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Experimental analysis on the performance of lithium based batteries for road full electric and hybrid vehicles

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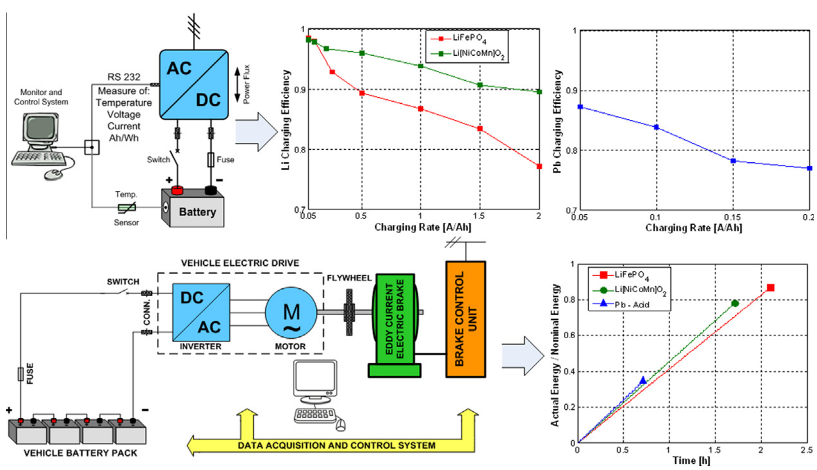
HIGHLIGHTS

- Performance analysis for lithium storage technologies, such as Li[NiCoMn]O_2 and $LiFePO_4$ batteries.
- Actual capacity of lithium technologies analyzed almost close to their nominal capacity also for high discharging current.
- The charging efficiency for Li[NiCoMn]O_2 positively affects the regenerative breaking and fast recharging operations.
- The analyzed battery packs follow dynamic power requirements on performed road driving cycles.
- Experimental results demonstrate driving range is much higher when battery packs are based on lithium technology.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper deals with an experimental evaluation regarding the real performance of lithium based energy storage systems for automotive applications. In particular real working operations of different lithium based storage system technologies, such as Li[NiCoMn]O_2 and $LiFePO_4$ batteries, are compared in this work from the point of view of their application in supplying full electric and hybrid vehicles, taking as a reference the well-known behavior of lead acid batteries. For this purpose, the experimental tests carried out in laboratory are firstly performed on single storage modules in stationary conditions. In this case the related results are obtained by means of a bidirectional cycle tester based on the IGBT technology, and consent to evaluate, compare and contrast charge/discharge characteristics and efficiency at constant values of current/voltage/power for each storage technology analyzed. Then, lithium battery packs are tested in supplying a 1.8 kW electric power train using a laboratory test bench, based on a 48 V DC bus and specifically configured to simulate working operations of electric vehicles on the road. For this other experimentation the test bench is equipped with an electric brake and acquisition/control system, able to represent in laboratory the real vehicle conditions and road characteristics on predefined driving cycles at different slopes. The obtained experimental results on both charge/discharge tests and driving cycles demonstrate the advantages of using lithium technologies, mainly in terms of their high efficiency, particularly at high current values. That represents a feasible solution to offer vehicle designers and users extended driving ranges and reduced recharging times.

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1. Introduction

Battery powered electric vehicles represent an interesting alternative to conventional road vehicles toward the long awaited achievement of sustainable transportation systems. In fact, this new technology of transportation means is expected to reduce the fossil fuel dependency and to improve the energy efficiency and impact on global warming. However, it is important to underline that the wide spread of this kind of technology is affected by the actual performance of electric energy storage systems on board.

Lead batteries were largely used for traction applications in the last century, when different types of lead-acid batteries were developed, such as their main categories classified as 'flooded' and 'valve regulated' lead acid batteries (VRLA) [1]. In particular, the VRLA lead batteries presented the main advantage of keeping the right levels of distilled water inside the battery and avoiding any drying of the cells. In the past years, these characteristics made this kind of batteries particularly suitable for the first typologies of road electric vehicles. The VRLA batteries are also commonly refereed as 'no maintenance batteries', for the minimal level of attention and operations required. Typical values of energy density for lead acid batteries are estimated in the ranges from 35 to 50 Wh/kg [2]. These kinds of batteries, as a matter of fact, are not used anymore for road electric vehicles, despite their characteristic advantages in terms of security, low cost and performance not affected by the working temperature. On the other hand, they present the disadvantages of very low energy density, low performance at high discharging currents, low charging rate, plus the need of recycling their own materials to avoid environmental issues [3].

Nowadays lithium technologies, which have achieved a large diffusion in the field of the portable consumer electronic, are supporting the transition towards the large applications of electric and hybrid vehicle. This is mainly due to their characteristics of light weight, high specific energy, good life cycle performance and low self discharge rate, which represent the main requirements in the design of electric vehicles, characterized by high performance in terms of acceleration and driving range [4–9].

Used as battery anode material, lithium is an interesting metal, mainly for its characteristics of lightness and high potential. Anyway, its utilization implies some concerns of safety hazard, due to the high reactivity of this metal. This is the reason why in lithium-ion batteries both positive and negative electrodes employ lithium "host" compounds. In the realization of great part of lithium ion batteries, carbon is used in its different forms, such as graphite, hard carbon and microspheres. In this case, the use of carbon as a negative pole defines the lithium ion system, with lithium intercalation into the carbon, avoiding any use of lithium metal as a negative electrode, with the risks resulting from possible irregular lithium plating and dendrite formation [4]. The positive pole is generally made of metal oxide, such as $LiMO_2$ or $LiMO_4$ (M = Co, Ni or Mn) , which represents a lithium source compound. The resultant electrochemical reaction involves a cyclic transfer of lithium ions from the cathode (the lithium source) to the graphite anode, with no presence of metallic lithium. The lithium cobalt oxide ($LiCoO_2$) presents significant advantages, mainly based on reliable performance and long cycle life. Although $LiCoO_2$ is still a widespread cathode material, different alternative solutions are being developed to lower cost and improved stability. In fact cobalt is less available and thus is more costly than other metals such as manganese, nickel and iron. Moreover, cobalt is a toxic element and its environmental effect needs to be properly considered [10]. The cathode materials based on lithium cobalt nickel oxide ($LiCo_{0.2}Ni_{0.8}O_2$) present potential advantages of lower cost and higher specific energy with respect to the $LiCoO_2$ cathode. For this technology the principal issue, which has largely limited the diffusion of these compounds, is the capacity loss on cycling operations. Lithium manganese oxide spinel ($LiMn_2O_4$) continues to attract attention, because of the lower price and toxicity advantages of manganese over cobalt. However, the fundamental issues for this kind of technologies remain the instability during the storage phase in the charged state, and limited duration of cycled life. Higher voltage cathodes have also been investigated, such as Li–Co–Mn mixed oxides, characterized by quite interesting performance, especially in terms of high capacity, good charging/discharging rate capability and good aptitude to operate at high voltage [11].

