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***Abstract*—Lithium-ion batteries are becoming more and more ubiquitous in many applications and appear as a key element for the success of energy transition. Their energy efficiency needs to be carefully understood and studied. In this work, we study the influence of the state of charge and of the shape of the current on the value of the efficiency of LFP (lithium-ion iron phosphate) lithium-ion cells. This is a preliminary step toward a full efficiency modeling.**

***Keywords*—batteries, lithium-ion, efficiency**

I. Introduction

Energy transition requires to associate new consumers behaviors (to reduce the consumption) with renewable energy sources (to avoid carbon emission). A key element for the success of this virtuous process, is the capacity for energy storage in order to adapt the energy availability to the users needs. Lithium batteries already play a leading part in the storage of energy in a large variety of domains [1], [2]: electronics, power tools, electro-mobility. In application with higher level of energy as power networks, pumped hydroelectric storage is center stage but batteries begin to be considered as a serious solution particularly in the case of smart grids [3].

Concerning characteristics required for optimal storage technology, the focus is usually on price, lifetime, safety, reliability. However, efficiency is very important as energy exchanges could be frequent in application as hybrid vehicles or smart-grids.

Even if lead acid remains the most used battery, lithium-ion is currently the main technology for batteries in new storage applications [4]. The main advantages of lithium-ion batteries are high energy and power density, high efficiency and long life time. In contrast, their major weaknesses are safety and fire hazards which implies strict monitoring of temperature and voltage of each cell in a pack. As another potential drawback, the environmental impacts of these technologies are still under observation [5]. The diversity of lithium-ion chemistry -associated with a diversity of performances- could be seen as an attractive feature to adjust the technology to fit the constraints of a given application. However, this diversity leads to the need to accurately understand the performances and the key factors acting on them [6].

Kang et al. [7] established that the efficiency of lithium-ion depends on current and State of Charge (SoC) and is higher than the efficiency of NiMH batteries.

In some previous works, we showed that the energy efficiency is modified by cell aging and that it would be important to consider not only the efficiency of fresh batteries but also the efficiency of aged batteries when comparing two technologies [8]. The degradation of the efficiency could be linked with the fade of capacity [9]. Analyzing and understanding the evolution of the energy efficiency strengthens this parameter as a powerful tool for the sizing of storage devices [10]. Other recent studies focus on battery efficiency as a key performance parameter [11]–[16].

II. Methodology

A. Efficiency definitions

In this work the cell model consists of an ideal voltage generator connected with an impedance Z. The generator is defined by an Open Circuit Voltage (OCV). The real part of the impedance causes losses which reduce the energy efficiency of the cell. Different energy efficiencies could be computed following a method exposed by [7]. The expressions are reminded in the following:

$$\eta_{net,ch} = \frac{W_{net}}{W_{ch}} \tag{1}$$

$$\eta_{net,dis} = \frac{W_{dis}}{W_{net}} \tag{2}$$

$$\eta_{ch,dis} = \eta_{net,ch} \cdot \eta_{net,dis} = \frac{W_{dis}}{W_{ch}} \tag{3}$$

$$W_{net} = \int_{DoD_a}^{DoD_b} I \cdot OCV \cdot dDoD \tag{4}$$

$$W_{ch} = \int_{DoD_a}^{DoD_b} I \cdot U_{bat,ch} \cdot dDoD \tag{5}$$

$$W_{dis} = \int_{DoD_a}^{DoD_b} I \cdot U_{bat,dis} \cdot dDoD \tag{6}$$

with:

- I: Current
- $U_{bat,ch}$: Cell voltage during charge
- $U_{bat,dis}$: Cell voltage during discharge
- DoD: Depth of Discharge, ($DoD(\%) = 100 - SoC(\%)$)

It must be noticed that if the current profile is constant during charge and discharge the efficiency expressions could be simplified by considering only the voltages. From previous expressions, it is clear that the efficiency depends on the value of DoD. The efficiency could be computed during a full discharge/charge cycle at constant current. In this case the considered range of DoD is 0 to 100%. It is also possible to compute efficiency at a given DoD with a sequence of pulses alternating discharging and charging currents.

