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Determining Lithium-ion Battery One-way Energy Efficiencies: Influence of C-rate and Coulombic Losses

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***Abstract*—This paper addresses the lithium-ion battery efficiencies, a fundamental characteristic normally not given in battery specification sheets and often overlooked in research papers that consider battery application and modelling. In-house experiments were performed to obtain: (i) charging/discharging curves with different C-rates and (ii) open-circuit voltage characteristic. The results were used to analyze battery coulombic and energy efficiencies, which lead to methodology for accurately assessing one-way energy efficiencies. Utilization of accurate one-way efficiencies potentially improves a variety of battery models and algorithms for state-of-charge estimation. In addition, residual capacities (after discharging with higher C-rates) are measured and their influence on roundtrip efficiencies is assessed.**

Keywords*—*Li-ion batteries, efficiency, experimental research

I. Introduction

Lithium-ion (Li-ion) batteries are widely used in a range of applications, from consumer electronics to electric vehicles and energy storage. There is a large number of papers addressing various electrochemical aspects of Li-ion batteries. Most papers concentrate on the battery behaviour modelling, be it either (i) detailed, low-level modelling of chemical properties, or (ii) high-level modelling of electrical properties aimed for inclusion in higher-level (mixed-integer linear) optimization models. However, majority of papers neglect some basic Li-ion battery properties, e.g. most high-level battery operational and investment models neglect the fact that the battery charging characteristic is highly non-linear [1]. More than few papers refer to the state-of-charge assessment, without accounting for the efficiency in their models [2], [3], while some papers discuss only discharge efficiency, disregarding the charging efficiency, e.g. [4]. Finally, there are papers that simply assign constant values both to the charging and discharging efficiencies, disregarding their variability for different charging/discharging levels [5].

The roundtrip coulombic and energy efficiencies are determined in [6] for Ni-MH batteries, while the roundtrip voltaic efficiencies are determined in [7] for Li-ion batteries. Most methods for assessing one-way efficiencies rely on battery's open-circuit voltage (OCV) characteristic, which normally has to be obtained experimentally. In [8] the OCV characteristic is determined by subjecting a battery to the full cycle with low C-rates and then averaging the measured voltage over a charge/discharge cycle. This approach is utilized in [9], [10], where one-way energy efficiencies of Li-ion and Ni-MH batteries are determined. Two rapid methods for determining the OCV characteristic, based on periodical pausing of charging/discharging, are presented in [11]. Another, less time-consuming method, is presented in [12], where one-way energy efficiencies are determined with reference to the estimated open-circuit voltage during a pulse charge/discharge cycle. None of the above methods, however, take into account coulombic efficiency when assessing the one-way efficiencies. Coulombic efficiency for Li-ion batteries is expected to be very high, close to 99% [13].

This paper presents experimental results with the aim to demonstrate some fundamental Li-ion battery characteristics related to the battery efficiency and charging/discharging C-rate. These characteristics should be accounted for when developing higher-level optimization models that include Li-ion battery operation. The paper is organized as follows. Section II presents the laboratory setup and the tested battery cell. Rechargeable battery basics, as well as formulae to calculate the battery efficiencies are given in Section III. Experimental results are presented in Section IV, while conclusions are duly drawn in the final Section V.

II. Experimental Setup

Li-ion battery charging/discharging experiments are conducted on an advanced grid-tied bidirectional AC-DC converter. This custom-made converter is coupled with National Instruments (NI) hardware and software that allows great flexibility in assigning the battery experiments, as well as

TABLE I
SPECIFICATIONS OF THE TESTED NMC 18650 CELL

Chemistry	NMC
Nominal capacity	3.0 Ah
Nominal energy capacity	10.8 W
Nominal voltage	3.6 V
Charging voltage	4.2 V
Discharge cut-off voltage	2.0 V
Max. charge current	4.0 A (1.33C)
Max. discharge current	20 A (6.67 C)

full control over them. A more detailed description of this laboratory testbed can be found in [1], [14].