The absence of liquid phases for the above lithium technologies facilitates the realization of leak-proof and light-weight containers, which represents an additional advantage for automotive applications. In particular, sandwich of foils at low cost and high capacity can be realized, with the advantage on the packaging flexibility and insensitivity to shock and vibration damage, as required by many car manufacturers.

Recently, other low-cost cathode materials have been studied and proposed. In particular a promising class of cathode materials is represented by phosphates ($LiMPO_4$). One of the phosphates most commonly used is the $LiFePO_4$ technology, based on olivine crystal structure, which has shown promising characteristics when supplying road electric and hybrid vehicles [12,13]. The main advantages of $LiFePO_4$ batteries are based on the low cost, long cycle life and high availability of Fe, high thermal stability and safety properties, due to the strength of the covalent Fe–P–O bond with respect to Co–O bond, which reduces the risk of oxygen release [14]. Their energy density is lower than $LiCoO_2$ cathode, but their main limitation is represented by a low electrical conductivity, which is usually faced either by reducing the particles size, or coating/doping the $LiFePO_4$ particles with conductive additives [11,15–17].

The main advantage of lithium-ion batteries consists in the higher charging and discharging rate in comparison with other batteries, such as Pb-acid batteries, because of the quick reversibility of the lithium ions. Moreover, the specific energy of lithium-ion batteries is more than 150 Wh/kg, which means a large increase of driving range for electric vehicles, with respect to the previous types of batteries. Another point to be taken into account is that lithium batteries are required to be controlled during their charging/discharging operations to avoid operative conditions, such as overcharge/discharge and cell voltage unbalancing, which might be cause of damage for the whole battery pack. For this reason the development of battery management systems, able to guarantee the correct behavior of each battery cell in each working condition, is a key issue to be carefully considered in the design of battery packs based on this technology [18].

Supercapacitors have been also proposed as possible additional energy storage systems in the automotive field, because of their unique characteristics of very high power density. These storage devices find the right use in electric and hybrid vehicles to support the peak power demands, obtaining a more efficient utilization of other storage systems on board, such as batteries, or power generators such as fuel cells [9,19]. However, their very poor energy density can limit their application in the automotive field. For this reason innovative capacitor devices, based again on Li, have been recently proposed in this sector, as they could obtain a better compromise between specific energy and power density in view of an optimal future design of hybrid power-trains [20–25].

The aim of this work is to carry out an experimental analysis of the most commonly used lithium based energy storage systems. Different aspects related to $Li[NiCoMn]O_2$ and $LiFePO_4$ batteries are studied and tested in both stationary and dynamic operative conditions, from the point of view of their application as storage systems in road full electric and hybrid vehicles, using the well known performance of lead acid batteries as reference. The experimental tests reported in this paper are carried out at ambient temperature of about 300 K with a forced air ventilation system. The effect of temperature on battery performance, which is not considered as the main objective of this paper, is analyzed by other authors, with particular focus on the effect of temperature on State of Charge (SoC) estimation, battery impedance, cycle life assessment [26–28]. The obtained laboratory results reported in this paper will allow electric vehicle designers to obtain a clear view on lithium technology performance, extended driving ranges and fast charging operations.

2. Experimental

The experimental analysis of this paper is carried out on lithium and lead acid battery modules, each one composed by elementary cells of 40 Ah rated capacity. The first Li based module is a lithium-ion polymer battery, composed by a graphite based anode, a $Li[NiCoMn]O_2$ based cathode and a Li+ conducting polymer electrolyte as separator. The second one is a $LiFePO_4$ battery, composed by a natural mineral of the olivine family ($LiFePO_4$) as a cathode material. A VRLA Pb acid battery is also tested and used as a reference for the comparisons through the following experimental characterizations.

The main characteristics and manufacture recommended operative conditions of the cells are reported in a preliminary study, already published by the authors [29]. The battery modules have been provided by *Exide Technology* for the Pb acid, *EIG* for the $Li[NiCoMn]O_2$ and *Winston Battery* for the $LiFePO_4$ modules. In Table 1 a numerical comparison among the main characteristics of the related battery modules is reported.

From Table 1 it follows that the traditional lead acid batteries still present some advantages, compared with the most recent battery technologies, such as the maximum peak discharge current. Moreover, the lead batteries present the highest reliability and lowest costs, also taking into account the maintenance quote. On the other hand, the spreading of this old technology for road electric vehicle applications is limited by its very low values of energy density and specific energy, whereas the new technologies of lithium are mainly supported by high values of specific energy/power. Moreover the $Li[NiCoMn]O_2$ technology is characterized by higher energy density, whereas the $LiFePO_4$ batteries by higher durability in terms of cycle life. In the above table the specific power is evaluated considering the peak discharging current at nominal battery voltage. Anyway the dynamic estimation of peak power would be required for lithium battery technologies to avoid battery overcharging or discharging and extend its lifespan [30].

The first experimental tests are focused on a deepened analysis of the above batteries, by means of a specific laboratory test bench, devoted to analyze the real behavior of electrochemical batteries. The block scheme of the laboratory test-bench for battery characterization is shown in Fig. 1.

The architecture of the battery test bench is mainly based on a bidirectional AC/DC power converter, controlled through RS232 communication protocol, which allows the electric parameters, such as battery voltage, current, power and temperature to be set, acquired and monitored. In this way the bench is able to perform battery charging and discharging tests at constant current/voltage/power values, whereas different charging and discharging profiles of current/voltage/power can be set as a sequence of phases, with a transition time of 900 ms between two following phases. In addition, the thyristor pulse technology and appropriate choke allow reducing the ripple current down to 7% rms, in order to obtain fast transient response time and a good accuracy in following the reference values. Thanks to these operative modes, the working conditions, related to the single battery module supplying an electric traction drive, can be studied for various specific operations. The main battery electric constraints, such as minimum discharging voltage, maximum current, maximum power, maximum battery temperature, generally provided by the manufacturer with data-sheets, can be set through a specific computer interface, in order to guarantee the expected durability of the battery under test. More details about the characteristics of the battery test bench are reported in [29].

