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Characterizing different types of lithium ion cells with an automated measurement system

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A B S T R A C T

Lithium ion batteries are among the most promising electrochemical storage systems currently available. However, even though their high values of specific energy and energy density make them suitable for the development of new research approaches to counteract the global energy consumption, its diffusion is still limited in several sectors because of the high costs and safety problems. Five different Lithium ion cells of similar energy size but different chemical composition have been studied here, with the aim of pinpointing the fundamental characteristics of each battery. A comprehensive knowledge of these technologies can help finding out the critical parameters indicating dangerous situations. An automated test system based on the synchronous measurement of battery voltage, current and temperature has been employed in this comparative study. The system allows for testing the cells with a huge variety of protocols, from the standard charge cycle to the more complex power control test. Experimental results highlight that, for example, the $LiNiCoO_2$ and the Lithium Polymer batteries outperform for their energy density and specific energy while the $LiFePO_4$ show the highest versatility, efficiency and safety.

1. Introduction

In the last 60 years, the global energy consumption for the human well-being and comfort dramatically increased of about 180% and the projections for the next 30 years estimate a further growth of 10% [1–3]. This energy consumption is yet mainly based on fossil fuels, because of their high energy efficiency and facility to be used in many different areas, especially in power generation and automotive application. On the other hand, fossil fuel employment entails several dangerous effects, such as the depletion of non-renewable resources and the carbon dioxide (CO_2) emission.

To overcome these issues, the global research approach on energy supply is currently aimed at the development of new integrated systems able to join the use of renewable energies with the employment of more efficient energy saving strategies. In addition, the yield of these systems can be increased through the use of efficient energy storage technologies. As regarding the electric and hybrid mobility sectors, for example, this approach has the final purpose of developing fully renewable energy-based systems.

Among all the storage technologies, the lithium–ion battery (Li-ion) is one of the most encouraging. Li-ion batteries are composed of a lithiated carbon negative electrode (anode), a lithium metal oxide positive electrode (cathode) and an organic solvent electrolyte. Their distinct characteristic is the type of energy conversion, which is based on the lithium ions moving between the electrodes: the intercalation reaction. All these chemical features allow obtaining considerable values of operative voltage per cell, about three times higher than in NiCd and NiMH batteries. Moreover, the main material employed within the cell, the lithium, is one of the lightest metals available, thus allowing to obtain high specific energy and energy density values. Finally, the high rate capability and power density, the low self-discharge rate, the long cycle life, as well as the absence of memory effects and a broad range of operative temperature make this electrochemical storage technology a promising tool for several applications [4–6]. Nonetheless, to enhance their diffusion in all those sectors where their use is still limited, further studies are necessary to relieve the battery safety problem, as well as to reduce the costs. In the automotive and the renewable energy storage areas, for example, a significant scale-up of the Li-ion battery system is, in fact, yet crucial. Indeed, the Li-ion batteries are thermodynamically unstable because of the material reactivity [6]. Moreover, during operation, the anode and the cathode decomposition processes involve the consumption of active masses and electrolyte,

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accompanied by gas evolution [5], with a consequent loss of battery capacity and explosion hazards. In addition, the dendritic lithium formation can also occur during cycling, leading to the separator penetration. All these issues, in turn, can elicit an internal short circuit between positive and negative electrodes [7] with a possible thermal runaway, which becomes more and more serious with the increase of the battery size. Finally, it has to be remarked that the materials within the cells are incompatible with the environment and the human health [5], thus making this technology intrinsically dangerous if not correctly managed [8].

To reduce the risk of incidental and dangerous circumstances, the actual studies focus on the replacement of one of the constituent materials, namely the cathode, the anode and the electrolyte. Nickel (Ni), manganese (Mn) and iron (Fe) have been proposed for the cathode to increase cell efficiency and safety, as well as to reduce the costs [9–11]. Moreover, titanium (Ti) anodes and electrolyte polymeric structures are studied to increase the battery safety, even if inducing a reduction in the number of life cycles [12].

Within this context, in this work we studied five battery types based on different chemical composition, to highlight their fundamental characteristics. A deep understanding of this technology, in fact, can help determining which are the critical parameters involved with the beginning of any dangerous situation. To this aim, we subjected the selected batteries to a variety of testing protocols, from the standard ones (charge and discharge cycles) to the simulation of real loading conditions [13–16], with the use of an experimental system based on a power supply and an electronic load that can be run in remote mode. Moreover, for the entire duration of the protocols, the system provides a continuous control of both battery voltage and current and of the electrodes' temperature [17–20]. In parallel, to have a comprehensive understanding of the cell behavior, we also computed the inner resistance (IR) for all the batteries.

