Electrical Power and Energy Systems 99 (2018) 722–732

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

journal homepage: www.elsevier.com/locate/ijepes

# Characterisation of batteries with *E*–*P*-curves: Quantifying the impact of operating conditions on battery performance

Ishwar Singh Sarpal[a], Astrid Bensmann[a,*], Jochen Mähliß[b], Dominik Hennefeld[b], Richard Hanke-Rauschenbach[a]

[a] Electrica Energy Storage Systems, Leibniz Universität Hannover, Appelstr. 9 A, 30167 Hannover, Germany
[b] Batteryuniversity GmbH, Am Sportplatz 30, 63791 Karlstein, Germany

ARTICLE INFO

*Keywords:*
Ragone diagram
*E*–*P*-curve
Li-ion battery
Battery performance
Battery characterisation

ABSTRACT

Batteries find their application in various fields. The resulting requirements are characterised in terms of necessary power and energy. In this paper, we suggest to characterise batteries in the same coordinates by determining the energy for varying load power. The resulting *E*–*P*-curves can help to compare different cells in the relevant aspects and can be used to design battery storage systems. Therefore, we show the influence of different operating parameters on the charging as well as the discharging behaviour. These are the minimum voltage, the maximum discharge current, the maximum operating as well as the ambient temperature and the initial state of charge. If it is allowed to discharge the battery with a peak current for a short time, the influence can be quantified by the suggested method as well. The method is illustrated by taking different lithium-ion batteries as examples.

## 1. Introduction

In the last decades, rechargeable batteries are becoming increasingly more important for various applications. They are used as backup systems, as supply for off-grid applications and also as traction batteries in automobiles. In the course of the transformation of our energy system, they are even applied for system ancillary services, such as balancing power.

For most of these examples a battery performance characterisation is required for an appropriate comparison and the subsequent battery selection. Especially when choosing one for the assembly of a battery pack, the comparison on the basis of single cells is important. There are different possibilities to characterise single cells, but typically this is done with their data sheet values. The nominal discharge capacity $Q^{\mathrm{nom}}$, the maximum discharge current $I_{\mathrm{dis}}^{\mathrm{max}}$ and the operational voltage range from the end-of-discharge voltage $U^{\mathrm{min}}$ to the end-of-charge voltage $U^{\mathrm{max}}$, are considered for the characterisation.

A more application oriented way is to characterise energy storage systems in terms of their energy-power relationship because battery performance and application requirements can be matched. Originally, this was introduced by Ragone who plotted the specific power against the specific energy to show the behaviour of different battery systems for electrically operated vehicles [12]. Since then, these so called Ragone plots were topics of various publications and used in different contexts.

Several groups formulated theoretical models for describing Ragone curves. Pell and Conway [10], for example, constructed Ragone plots considering the ohmic and Tafel polarisation for high-power capacitors and high-energy batteries as well as for the combination of both. Christen and Carlen [1] proposed device independent mathematical definitions with a power dependent energy relation and among others they discussed the approach using examples of an ideal battery and capacitor. Furthermore, they investigated a general case of a mixed energy device with an ideal battery and series inductance.

The method of representing storage characteristics with Ragone plots allows an appropriate way to highlight differences of various technologies and thus, eases the comparison, e.g. Christen and Carlen [1], Martinez [7] or McCloskey [8]. Furthermore, Ragone plots are useful when economic aspects are taken into account, specifically when they serve at optimising and sizing of an energy storage devise or even for hybrid systems [2,15].

Other works employ Ragone plots to investigate the storage performance dependent on operating conditions. Verbrugge and Ying [13] and Ji et al. [5] investigated the performance of lithium-ion batteries subject to a wide temperature range, including measurements sub-zero, with Ragone plots.