Experiments are conducted on a commercial NMC[1] 18650 battery cell. Manufacturer's specifications for this cell are given in Table I. In line with [15], the numerical ratio between the maximum allowed electric power and the energy outputs at 1C discharge rate is 6.67 (lower than 10), so this battery cell is considered to be a high energy cell.

III. RECHARGEABLE BATTERY CHARACTERISTICS

Battery capacity can be expressed either in Ampere-hours (Ah) or in Watt-hours (Wh), describing charge and energy capacity, respectively. In theory, a battery rated at 3.0 Ah and 11 Wh, can deliver: (i) current of 3.0 A (power of 11 W) for 1 hour, or (ii) 1.5 A (5.5 W) for 2 hours, etc.

C-rate is the current at which the battery is charged or discharged, defined as: $C-rate=\frac{Ah-rating}{1\,hour}$. Thus, the unit for C-rate is Ampere (A) and a battery rated at 3.0 Ah will charge/discharge with: (i) 3.0 A at 1C, (ii) 1.5 A at 0.5C, (iii) 6.0 A at 2C, etc.

Battery efficiency can be categorized as (i) coulombic, (ii) voltaic, and (iii) energy efficiency. The coulombic efficiency η^{I} is associated with the charge (Ampere-hours, Ah) extracted from or injected into a battery. The voltaic efficiency η^{V} is associated with an average charging/discharging voltage. Finally, the energy efficiency η^{E} is associated with the energy (Watt-hours, Wh) extracted from or injected into a battery.

Battery efficiency can also be divided into (i) one-way, and (ii) roundtrip. The one-way efficiency refers to either charging or discharging efficiency (η^{ch}, η^{dis}), while the roundtrip efficiency (η) refers to the efficiency of the overall charging-discharging cycle. In order to obtain relevant roundtrip efficiency, charging and discharging must be performed over the same state-of-charge range. In this paper, all efficiencies are obtained over the full state-of-charge range (0-100%).

Battery state-of-charge (SoC) is a measure of the amount of charge stored in a battery with respect to the charge that the battery contains when fully charged. In real-time implementations, battery SoC is not straightforward to determine and there is a number of methods that tackle this problem (e.g. see the review in [16]). The most common method for SoC estimation is coulomb counting, which is based on integration of the charging/discharging current (Ah-counting) [14]. Analogously, state-of-energy (SoE) can be used as a measure of the amount of energy stored in a battery [1]. SoE can be determined by integration of the charging/discharging power (Wh-counting) as follows:

$$\begin{aligned} soe(t) =& soe(t-1)+\eta^{\mathrm{ch}}\cdot\frac{100}{C^{\mathrm{E}}}\int_{t-1}^{t}P^{\mathrm{ch}}(\tau)d\tau \\ &-\frac{1}{\eta^{\mathrm{dis}}}\cdot\frac{100}{C^{\mathrm{E}}}\int_{t-1}^{t}P^{\mathrm{dis}}(\tau)d\tau, \end{aligned} \tag{1}$$

where $soe(t)$ is expressed in percentages, C^{E} is the cell energy capacity (Wh), P^{ch} and P^{dis} are charging and discharging powers (W) (both always assumed positive), while η^{ch} and η^{dis} are charging and discharging energy efficiencies. An expression analogous to (1) can be derived for determining SoC, which might be more suitable for online assessment of the remaining battery runtime, especially since the coulombic efficiency is always higher than the energy efficiency, thus making the SoC assessment less prone to deviations due to (in)accuracy of the used efficiency. On the other hand, SoE might be more practical for offline analyses and applications where the primary concern is energy, such as energy markets where participants trade energy (Wh), not electric charge (Ah). In this paper, SoE is used for measurement analysis and results presentation.

Determining SoC and SoE is somewhat intertwined with determining battery efficiencies since accurate assessment of one is a prerequisite for accurately assessing the other.

A. Calculating Battery Efficiency

Roundtrip energy efficiency is a ratio of the total energy extracted from a battery (E^{dis}) and the total energy injected in a battery (E^{ch}) over a partial or full charge-discharge cycle:

$$\eta^{\mathrm{E}}=\frac{E^{\mathrm{dis}}}{E^{\mathrm{ch}}}. \tag{2}$$

where E^{dis} and E^{ch} are calculated from the measured voltage (V) and current (I), as follows:

$$E=\int_{0}^{T}V(\tau)I(\tau)d\tau, \tag{3}$$

with T being the charge/discharge duration.