The battery test system here proposed is a simple low-cost assembled set-up, suitable for laboratory tests. The use of commercial instrumentation that can be managed by remote allows developing ad hoc control software easy to be changed and improved. At this point, we developed a versatile software able to simulate several standard testing protocols that, together with the modularity of the instruments, enables to select the most appropriate test according to the requirements.

2. Materials and methods

2.1. Battery test system: hardware

The battery test system architecture is composed of two main sections: the power section and the signal section, as shown in the block diagram of Fig. 1. The power section is made up of a power supply (TDK Lambda GEN 10-240) and a DC electronic load (made up of two Agilent N3306A modules). The signal section is composed of a personal computer equipped with two data acquisition boards (NI 6052E) and a NI c-DaQ 9178 chassis with a NI 9211 module, and has the role of synchronizing the signal generation and the data acquisition for the entire duration of the experiment. In particular, it controls the power supply and the DC electronic load, and acquires the cell voltage, the flowing current and the electrodes' temperature. The voltage is acquired directly on the battery poles, while a shunt resistor, with a nominal value of 0.1 Ω ± 5%, measures the current. It is notable that this resistor is able to dissipate up to 200 W so that the resulting thermal errors for all the tests performed in this work (dissipated power < 10 W) are negligible. The cell temperature is measured through two "copper disc" k-thermocouples placed on the electrodes' connectors, while a standard k-thermocouple is employed to acquire the room temperature. The experimental system here described allows to test single or stacked cells within a maximum supply of 10 V and 240 A, and a maximum load of 60 V and 240 A.

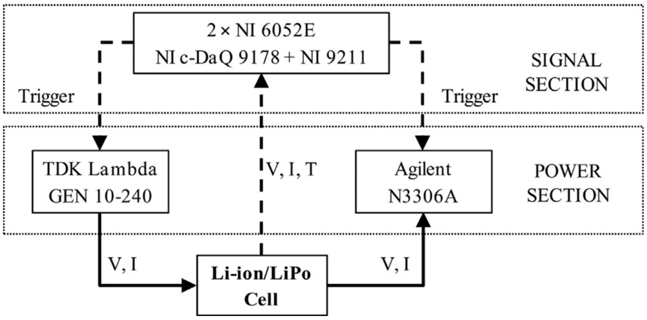

Fig. 1. Test system. Block diagram of the test system hardware.

Despite the fact that the automated system could work with an acquisition frequency up to 5 kHz, preliminary experiments showed that 10 Hz was sufficient to properly measure the current and the voltage of our cells. Therefore, this value was chosen to avoid data overflow, and was kept fixed for the entire duration of the experiment.

The repeatability of the proposed testing system was measured in advance. The capacity of 1 $LiFePO_4$ cell was measured during 5 repetitive charging and discharging cycles. The ratio between the Standard Deviation and the mean of the measured capacity was taken as a measurement of the system repeatability, and our tests returned a value of 0.41% for the charging and 1.41% for the discharging, pointing out the high reproducibility of the proposed system. Of note, the decline occurring in tested battery was considered negligible for such a small number of cycles.

2.2. Battery test system: software

The test system proposed in this work was designed to be fully automated and flexible, and to continuously control and synchronize all the instrumentation through a user interface developed in LabVIEW 2012. In particular, it allows for reproducing the main characterization tests currently utilized in literature, which can be divided in four main groups [13–16], as follow:

i Basic tests: the battery is tested in nominal conditions, such as the full and partial charge and discharge.
ii Basic characterization tests: the battery is studied in different conditions (charge and discharge tests performed at different current or operating temperature values), but the parameters are still kept within the safe operation ranges supplied by the manufacturer. These tests allow calculating capacity, energy, average power, coulomb and energy efficiency, energy and power density, specific energy and power and the self-discharge of the tested battery.
iii "Simulation" tests: the battery is subjected to experimental protocols aimed at reproducing automotive application (electric and hybrid-electric vehicles) or stationary application obtained combining discharges, charges and stand-by cycles. During these tests, is possible to compute the battery amperometric efficiency related to the specific protocol.
iv Critical tests: the battery is tested in critical conditions, carefully forcing the control variables beyond the safe limits to study the pre-incidental conditions.

A scheme of the software's logic is shown in Fig. 2, while Table 1 shows the nominal parameters and the safe operation ranges given by the manufacturers of the cells utilized in this study.