B. Experimental Setup

The cell under test is a LFP-C (lithium-ion iron phosphate / graphite) technology from A123. The rated capacity is 4.4Ah with a max voltage of 3.6V. The experiments plan is conducted at 25°C and contains three types of tests: pseudo-OCV test, cycle tests and pulse tests. Tests were conducted with a Biologic VSP/VMP potentiostat, cells under test were put in a climate chamber (Friocell707) to ensure ambient temperature. Data will be publicly available at Univ. Eiffel Open Data repository [17]. Data have been processed using DATTES library [18].

1) Pseudo-OCV test: Classically the OCV could be obtained from a constant discharge/charge cycle at low current (i.e. C/20). OCV obtained with this measurement technique is commonly known as pseudo-OCV. The pseudo-OCV is the average between the charging and the discharging voltages. The gap between charge and discharge voltages is commonly called hysteresis. This hysteresis is amplified if the current increases, therefore, the lower the current, the better the accuracy but the longer the test duration.

In the present work, we propose to obtain OCV values with a modified protocol. From a full charged state, the cell is discharged by a sequence of discharging pulses at 1C. Each pulse lasts 36s and is followed by a 684s period of rest. The equivalent average current is C/20 – and length of time is the same. Then, the cell is charged by a similar profile.

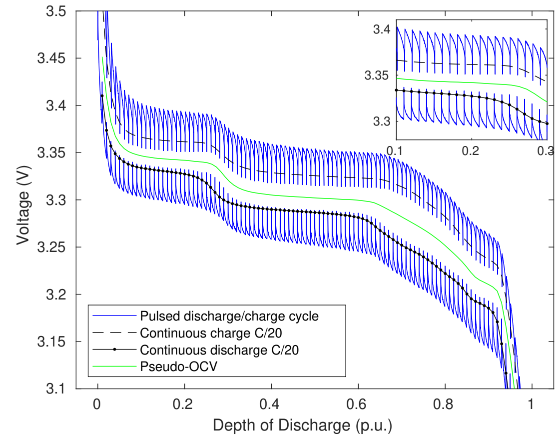
For both tests, a minimum rest time of 60 minutes precedes each half cycle. Both tests have similar durations, that is about 42 hours depending on initial and intermediary rests times before each half-cycle.

Fig. 1a shows the cell voltage versus DoD (blue line). First step to obtain pseudo-OCV is to keep only final rest voltages: those are local maximum points in discharge and local minimum points in charge. Afterwards, pseudo-OCV is computed as the mean value between discharge and charge (green line in Fig. 1a). For comparison, cell voltage during continuous discharge and charge at C/20 are also included in this figure.

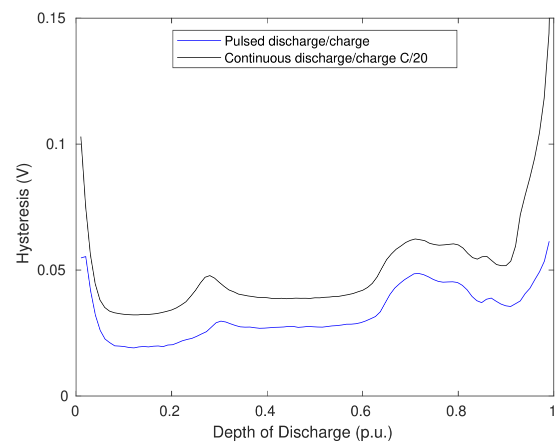
From Fig. 1b, it is obvious that this method enables to get a lower hysteresis in the voltage without increasing the test duration.

2) Cycle tests: Cycle tests consist in a full discharge followed by a full charge at different current rates. In this work, we included the following C-rates: 1C, 2C, 3C, 4C. A 30 minutes rest follows each half cycle.

3) Pulse tests: Sequences of discharging and charging pulses are applied as shown in Fig. 2a. First step is a full charge followed by a partial discharge and 40 minutes rest. This step is used to set the target DoD. Then, several sequences are applied to scan different levels of current (1C, 2C, 3C and 4C), for each pulse duration (1s, 10s or 100s) and different values of duty cycle (1/2, 1/4 and 1/10). Fig. 2b illustrates one pulse sequence composed of 4 alternating



(a) Pulsed discharge/charge cycle, continuous C/20 cycle and pseudo-OCV obtained from pulsed cycle.



(b) Hysteresis.