One-way energy efficiencies are defined as:

$$\eta^{\mathrm{ch}}=\frac{E^{\mathrm{batt}}}{E^{\mathrm{ch}}}, \tag{4}$$

$$\eta^{\mathrm{dis}}=\frac{E^{\mathrm{dis}}}{E^{\mathrm{batt}}}, \tag{5}$$

where E^{batt} is the total energy stored in the battery. This is a theoretical value that cannot be determined from the measured current and voltage values. However, the following expressions, substituting E^{batt}, can be calculated for charging and discharging individually:

$$E^{\mathrm{batt,ch}}=\int_{0}^{T^{\mathrm{c}}}V^{\mathrm{OC}}(\tau)I^{\mathrm{ch}}(\tau)d\tau, \tag{6}$$

[1]Lithium Nickel Manganese Cobalt Oxide ($LiNiMnCoO_2$) cathode, graphite anode

$$E^{\text{batt,dis}} = \int_0^{T^{\text{d}}} V^{\text{OC}}(\tau) I^{\text{dis}}(\tau) d\tau, \tag{7}$$

where I^{ch} and I^{dis} are charging and discharging currents (both assumed positive), T^{c} and T^{d} are charging and discharging durations, while V^{OC} is an open-circuit voltage (OCV) characteristic which is to be determined experimentally.

Roundtrip coulombic efficiency is a ratio of the total charge extracted from a battery (C^{dis}) and the total charge injected in a battery (C^{ch}) over a partial or full charge-discharge cycle:

$$\eta^{\text{I}} = \frac{C^{\text{dis}}}{C^{\text{ch}}}, \tag{8}$$

where C^{dis} and C^{ch} are calculated from the measured current (I) as follows:

$$C = \int_0^{T} I(\tau) d\tau. \tag{9}$$

To the best of the authors' knowledge, no method exists for determining one-way coulombic efficiencies purely from the logged current and voltage.

IV. Experimental Results

A. Charging/discharging Experiments with Different C-rates

Seven full charge/discharge cycles at different C-rates (0.2, 0.4, 0.6, 0.8, 1.0, 1.2 and 0.05) are performed on the tested battery cell, always starting with a fully discharged cell. In addition, discharge cycles at C-rates higher than 0.2 are followed by a resting period of 60 min and an additional discharge at 0.2C to assess the remaining energy in a rested cell after the fast discharge (C-rate > 0.2) cut-off. Experimental test cycles are presented in Fig. 1.

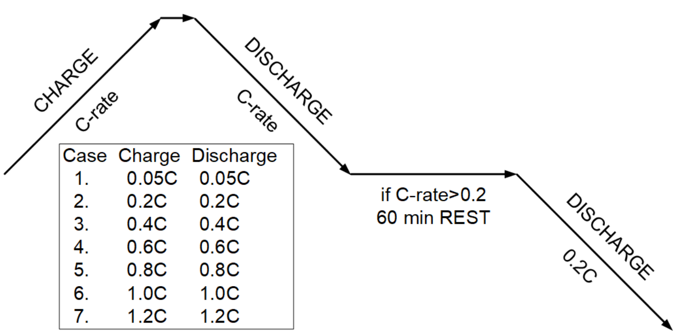

Fig. 1. Experimental test procedure

Charge/discharge curves for 0.4C are given in Figs. 2 and 3, where the displayed voltage and current are logged values (1-second sample time), while the power is calculated by multiplying the two. Fig. 2 displays a typical non-linear constant-current-constant-voltage (CC-CV) charging characteristic, while Fig. 3 displays a typical discharging characteristic, where shape of the power curve is determined by the shape of the voltage curve, since the current is kept constant until the cut-off voltage is reached. Figs. 4 and 5 display the obtained charge/discharge power curves and demonstrate that their shapes are highly dependent on the C-rate. These curves are used for calculating charge/discharge energies via eq. (3).