Recently, Krieger and Arnold [6] completed a comprehensive analysis with a lithium-ion battery by using Ragone plots in absolute

* Corresponding author.
*E-mail address:* astrid.bensmann@ifes.uni-hannover.de (A. Bensmann).

https://doi.org/10.1016/j.ijepes.2018.01.017
Received 19 April 2017; Received in revised form 8 December 2017; Accepted 11 January 2018
0142-0615/ 

coordinates, in the following *E–P*-curve, for the first time. They investigated the discharging and charging behaviour as well as the efficiency for both sides.

In our research, we use *E–P*-curves for the characterisation of lithium-ion batteries as well. In contrast to Krieger and Arnold [6], we consider the influence of various aspects on the *E–P*-curve to quantify the battery performance. Therefore, first, the complete measuring procedure is introduced in Section 2. In Section 3, we characterise batteries with their *E–P*-curves. Subsequently, we discuss the influence of different operational aspects such as minimum battery voltage or maximum discharge current by using three batteries as an example. Furthermore, we quantify the impact through a temporary extension of the maximum discharge current $I_{dis}^{max}$, the influence of the initial state of charge $SOC_0$ and the charging behaviour with *E–P*-curves. In Section 4, the relation of conventional constant current characterisation and our proposed method using *E–P*-curves is discussed. Finally, the results are summarised and concluded in Section 5.

## 2. Experimental method

This section describes the procedure to identify the *E–P*-curves including the discharge efficiency for rechargeable batteries. It is illustrated in the following, using four different lithium-ion 18650 batteries. The relevant information of the data sheets are listed in Table 1. All measurements were run on a Basytec Cell Test System (XCTS) in combination with a temperature chamber to control the ambient battery temperature. Whereas, the actual battery temperature depends on the heat transfer as well and differs from the ambient temperature and is not directly controlled.

### 2.1. Measurement procedure

The experimental procedure consists of a preliminary investigation to determine the maximum capacity $Q^{max}$ as well as the maximum chargeable ($E_{ch}^{id}$) and dischargeable energy ($E_{dis}^{id}$). The main investigation consists of multiple discharging experiments with various constant power values. In the following, the procedure is described in detail.

**Preliminary Step 1:** At first, the battery is completely charged by applying CCCV method and using a charge current as specified by the manufacturer. Hereby a $SOC = 1$ is assured.

**Preliminary Step 2:** The battery is completely discharged with CC method. The losses are kept low by applying a small discharge current, e.g. 0.1 C rate, as given in the data sheets. This step is terminated as soon as the minimum voltage $U^{min}$ is reached and hence the state of charge is $SOC = 0$. The depth of discharge (*DOD*) is determined at run time by current integration method. Afterwards, the capacity $Q^{max}$ can be calculated with Eq. (1).

$$Q^{max} = \int_{t_1}^{t_2} I(t)\,dt \tag{1}$$

The ideal discharge energy $E_{dis}^{id}$ dependent on a particular *DOD* is calculated with Eq. (2), therein the losses are assumed to be low.

$$E_{dis}^{id}(DOD) = \int_{t_1}^{t_2} U(t)\cdot I(t)\,dt \tag{2}$$

In both equations, $t_1$ defines the beginning of Preliminary Step 2 and $t_2$ is used for the time at which a particular *DOD* is reached.

**Preliminary Step 3:** Thereafter, the battery is charged with CC method and a low charge current $I_{ch}$, namely the cut-off current value $I^{min}$ is chosen. The *SOC* is measured with current integration method. At the end of Preliminary Step 3, the maximum voltage is reached and the $SOC = 1$. The ideal charge energy $E_{ch}^{id}$ is determined with Eq. (3).

$$E_{ch}^{id}(SOC) = \int_{t_2}^{t_3} U(t)\cdot I(t)\,dt \tag{3}$$

Herein $t_2$ defines the beginning of Preliminary Step 3 and $t_3$ the time at which a particular *SOC* is reached.