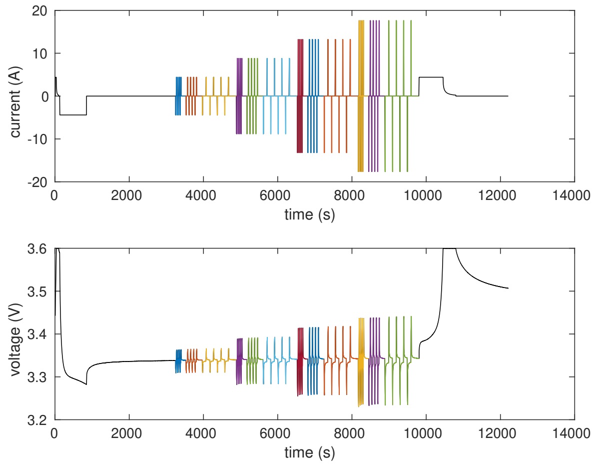
Fig. 1: Results of pulsed pseudo-OCV test compared to continuous C/20 cycle.

discharge/charge pulses followed by corresponding rests for one combination of C-rate, pulse duration and duty cycle. This test is performed at two different values of DoD (20 and 50%) and for three different values of pulse duration mentioned above.

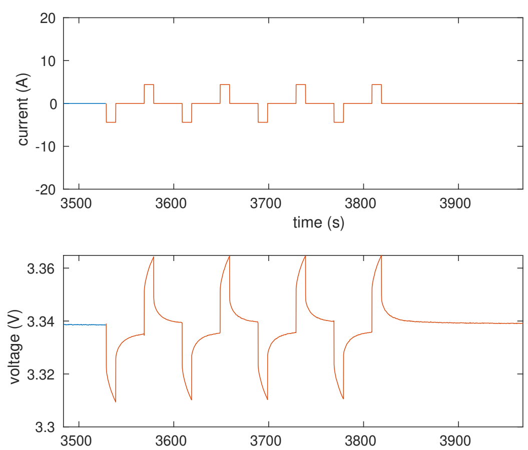
III. Results

A. Pseudo-OCV

In Fig. 1b we can see that cycle hysteresis is minimized with the pulsed technique related to the continuous current technique. From DoD 10 to 90%, pulsed technique hysteresis is 10 to 20mV lower compared to that obtained with continuous current technique, which represents a relative improvement of 20 to 50% at these DoD range. This difference is even higher at extreme DoD levels (under 10% or above 90%). From this, we can state than the pulsed technique is more accurate that the classical one to measure OCV.

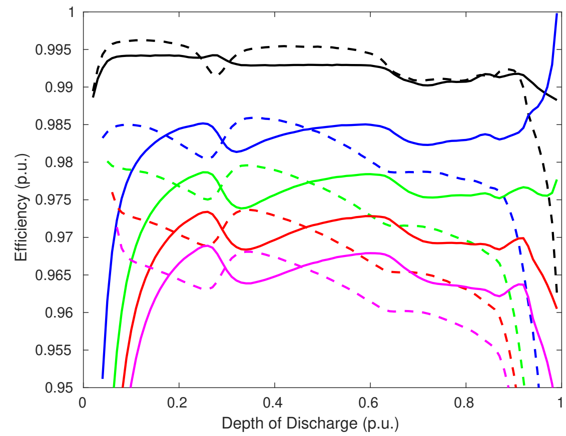


(a) Profile for 20% DoD, 10 seconds pulses at different C-rates and duty cycles.

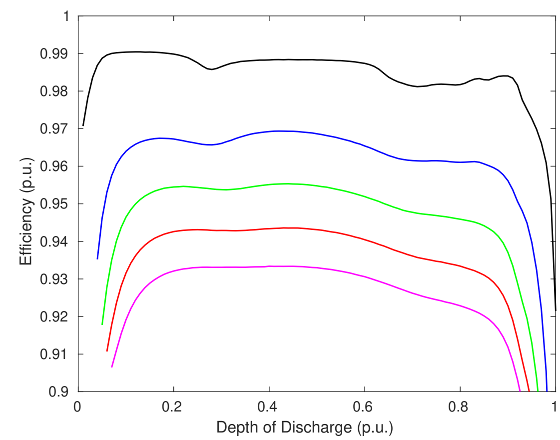


(b) Zoom on one pulse sequence (10s, 1/4 duty cycle, 1C).

Fig. 2: Pulse efficiency test.



(a) Charge and discharge efficiency (respectively continuous and dashed lines).



(b) Cycle efficiency.