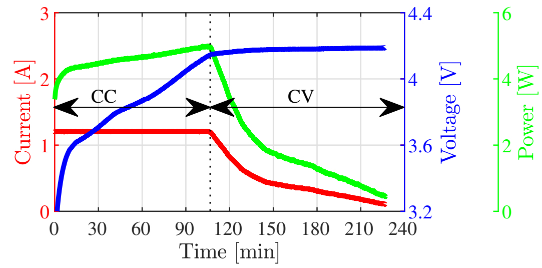

Fig. 2. Charging characteristic for 0.4C charging current

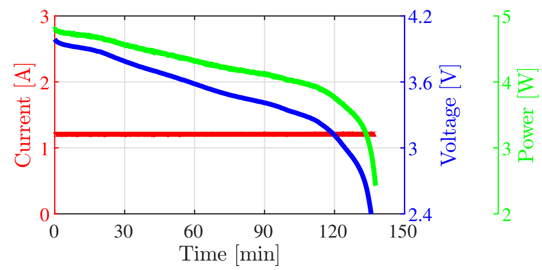

Fig. 3. Discharging characteristic for 0.4C discharging current

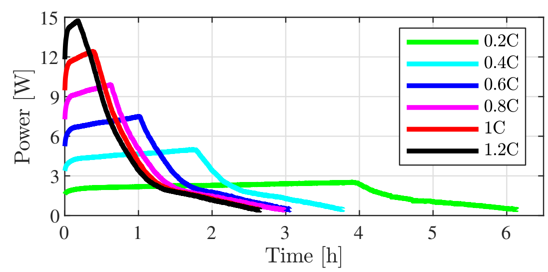

Fig. 4. Charging power characteristics with different C-rates

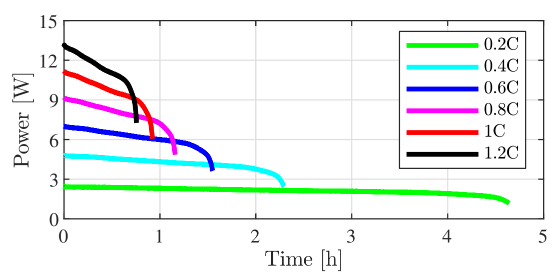

Fig. 5. Discharging power characteristics with different C-rates

B. Roundtrip Efficiencies

Energy and charge capacities obtained during the charging/discharging experiments at different C-rates are displayed in Figs. 6 and 7. The size of blue bars (lying on top of green bars) indicates that not much energy (charge) can be drained from a rested battery cell after the high-current discharge. Table II displays the roundtrip energy efficiencies calculated from Fig. 6 via eq. (2) and roundtrip coulombic efficiencies calculated from Fig. 7 via eq. (8). Subscript 'drain' indicates that the efficiency was calculated by including the energy/charge of the second 0.2C discharge (blue bars) in E^{dis} and C^{dis}. It can be concluded that an additional draining at

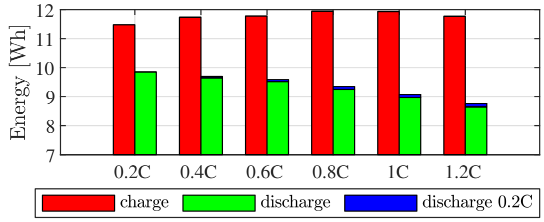

Fig. 6. Charging/discharging energy capacities

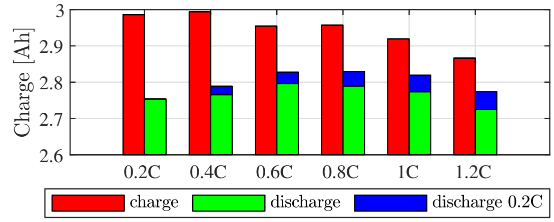

Fig. 7. Charging/discharging charge capacities

TABLE II
ROUNDTRIP EFFICIENCIES

C-rate \ Efficiency	η^{E}	η^{E}_{drain}	η^{I}	η^{I}_{drain}
0.2C	0.86	-	0.92	-
0.4C	0.82	0.83	0.92	0.93
0.6C	0.81	0.81	0.95	0.96
0.8C	0.77	0.78	0.94	0.96
1.0C	0.75	0.76	0.95	0.97
1.2C	0.73	0.75	0.95	0.97

0.2C increases the battery roundtrip efficiencies by roughly 0-2%. The obtained coulombic efficiencies are relatively low compared to what might be expected from the literature [13]. This might be due to long connection cables between the converter and the tested cell or simply due to current measurement inaccuracies. Anyhow, we consider these values to be realistic and proceed to evaluate their effect on one-way efficiency assessment.