Other tests are carried out to evaluate the battery performance figures during dynamic operations when the storage systems under test, analyzed in this paper, supply an electric drive on real driving cycles for road vehicles. These tests are performed through a laboratory test bench, composed of an electric propulsion system for urban scooters supplied by battery packs, which are properly assembled by the modules of Table 1. In particular an eddy current brake, coupled to the electric motor, is controlled to simulate the road resistant forces. Whereas, a flywheel, specifically designed to take into account the real vehicle inertia during the laboratory simulations, is interposed between electric motor and brake. The vehicle electric drive is based on a brushless electric motor of 1.8 kW nominal power, with a maximum power of 2.5 kW, nominal torque of 6 Nm, nominal speed of 3000 rpm, DC link rated voltage of 48 V, maximum current of 100 A. This electric drive is controlled by means of a bidirectional AC/DC converter, based on IGBT technology, which allows regenerative braking operations. Moreover, the laboratory is provided with on-board battery pack chargers, realized by means of electronically controlled AC/DC power converter connected to the electric network. The test bench control and acquisition signals are managed through a hierarchical control strategy, embedded in the DSP processor of a dSPACE board, interacting with the electric drive and brake controllers to perform the required driving cycle. The block scheme of the described laboratory test bench is shown in Fig. 2 and more details about the technical characteristics of the test bench sub-components are reported in [29].

Table 1
Main characteristics of Pb and Li battery modules.

	Pb acid	$Li[NiCoMn]O_2$	$LiFePO_4$
Nominal battery voltage (V)	12.0	14.6	12.8
Nominal capacity C_{10} (Ah)	40	40	40
Nominal energy (Wh)	480	584	512
Specific energy (Wh/kg)	25	176	80
Energy density (Wh/l)	67	350	142
Maximal continuous discharge current (A)	200 (5 C)	200 (5 C)	120 (3 C)
Peak discharge current (A) for less than *t* (s)	800 (20 C) *t* = 5	400 (10 C) *t* = 10	800 (20 C) *t* = 5
Specific power (W/kg)	660	1700	1600
Working temperature (K)	253–323	243–323	243–353
Cycle life at 80% DOD	500	1000	3000

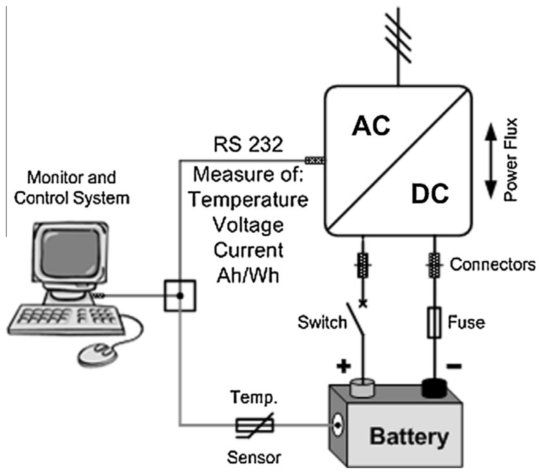

Fig. 1. Laboratory test bench for battery characterization.

The control and data acquisition system of the laboratory test bench is shown In Fig. 3. In particular a speed and a torque PID controller, programmed through the dSPACE software interface, based on MATLAB-Simulink environment, implement the automatic pilot function, which follows the speed and torque references of the defined driving cycle.

The actual speed and torque signals, required to control the dynamic operations of the test bench, are measured using an encoder, connected to the electric brake shaft, and a force sensor, connected to the balancing stator of the eddy current brake machine. The accelerator signal is given to the AC electric drive as output of the first PID controller, on the base of a comparison between the speed reference with the measured motor speed. The torque signal is given to the eddy current braking machine as output of the PID torque controller, which is embedded in the brake control unit. This controller works on the base of the comparison between the measured torque and the reference torque, evaluated as a quadratic function of the measured speed, taking into account the related road and aerodynamic resistant forces [31].

In the following section experimental results obtained by means of the above test benches are reported, focusing the attention on the behavior and performance of the battery technologies, studied in this paper, when supplying electric vehicles.

3. Results and discussion

The three battery technologies described in the experimental section are considered for the laboratory experimentation, which is obtained with different kinds of tests based on steady-state and dynamic operative conditions. The batteries used to perform the tests described in this section have been preliminarily cycled until reaching 50% of their rated life cycle. In the steady-state tests the battery modules are characterized at different constant values of discharging current, using the battery test bench described in Fig. 1, in order to evaluate their real operating limits in terms of voltage drop, actual energy in Wh, temperature and charging efficiency. The first set of tests is performed under the same preliminary charging operations, which are repeated for each test. In

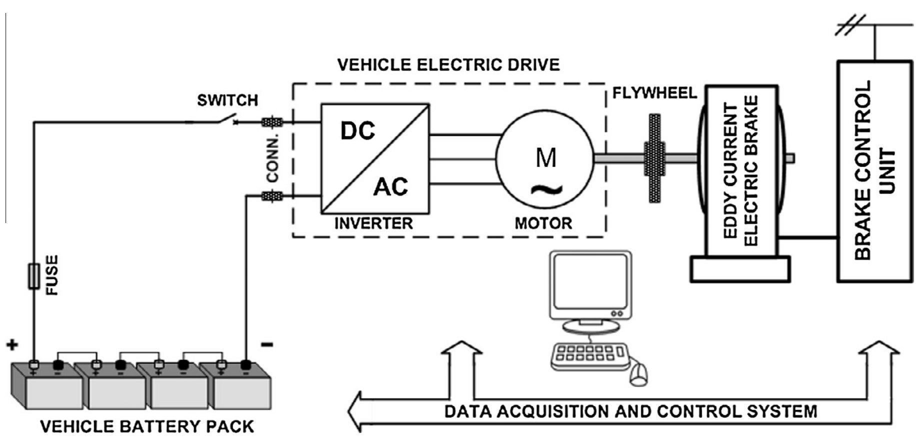

Fig. 2. Block scheme of the laboratory test bench for electric propulsion systems.