Fig. 3: Efficiency for different C-rates (black, blue, green, red and magenta for C/20, 1C, 2C, 3C and 4C respectively).

B. Cycle efficiency

In this section, we present the results of efficiency from discharge/charge cycles at different C-rates (C/20, 1C, 2C, 3C and 4C. Charge and discharge efficiencies can be calculated by using equations (1) and (2). Afterwards, global efficiency can be calculated from half-cycle efficiencies with equation (3). Fig. 3 illustrates efficiencies of each half-cycle and global efficiency. Of course, efficiency generally decreases with increasing C-rates.

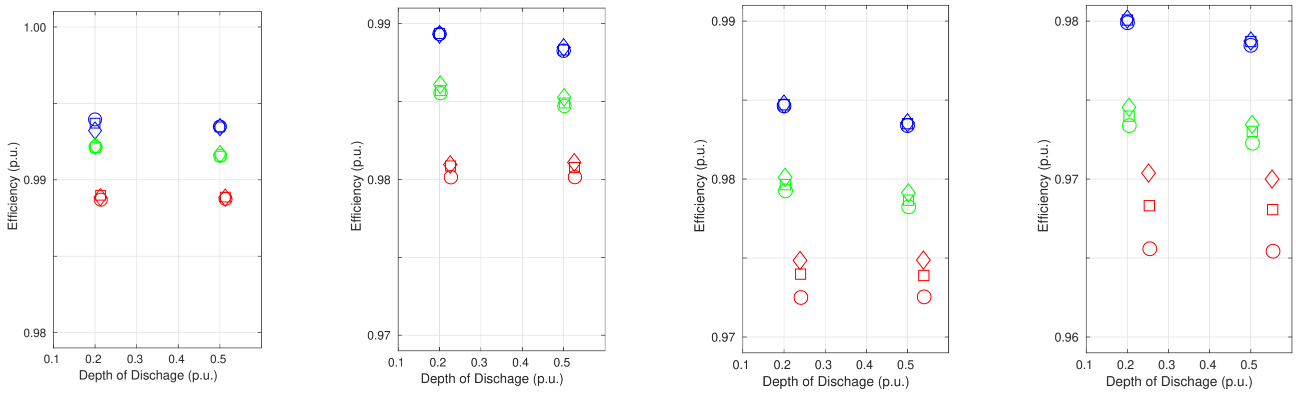
As shown in Fig. 3a charge efficiency is generally higher than discharge efficiency at higher levels of DoD and inversely, for lower DoD levels (under 20%) discharge efficiency is higher than charge efficiency. At medium DoD levels both efficiencies oscillate and sometimes charge efficiency is higher than discharge efficiency and sometimes the contrary. Three crossing points between charge and discharge efficiencies can be observed for 1C to 4C. These crossing points seem to be at three stationnary DoD levels: at about 20, 30 and 45% DoD.

Another interesting result is that efficiency is generally quite constant in medium DoD levels and it rapidly decreases with extreme values (full charge or full discharge). This result is quite characteristic of LFP cells and differs from that obtained in NMC (Nickel Manganese Cobalt) cells [8], where efficiency is continuously decreasing with DoD.

C. Pulse efficiency

Pulse efficiency has been measured following the test protocol described above. Fig. 4 summarizes the results for all tests at 4 current rates (1 to 4C), 2 DoD levels (20, 50%), 3 pulse durations (1, 10 and 100 s) and 3 duty cycles (10, 25, 50%). In total, efficiencies for 72 different conditions are shown.

Every factor (C-rate, DoD, pulse duration, duty cycle), has some influence on efficiency. C-rate influence is quite important, making efficiency decrease at higher C-rates. For example, for 1C efficiency is between 98.5 and 99.5% while



(a) 1C (b) 2C (c) 3C (d) 4C

Fig. 4: Efficiency for pulses from 1C (a) to 4C (d). Color indicates pulse duration: blue = 1s, green = 10s, red = 100s ; marker shape indicates duty cycle: circle = 1/10, square = 1/4, diamond = 1/2.

for 4C it is between 96.5 and 98% (Fig. 4). The same trends have been shown for cycle efficiency in the preceding section but with lower efficiencies: about 96.5 and 93% respectively for 1 and 4C for the same DoD levels as it could be read in Fig. 3.