**Table 1**
Analysed batteries with relevant data sheet information.

| Label | $Q^{nom}$ | $U^{min}$ | $U^{max}$ | $I_{dis}^{max}$ | $I_{ch}^{max}$ | $I^{min}$ | $T_{dis}^{max}$ |
|---|---|---|---|---|---|---|---|
| #1 | 1500 mAh | 2.5 V | 4.2 V | 30 A | 4 A | 0.05 A | 60 °C |
| #2 | 1500 mAh | 2.5 V | 4.2 V | 18 A | 4 A | 0.1 A | 75 °C |
| #3 | 1500 mAh | 2.5 V | 4.2 V | 30 A | 10 A | 0.1 A | 80 °C |
| #4 | 2900 mAh | 2.5 V | 4.2 V | 8 A | 3 A | 0.1 A | 80 °C |

After this preliminary investigation the actual procedure consisting of the following steps is executed.

**Step 1:** First, the battery is set to the reference point ($SOC = 1$) by charging the battery with the CCCV method.

**Step 2:** The second step is discharging it with constant power (CP). The voltage $U$, current $I$ and battery surface temperature $T$ are measured at run-time. Step 2 is terminated, if one of the operating criteria (Eq. (4)–(6)) given in the data sheet is not fulfilled anymore.

$$U(t) \geqslant U^{min}, \quad \forall\, t \tag{4}$$

$$|I(t)| \leqslant I_{dis}^{max}, \quad \forall\, t \tag{5}$$

$$T(t) \leqslant T_{dis}^{max}, \quad \forall\, t \tag{6}$$

These two steps are repeated multiple times while discharge power is increased for each run in the range of $0 < P_{dis} \leqslant P_{dis}^{max}$. Here, the maximum discharge power $P_{dis}^{max}$ is defined as the value at which no energy can be drawn from the battery. It can be approximated prior to any experiment with Eq. (7). Therein data sheet information for the nominal battery voltage and maximum discharge current are used.

$$P_{dis}^{max} = U_{nom}\cdot I_{dis}^{max} \tag{7}$$

Fig. 1 shows exemplary the measured time series. Here, for Step 2, a constant discharge power of 1 W is applied (Fig. 1(a)). On the basis of a completely charged battery, the discharging process (Step 2) takes place in the time span from $t_2$ to $t_3$. Therein, voltage decreases (Fig. 1(b)) and simultaneously current rises (Fig. 1(c)) to maintain constant power for the discharge. The temperature stays around ambient temperature (Fig. 1(d)). At the end of the discharge, the voltage reaches the lower limit $U^{min}$.

Besides the minimum battery voltage $U^{min}$, the termination of the discharge (Step 2) can be caused by reaching the current or temperature limit as well (see Eqs. (4)–(6)). Which criteria is reached first, depends on the corresponding data sheet limits and the applied discharge power.

Fig. 1(e)–(h) presents the time series for discharging with $P_{dis} = 60$ W. Due to the higher discharge power, higher current occurs at the end of Step 2 (Fig. 1(g)) and temperature rises (Fig. 1(h)). Since the temperature limit $T_{dis}^{max}$ is reached, Step 2 is terminated. Overall, the complete procedure with all steps is faster than the one with 1 W.

The courses in Fig. 1(i)–(l) with $P_{dis} = 100$ W show an example of meeting the maximum discharge current $I_{dis}^{max} = 30$ A. In this case, the same effects as before arise but the temperature does not exceed its limit (Fig. 1(l)). This is explained with the short discharge time which is not sufficient to heat up the battery to its critical limit.

By meeting the current or the temperature criteria, the battery voltage stays above the lower limit at the time of abortion (Fig. 1(f) and (j)), which means that residual charge is left in the battery and $SOC(t_3) > 0$. However, the shown battery #1 has a low temperature limit in comparison to other lithium-ion cells (see Table 1). Therefore in most cases, this limit is not reached during the discussed constant power experiments for single cells. That is why, we introduce the evaluation procedure in the following with battery #2.