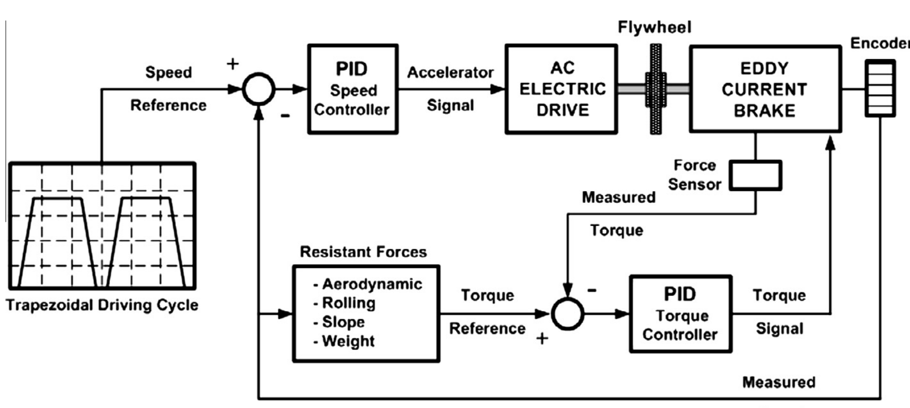

Fig. 3. Block scheme of the control system for the laboratory test bench for electric propulsion systems.

particular, each one of battery modules is separately charged at 4 A as current limit with CC/CV (constant current/voltage) profile, corresponding to a charging rate of 0.1 C, following the prescriptions of the battery manufacturer, until the charging current is around zero for more than two hours. Then, after a resting time of 1 h, each battery module is fully discharged at a constant current of 20 A and then 40 and finally 60 A, following the same procedure. The results obtained for the discharging currents from 20 to 60 A are shown in Figs. 4–6, where the battery voltage in V (figures A) and discharged energy in Wh (figures B), referred to their nominal values reported in Table 1, and also the temperature in K (figures C) are shown as a function of time [29,32]. Each discharging test is stopped when the battery voltage reaches its minimum value, suggested by the battery data sheet. During these tests the voltage curves of the three battery technologies present different behaviors in terms of voltage drop. In particular, the $LiFePO_4$ shows an almost flat discharging voltage curve versus time, due to the cathodic process reversibility, related to the similar structure of the two phases involved in Li insertion/extraction, i.e. $LiFePO_4$ and $FePO_4$ [13]. The actual battery energy in Wh, divided by its corresponding nominal value, is mainly affected by the discharging current values. In particular lead acid batteries present higher reduction of actual discharged energy, especially at high discharging currents, reaching values up to 50% of their nominal energy at the end of the test at 60 A. The same high discharging current on both the other lithium batteries is less effective. In fact at the end of the tests the lithium batteries present values of the actual energy quite similar to their nominal capacity in Wh. This aspect is particularly clear at a discharging current of 60 A, when an actual discharged energy value of about 75% for $Li[NiCoMn]O_2$ and around 100% for $LiFePO_4$ is reached. The battery temperature is measured on the external box of each battery module during the discharging tests. The results of this measurement shows that for the three types of batteries the temperature rising is in a range compatible with the safety values suggested by the manufacturer (Table 1). The temperature increase observed during the discharge phase can be correlated to resistive dissipation of all conductive materials inside the battery packs, and to the exothermic nature of the discharge processes. Higher values of discharging current are not tested in this paper because during the tests on driving cycles, which are described at the end of this section, the maximum value of discharging current is not higher than 60 A.

Another set of tests is carried out with the aim of evaluating the performance figures of the batteries considered in this paper during the recharging phases. For these tests the charging efficiency, evaluated at the battery terminals, is identified as a parameter to compare the different types of batteries. This parameter is evaluated as the actual value of the electric energy that is possible to take out from each battery, during its discharging phase at a fixed current, with respect to the electric energy supplied to the battery during its recharging phase at different values of constant recharging current. On this purpose, each battery is charged at different values of charging rate, defined as the charging constant current in Ampere divided by the nominal value of battery capacity in Ah. These tests are carried out with charging currents from 2 to 80 A (from 0.05 C to 2 C) for the lithium batteries and from 2 to 8 A (from 0.05 C to 0.2 C) for the lead acid batteries, as suggested by the manufacturers of the different batteries. Then, after a resting time of 1 h, each battery is discharged at a constant current of 8 A until its minimum voltage value is reached, in order to evaluate the electric energy effectively available at battery terminals and therefore the charging efficiency [33].

The results of the described tests are reported in Fig. 7A for lithium and Fig. 7B for lead acid batteries. Both these figures show that the higher is the charging current the lower is the efficiency, and also that the lithium technologies present a higher efficiency with respect to the lead acid batteries for each charging rate. In particular, the efficiency values of the lithium batteries, at high charging currents, are quite similar to those evaluated for lead batteries at low charging rates. As a consequence electric and plug-in hybrid vehicles can take advantage of higher charging efficiencies of lithium compared to lead batteries to improve their driving range and charging time, when the vehicle is connected to charging station.

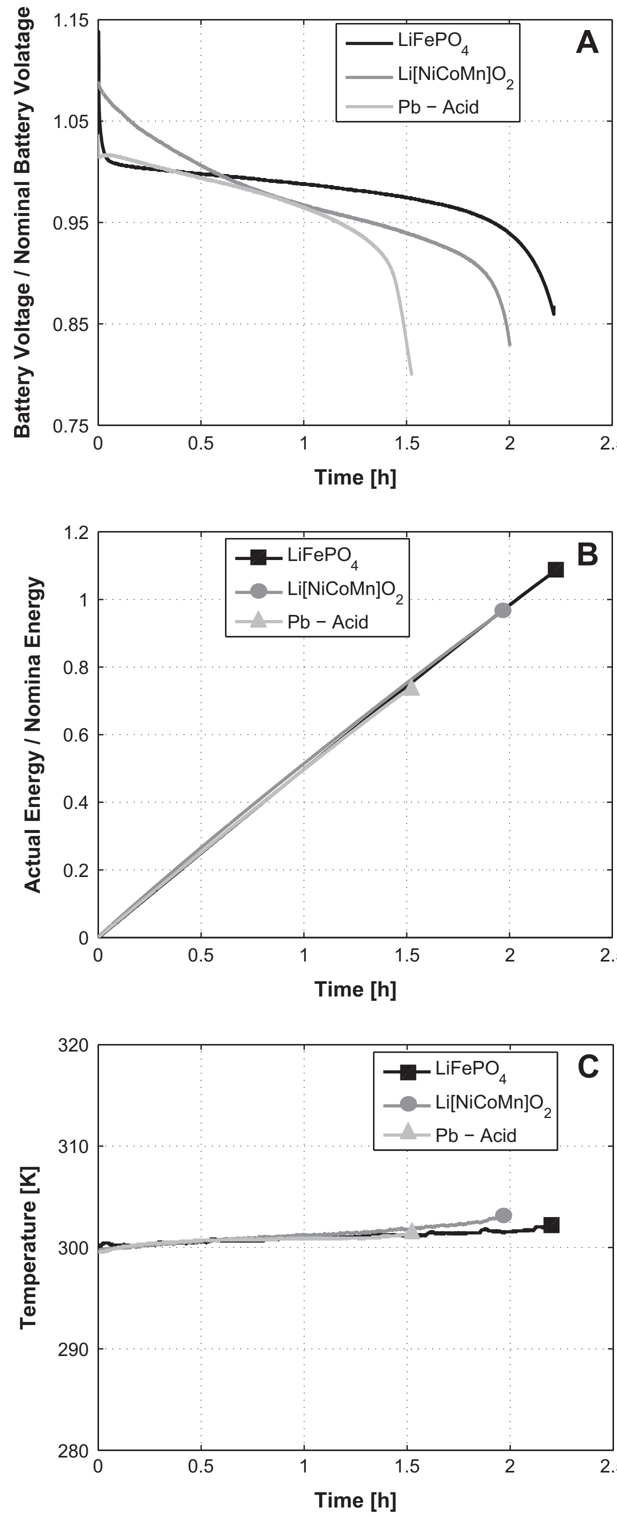

Fig. 4. Discharging tests on $Li[NiCoMn]O_2$, $LiFePO_4$ and Pb batteries @ constant discharging current of 20 A.