Efficiency is less influenced by DoD, but in many test conditions efficiencies are slightly lower for 50% DoD compared to those obtained at 20% DoD.

Pulse duration has quite an important influence. For all combinations of C-rate, DoD and duty cycle, efficiency decreases with pulse duration: in Fig. 4 points are always in the same color order, blue-green-red, respectively for 1, 10 and 100s.

Finally, duty cycle has a little but sensible influence on efficiency. For most of C-rate, DoD, pulse duration combinations efficiency is decreasing with increasing values of duty cycle. In Fig. 4 the same sequence of marker shape can be found (diamond-square-circle for respectively 1/10, 1/4 and 1/2 duty cycle) for 10 and 100 seconds tests at 2C, 3C and 4C (green and red markers in Figs. 4b, 4c and 4d), indicating the same trends from high efficiency (diamonds) to low efficiency (circles).

IV. Discussion

A. Pseudo-OCV

In this work we used a new technique derived from pseudo-OCV. The classic pseudo-OCV technique consists in discharging and charging the cell with a constant current. The new technique consists in using a pulsed discharge/charge cycle and take the measured voltage at the end of each rest time. In order to enable the comparison between the classic pseudo-OCV technique and the pulsed one, we chose the same mean current value as in pseudo-OCV (C/20).

As stated in the preceding section, the pulsed OCV technique is 10 to 20mV more accurate than the pseudo-OCV (Fig. 1b). The difference between charging and discharging voltage measured in pulsed test technique is significantly lower than one measured in continuous current technique for the same test duration, i.e. for the same average current, C/20. In fact, pulsed discharge (or charge) can be considered as a superposition of a continuous discharge (charge) and a pulsed one, then cell voltage in the pulsed technique will oscillate around the mean value (continuous current), as shown in Fig. 1a. Pseudo-OCV is then calculated by retaining only the voltage values at the end of each rest time, which are probably nearer to real OCV than voltage points obtained in the continuous current discharge (charge).

The accuracy of this new technique may depend on the pulse parameters: pulse amplitude, pulse duration and rest duration. Further studies could be conducted to find an optimal combination of the pulse parameters for even better results.

B. Cycle efficiency

In LFP-C batteries, OCV is mainly flat at middle DoD levels, from about 20 to 90%. As shown in Fig. 3 some fluctuations appear in the DoD range from 20 to 90%. These fluctuations are found for the DoD levels (30, 70, 90%) corresponding to OCV variations. In LFP/C batteries these OCV variations correspond to phase changes of graphite with lithiation level.

C. Pulse efficiency

Fig. 4 shows that the efficiency regularly decreases as expected when the current increases. The DoD has nearly no influence at these levels (20 and 50%).

A sensible influence of pulse duration on efficiency was found and to a lesser extent, of duty cycle. For longer pulses efficiency is lower. The explanation to this can be found in impedance spectrum. In fact longer pulses involve lower frequencies. Generally, batteries impedance, including lithium-ion batteries, decreases with frequency in the low frequency range (from mHz to some Hz); therefore, efficiency for 1s pulses will be higher than for 10s pulses and even more for 100s pulses.

Concerning the influence of the duty cycle on efficiency, two factors have contradictory effects. In one hand, lower duty cycles lead to lower frequencies and this could lead to lower efficiencies (higher impedance). On the other hand, lower duty cycles lead to lower average current rates (longer rest times compared to pulse durations) and consequently lead to higher efficiency. This first effect (signal frequency) seems to have more influence on efficiency than the second one (average current rate) as shown in Fig. 4 for 10s and 100s pulses from 2 to 4C where it could be noticed that the efficiency values decrease when duty cycle values decrease.

V. Conclusion

In this work we have studied the efficiency of lithium-ion LFP based cells.

To study efficiency, first of all we need accurate measurements of OCV. This was done by a new pulsed technique showing less hysteresis than than equivalent continuous pseudo-OCV one with same test duration. Cycle efficiency tests showed that LFP efficiency versus DoD is quite constant and rapidly decreases with extreme values. Pulse efficiency has been tested at 72 different conditions: two DoD levels, four C-rates, three pulse durations and three duty cycles. Measurements reveal the influence of C-rate and pulse duration and, to a lesser extent, duty cycle and DoD level.

Further work will consist in studying pulse efficiency for other DoD levels and for other temperatures. This will enable to obtain accurate efficiency maps which can be used to develop efficiency models.

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