C. One-way Efficiencies

Charging/discharging voltages, logged during the experiments described by Fig. 1, are displayed in Fig. 8, with state-of-energy (SoE) on the x-axis determined from eq. (1) with: (i) fixing $P^{dis} = 0$ and $\eta^{ch} = 1$ for charging, (ii) fixing $P^{ch} = 0$ and $\eta^{dis} = 1$ for discharging, and (iii) taking C^{E} as the total energy injected/extracted during every charge/discharge. The SoE determined in this way (offline) is independent of the actual battery efficiency. From Fig. 8 it is clear that the distance between the charge/discharge voltage curves and the OCV curve is C-rate-dependent, which indicates that voltaic losses (voltaic efficiency) are also C-rate dependent. Higher C-rates imply higher voltaic charge/discharge losses.

An open-circuit voltage (OCV) characteristic is determined by applying a full charge/discharge cycle at low C-rate (0.05C, not shown in Fig. 8) and then averaging the obtained closed-circuit voltages (CCV) [8]. By utilizing the obtained OCV-SoE characteristics, the one-way energy efficiencies can be determined via the following expressions:

$$\eta_1^{ch} = \frac{E^{batt,ch}}{E^{ch}}, \quad (10)$$

$$\eta_1^{dis} = \frac{E^{dis}}{E^{batt,dis}}, \quad (11)$$

where E^{ch} and E^{dis} are calculated by the virtue of eq. (3), while $E^{batt,ch}$ and $E^{batt,dis}$ are calculated based on eqs. (6) and (7), respectively. The results are given in Fig. 9 and Table III, where it is seen that $\eta_1^{ch} \cdot \eta_1^{dis} > \eta^{E}$ (deviation is given in the last column of Table III), where η^{E} is the measured roundtrip energy efficiency. However, the product of the two one-way efficiencies should theoretically equal the roundtrip efficiency. The reason for the obtained discrepancy lies in the fact that $E^{batt,ch} > E^{batt,dis}$ which is the case since coulombic losses are not negligible. In other words, only voltaic efficiency is accounted for, while coulombic efficiency is neglected. In order to obtain more realistic one-way efficiencies, we assume that coulombic losses are equally distributed between the charging and discharging processes with same C-rates, and propose determining the one-way energy efficiencies as:

$$\eta_2^{ch} = \frac{E^{batt,ch}}{E^{ch}} \cdot \sqrt{\eta^{I}}, \quad (12)$$

$$\eta_2^{dis} = \frac{E^{dis}}{E^{batt,dis}} \cdot \sqrt{\eta^{I}}. \quad (13)$$

The results are given in Fig. 10 and Table IV, where it is seen that $\eta_2^{ch} \cdot \eta_2^{dis} \approx \eta_E$ (deviation is given in the last column of Table IV). Therefore, the one-way energy efficiencies η_2^{ch} and η_2^{dis} are much more realistic than η_1^{ch} and η_1^{dis}, which is a direct consequence of accounting for both the voltaic and coulombic losses in eqs. (12) and (13).

For charging/discharging experiments conducted with the same specified C-rate, η_2^{ch} is always higher than η_2^{dis}, which is explained by the fact that the average charging current is always lower than the average discharging current. This is conditioned by the typical shapes of the current charge/discharge curves (Figs. 2 and 3) and the fact that the efficiencies are determined over full cycles (0-100% SoE).