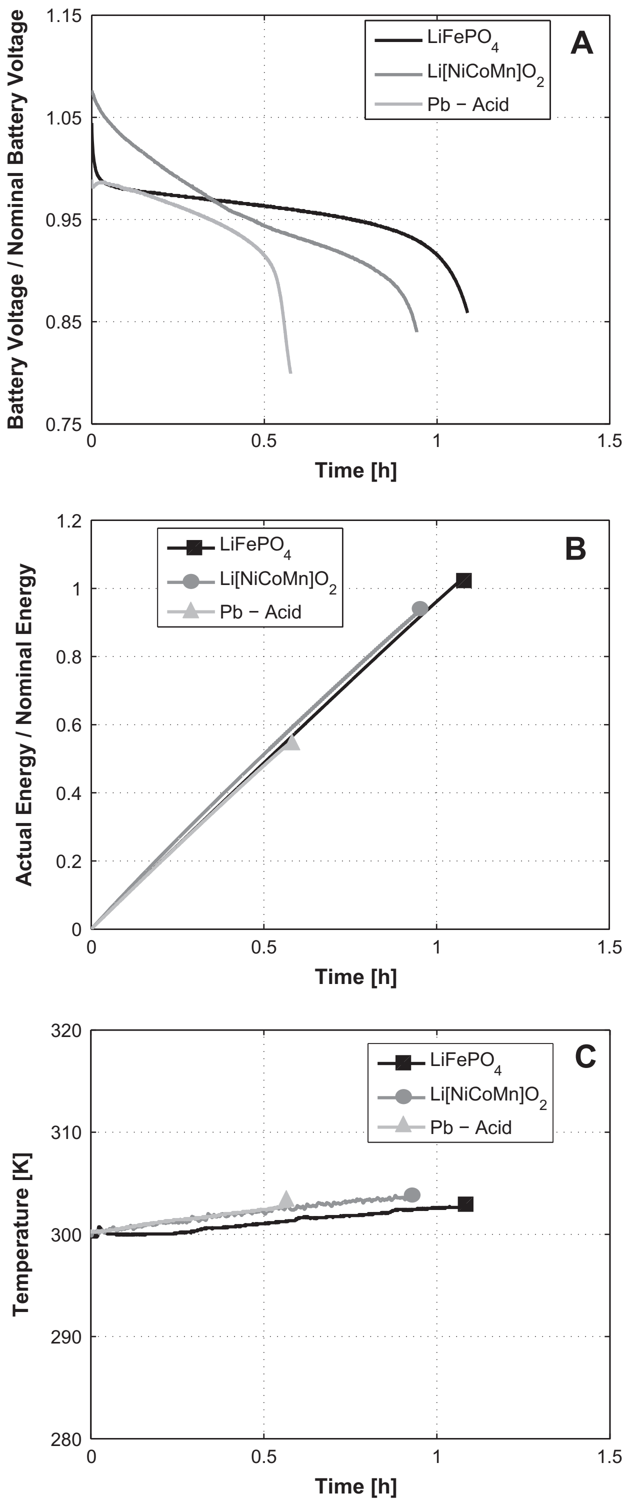

Fig. 5. Discharging tests on Li[NiCoMn]O_2, $LiFePO_4$ and Pb batteries @ constant discharging current of 40 A.

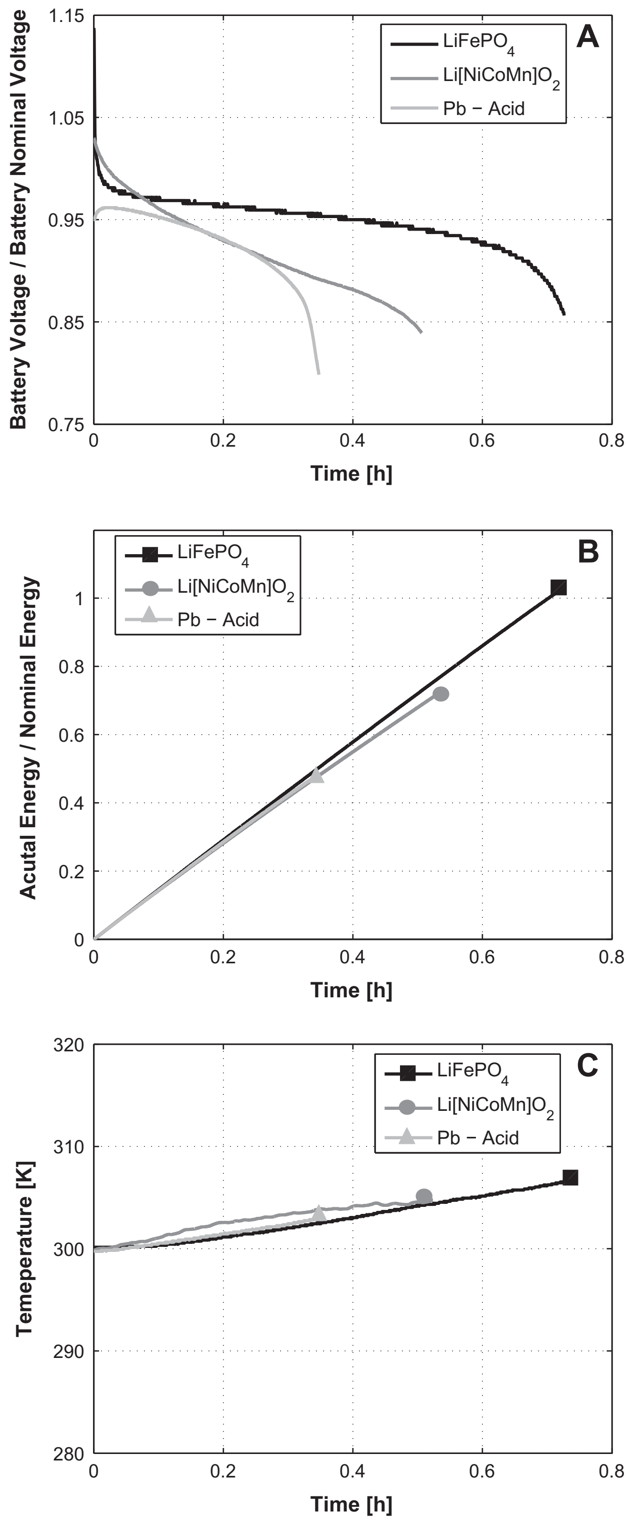

Fig. 6. Discharging tests on Li[NiCoMn]O_2, $LiFePO_4$ and Pb batteries @ constant discharging current of 60 A.

