion battery modeling and the design of electronic systems for the management of batteries.



Fabio Cignini graduated in mechanical engineering in 2013, he is research fellow at Research Center for Transport and Logistic at Rome University “La Sapienza” since 2014. He carries out technical support in research projects on innovative transport systems. During his professional experience, he got knowledge on electric and hybrid vehicles. In particular, he took part in a smart cities project for the development of a “call transport system” by means of a diesel-electric vehicle in L’Aquila’s Municipality.