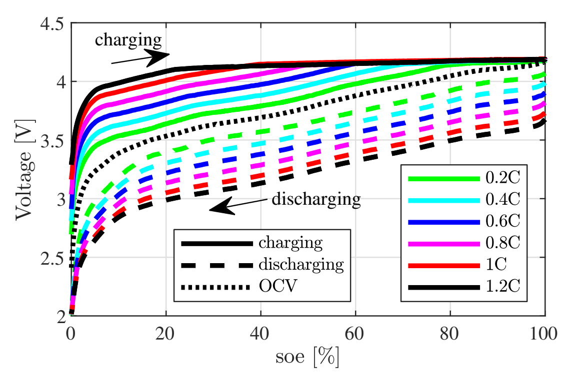

Fig. 8. Closed-circuit voltages (CCV) for different C-rates and open-circuit voltage (OCV)

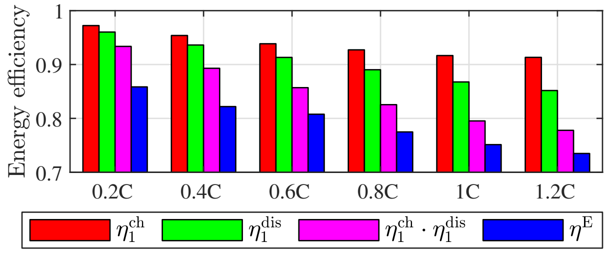

Fig. 9. Charging/discharging energy efficiencies without accounting for coulombic efficiency

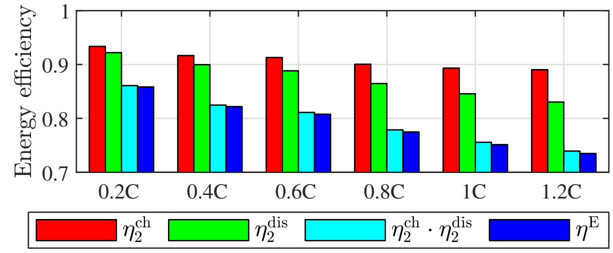

Fig. 10. Charging/discharging energy efficiencies with accounting for coulombic efficiency

TABLE III
ONE-WAY ENERGY EFFICIENCIES WITHOUT ACCOUNTING FOR COULOMBIC EFFICIENCY

Ener. eff. / C-rate	η_1^{ch}	η_1^{dis}	$\eta_1^{ch} \cdot \eta_1^{dis}$	η^E	$\Delta\eta$
0.2C	0.97	0.96	0.93	0.86	8.8%
0.4C	0.95	0.94	0.89	0.82	8.6%
0.6C	0.94	0.91	0.86	0.81	6.1%
0.8C	0.93	0.89	0.83	0.77	6.5%
1.0C	0.92	0.87	0.80	0.75	5.9%
1.2C	0.91	0.85	0.78	0.73	5.8%

TABLE IV
ONE-WAY ENERGY EFFICIENCIES WITH ACCOUNTING FOR COULOMBIC EFFICIENCY

Ener. eff. / C-rate	η_2^{ch}	η_2^{dis}	$\eta_2^{ch} \cdot \eta_2^{dis}$	η^E	$\Delta\eta$
0.2C	0.93	0.92	0.86	0.86	0.3%
0.4C	0.92	0.90	0.82	0.82	0.3%
0.6C	0.91	0.89	0.81	0.81	0.4%
0.8C	0.90	0.86	0.78	0.77	0.5%
1.0C	0.89	0.85	0.76	0.75	0.6%
1.2C	0.89	0.83	0.74	0.73	0.6%

V. CONCLUSION

This paper describes an experimental assessment of the Li-ion battery one-way energy efficiencies for different C-rates. The importance of accounting for coulombic efficiency has been demonstrated for cases when coluombic losses are not negligible. Since the batteries' charge and discharge C-rates can differ greatly, using separate charging and discharging efficiencies (instead of a single roundtrip efficiency) can provide a more precise information in many applications, such as determining SoC (or SoE) in real-time, scheduling of battery energy storage operation, sizing a battery storage, etc.

It can also be concluded that, for the tested Li-ion battery cell, the residual battery capacity (measured by a slow discharge after the high-current discharge and a period of rest) is not significant.

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