Moreover the Li[NiCoMn]O_2 batteries present the highest efficiency compared to the other batteries analyzed in this paper, with values of efficiency from 0.98, for low charging rate, to about 0.90 for the highest evaluated charging rate. On the other hand the efficiency of the $LiFePO_4$ batteries decreases from 0.98 to 0.78. This behavior is clearly justified by values of the internal resistance, which is rather high for this kind of lithium battery [14,15]. However, in the real use of the $LiFePO_4$ batteries the strong degradation of battery performance, in terms of cycle life, for high values of charging rates, needs to be considered, as described in [26].

The last set of tests is performed on the work bench described in Fig. 2, in order to evaluate the driving range, in steady state and dynamic operations, for the battery packs analyzed in this paper, when supplying the electric drive for road electric and hybrid vehicles. The operative parameters of the work bench are set in order to

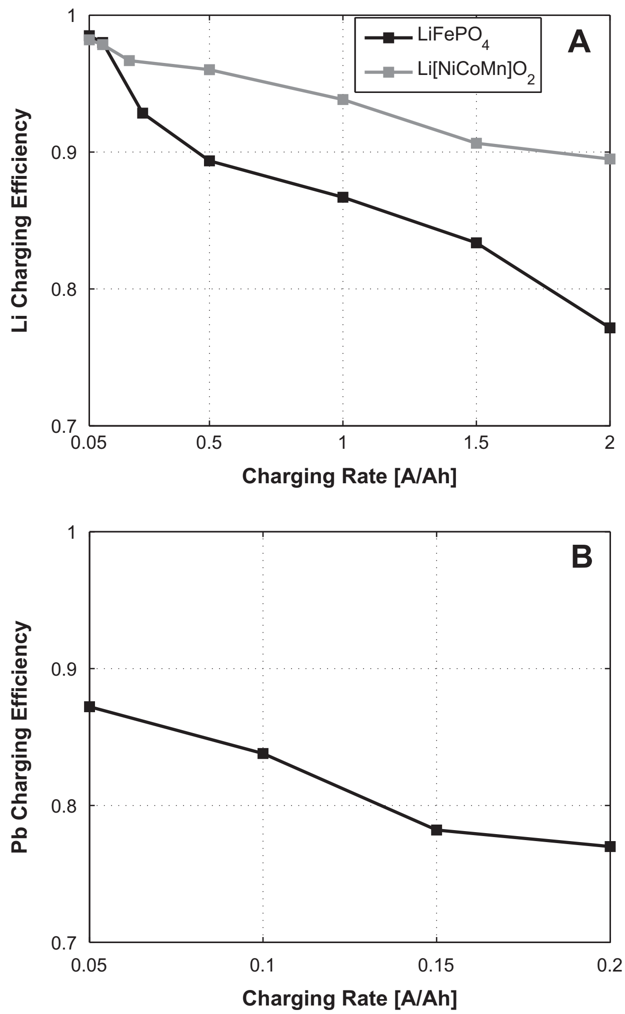

Fig. 7. Charging efficiency of Li[NiCoMn]O_2, $LiFePO_4$, and Pb acid batteries @ discharging current of 4 A versus charging rate.

simulate the real behavior of a road electric vehicle on specific driving cycles, in the hypothesis of neglecting the friction force term not dependant on the vehicle speed, to simplify the test bench control. In particular a road slope from 0 to 10% and a constant speed of about 20 km/h are considered. Moreover the weight related to the vehicle configurations with the three types of batteries is taken into account, considering their energy densities reported in Table 1.

The first three experiments of this set of tests, reported in Fig. 8, are performed on the electric power train, equipped with the three kinds of batteries analyzed, representative of an urban two wheeled electric vehicles. For these experiments a vehicle speed of 20 km/h on a road slope of 10% is considered and three values of resistant torque are evaluated taking into account the corresponding values of weight, i.e. 2.1 Nm and 221 kg for the vehicle equipped with the lead acid battery pack, 1.45 Nm and 186 kg for the Li[NiCoMn]O_2 battery pack, 1.78 Nm and 194 kg for the $LiFePO_4$ battery pack.

Fig. 8A shows the battery voltage behavior during the above tests. A first voltage drop for these three curves is due to the high value of the constant current required by the steady state operation fixed for these tests. Then, for the $LiFePO_4$ the voltage is almost flat around 47 V and finally reaches the minimum allowed voltage value of about 40 V, with the typical knee curve shape, after about 1 h, when the electric drive is decelerated and stopped. Whereas

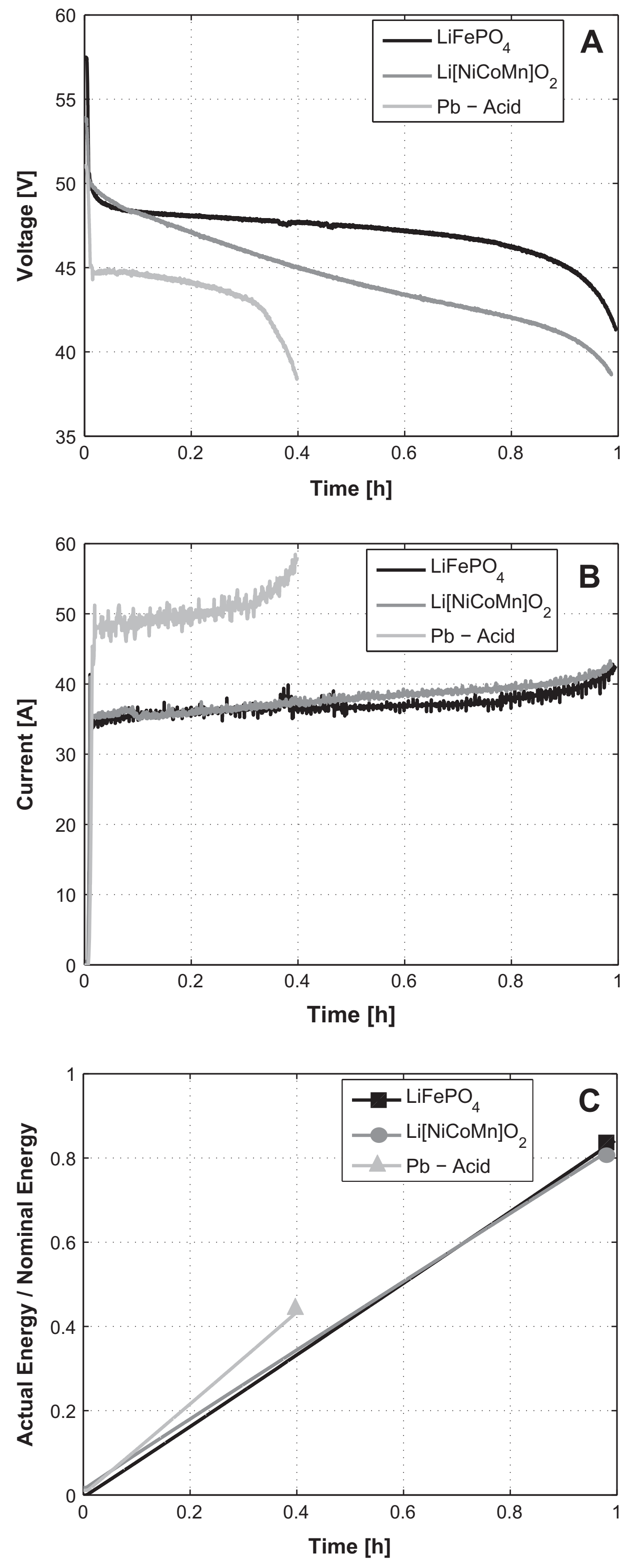

Fig. 8. Steady-state operation of the $LiFePO_4$, Li[NiCoMn]O_2 and Pb battery packs supplying a laboratory electric drive for urban vehicle.

the Li[NiCoMn]O_2 presents an almost constant gradient, reaching the minimum allowed voltage value of about 39 V with a smoother knee curve at the end of the test. The lead acid battery voltage curve rapidly drops to 38.4 V in less of half of the time compared to the other lithium battery packs.

Table 2
Effect of battery typology on driving range.

Road slope (%)	Pb 221 kg (km)	Li[NiCoMn]O_2 186 kg (km)	$LiFePO_4$ 194 kg (km)
0	170	190	190
5	30	40	43
10	8	19	20

The battery current curves are shown in Fig. 8B, evidencing that values from 35 to 45 A are measured for the lithium battery packs and from 48 to 58 A for the lead acid battery pack. These tests can be compared, in terms of average values, to the discharging tests for the same kinds of batteries, carried out at constant currents and shown in Fig. 5. The battery pack actual discharged energy values, referred to their nominal energy in Wh, are shown in Fig. 8C, where the value at the end of the test, which means on the whole driving range, is about 0.8 for both the lithium technologies, and less than 0.5 for the lead acid batteries. These values result lower than the same results obtained with the test at constant discharging currents of Fig. 5. These differences can be justified considering different reasons, i.e. the presence of the starting transient, to reach the steady state operations at constant vehicle speed; the high frequency harmonic noise of the battery current feeding the electric drive [34] and the cell voltage unbalancing due to the lack of a BMS for the battery packs considered.

For the same set of tests other similar experiments are performed with the same battery packs and related vehicle weights on other two different road slopes. Table 2 reports the effect of the battery typology on the vehicle driving range for the related slope percentage. The results of these tests show that on a plain road a slight increase of driving range (about 10%) is obtained with Li compared to Pb systems, mainly due to their lower weight. In fact in this case the battery currents are not so high to considerably reduce the actual Pb battery pack capacity. This aspect is more evident for a road slope of 5% and 10%, when lithium batteries guarantee an extended driving range up to 40% compared to the lead acid batteries. Nevertheless comparing the two lithium technologies, a slight advantage in terms of autonomy, in the same test conditions, is obtained for the $LiFePO_4$ batteries, despite their lower energy density. The battery temperature has been also monitored during the tests to avoid any damage of the battery packs analyzed, and no substantial difference in terms of temperature increase has been detected with respect to the experimental results related to the constant current discharges described in the above sets of tests.

In order to analyze the behavior of the battery packs studied in this paper in terms of driving range when following dynamic operations, the last experiments of this set of tests are run on the same test bench, taking advantage of the acquisition and control system

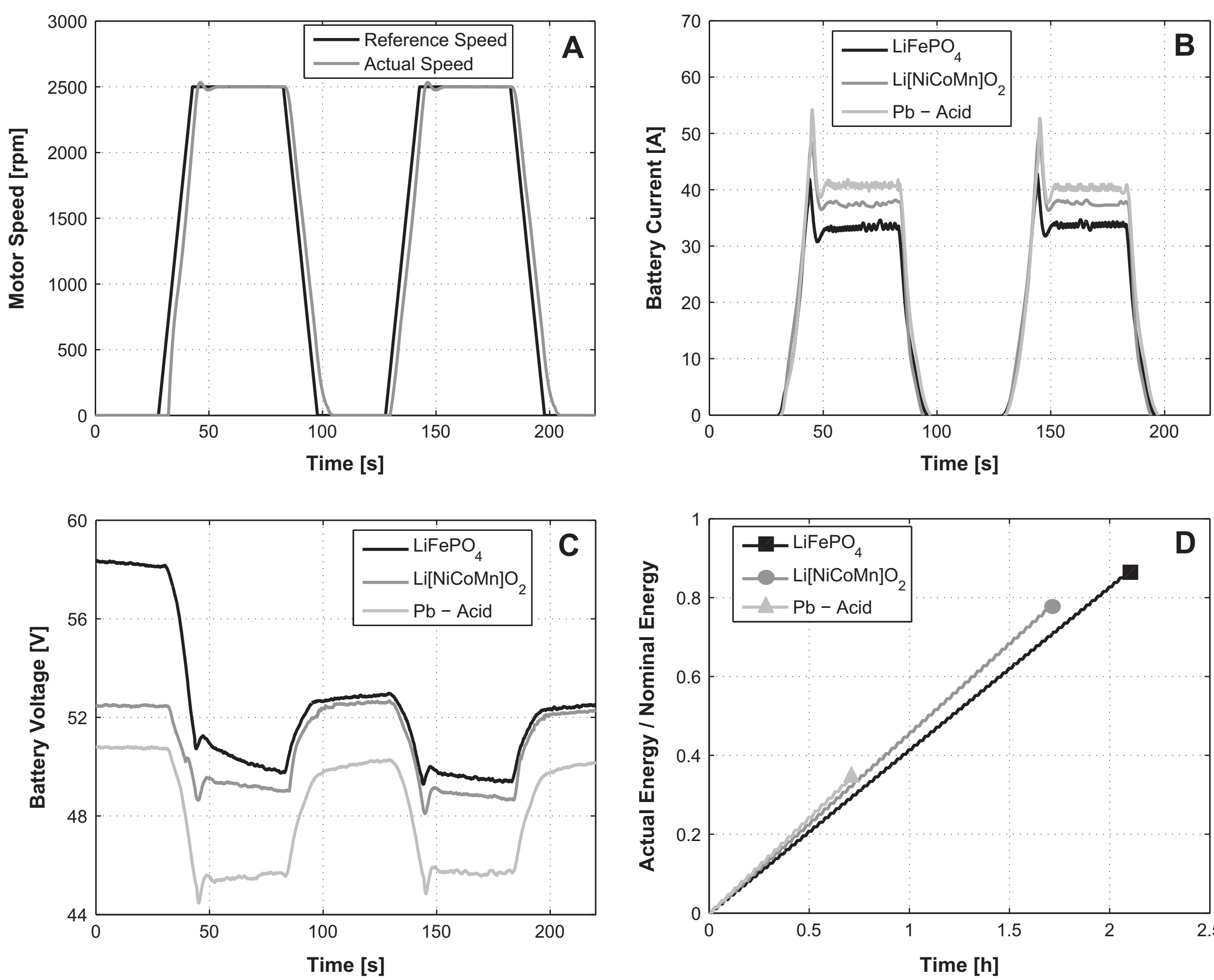

Fig. 9. Dynamic operations of $LiFePO_4$, Li[NiCoMn]O_2 and Pb battery packs supplying a laboratory electric drive for urban vehicle on a road slope of 10%.

described in Experimental. In this case, an identical weight of 194 kg, equals to the weight of vehicle equipped with $LiFePO_4$ battery pack, is simulated of the test bench for the three vehicle configurations, to avoid a physical change of the flywheel on the test bench. The obtained results for a road slope of 10% are shown in Fig. 9, referred to the driving cycle reported in Fig. 9A, in the first 220 s of the driving range, in terms of reference and actual motor speed for all the three batteries.

The speed cycle considered is based on a trapezoidal wave, with a resting time of about 20 s, acceleration/deceleration of 167 rpm s^{-1} and steady-state phase of 40 s at 2500 rpm. Therefore, the speed cycle has been repeated until each battery pack under test is considered fully discharged. In Fig. 9B the battery pack current profiles are shown, in the same first range of time of about 220 s considered for the motor speed. During this phase of the test, the maximum values of battery currents reach values of about 40, 48, 52 A, which are required during the maximum acceleration phases of the vehicle. These maximum current values increase, during the discharge, up to 62 A for the lead acid battery pack at the end of the test, when the battery voltage drops up to its minimum value. The higher value of battery currents for the lead acid batteries with respect to the other technologies is justified by the deeper voltage drop of the lead acid batteries, as clear from the Fig. 9C, where the profiles of the battery pack voltages are reported in the same first range of time. The last Fig. 9D shows the battery pack energy values, referred to their nominal values, for the above tests. In particular, the final value of the $LiFePO_4$ battery discharged energy is slightly increased compared to the corresponding steady state test of Fig. 8C. As a consequence of this comparison, an increased driving range of about 24 km is evaluated for the $LiFePO_4$ battery pack on the test bench for the dynamic cycle. This better result for the dynamic operation test is mainly due to the lower average value of the battery current along the driving cycle and to the resting times between two consecutive steps, when the battery chemical reactions can take place. For the $Li[NiCoMn]O_2$, the results in terms of discharged energy and autonomy on the dynamic cycle are quite similar to the corresponding steady state test of Fig. 8C. This means that the expected increase of autonomy, as evaluated for the $LiFePO_4$ battery pack, is balanced by higher vehicle weight for this test, which has been performed in the hypothesis of identical vehicle weight for each battery pack. It is clear that in case the right weight had been considered for the vehicle equipped with the $Li[NiCoMn]O_2$ battery pack, an increasing of autonomy would have been evaluated also for this case. On the other hand, the autonomy of the lead acid batteries on the dynamic driving cycle is evaluated of 5 km, with a discharged energy lower than its value evaluated in the corresponding steady state operations of Fig. 8C, despite the hypothesis of identical vehicle weight of 194 kg also for this battery pack, instead of the real value of 221 kg. This phenomenon is mainly due to the high current peaks during the acceleration phases, which affect the lead acid battery capacity in a negative way.

The laboratory results of this paper represent a useful knowledge base for electric vehicle designers to identify the real performance of each one of the analyzed battery technology, in terms of real capacity, power peaks on driving cycles and the efficiency during the recharging operations. However the proper choice of the technology to be used for the battery packs of full electric and hybrid road vehicles, in addition to the above advantages and disadvantages, should take into consideration other relevant aspects, such as size, durability and cost of the battery packs. On this regards Li batteries could be considered really promising in the short term. However, the use of other storage systems, such as EDL (Electric Double Layer) and lithium capacitors, characterized by lower energy density and higher power peaks, combined with batteries, might offer greater advantages in terms of dynamic performance and durability [19–25].

4. Conclusions

In this paper an experimental analysis of performance figures for different lithium storage technologies, in particular $Li[NiCoMn]O_2$ and $LiFePO_4$ batteries, have been carried out from the point of view of their application as storage systems for road vehicles powered by an electric traction system. The analysis and experimental results lead to the following conclusions:

- the actual capacity of both the two lithium technologies analyzed are almost close to their nominal battery capacity also for high discharging current (60 A), on the contrary lead acid batteries present, in the same case, an actual capacity reduced of about 40% referred to the nominal capacity;
- voltage profiles during discharge tests at high current evidence a better behavior of $LiFePO_4$, mainly due to a voltage curve almost flat in a wider range of SoC, compared to Pb and $Li[NiCoMn]O_2$;
- the charging efficiency test shows better performance of $Li[NiCoMn]O_2$, in particular at high charging rate, which positively affects the regenerative breaking and fast recharging operations;
- laboratory tests carried out on electric propulsion systems working on real road operations evidence that each battery pack, when supplying the electric drive, is able to follow the dynamic power requirements on the performed driving cycles;
- the driving ranges on predefined driving cycles of road electric vehicles, especially in dynamic operations, are much higher when battery packs are based on lithium technology due to their better performance in terms of battery capacity and voltage drop.

Other storage system technologies, different by electrochemical batteries, such as EDL and Li capacitors, might obtain a further improvement in the charging and discharging efficiency, driving range and the whole performance for road vehicle electrically powered.

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