Available discharge energy of non-aqueous electrochemical energy storage cells vs. discharge current

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Abstract

Available energy is one of the most relevant parameters for dimensioning and design of battery systems. The discharge duration of a battery and its dependence on the amplitude of the discharge current are described by Peukert's equation [1]. Other equations describe this dependence up to very high currents, including the currents that occur during a short circuit. Not the usually described quantities current and capacity, but energy and power are the decisive parameters for the dimensioning of battery systems.

The results of this work allow to determine the basic characteristics of a cell with just few current and voltage measurements and enables to answer the fundamental questions of battery system developers. The new empirical equation allows an easy determination of the available discharge energy of lithium-ion batteries that helps to design and check the suitability as energy storage e.g. for hybrid electric vehicles.

→ Even if all the project- and application-specific parameters are not sufficiently defined, the equation allows a fast and cost-effective feasibility study on technical conditions such as vehicle range.

Table 1 - Tested 18650 lithium-ion battery cells/lithium capacitors

Model	Manufacturer	Capacity in Ah	Cont. Disch. Current in A
HTCN26650	Lumos	4.50	13.0
APR18650MA1	A123	**1.10**	30.0
AMP20M1HDA	A123	20.0	300
HPNP3R220B	Lumos	20.0	100

Theoretical background

The basic Peukert-formula [1] was revised and modified/normalised, allowing it to be fed with information from cell-datasheets [2]:

$$I_{ra}^{k} \cdot t_{ra} = I_1^{k} \cdot t_1$$

Equation 1

$$t_{dis}(I_{dis}) = \frac{Q_{ra}}{I_{ra}} \cdot \left(\frac{I_{ra}}{I_{dis}}\right)^{k}$$

Equation 2

and introduction of parameter k_1

$$t_{dis}(I_{dis}) = \frac{Q_{ra}}{I_{ra}} \cdot \left(\frac{I_{ra}}{1\ \mathrm{A}}\right)^{k} \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k}$$

Equation 3

$$k_1 = \frac{Q_{ra}}{I_{ra}} \cdot \left(\frac{I_{ra}}{1\ \mathrm{A}}\right)^{k}$$

Equation 4

allows the calculation of the discharge time $t_{dis}(I_{dis})$, the normalized Peukert's law equation

$$t_{dis}(I_{dis}) = k_1 \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k} .$$

Equation 5

To accomplish the operation range beyond the technical specification of the batteries, the following Peukert-bend equation [3] is introduced to describe the capacity declining effect at high current loads by adding a root term similar to the cut-off frequency of electronic filters:

$$t_{dis}(I_{dis}) = k_1 \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k} \cdot \sqrt{\frac{1}{s_1^{\left(\frac{I_{dis}}{s_2}-1\right)}+1}}$$

Equation 6

The equation can be deployed to describe the maximum possible discharge duration and the amount of charge that can be taken from the cell.

Experimental setup

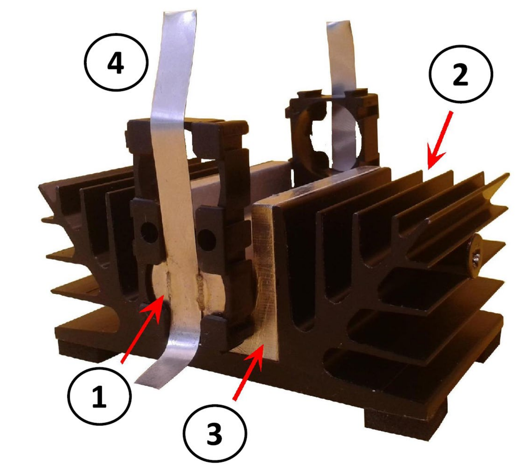

Figure 1

(1) test cell, (2) heatsink, (3) aluminum block to embed the cell, (4)nickel strips for contacting.

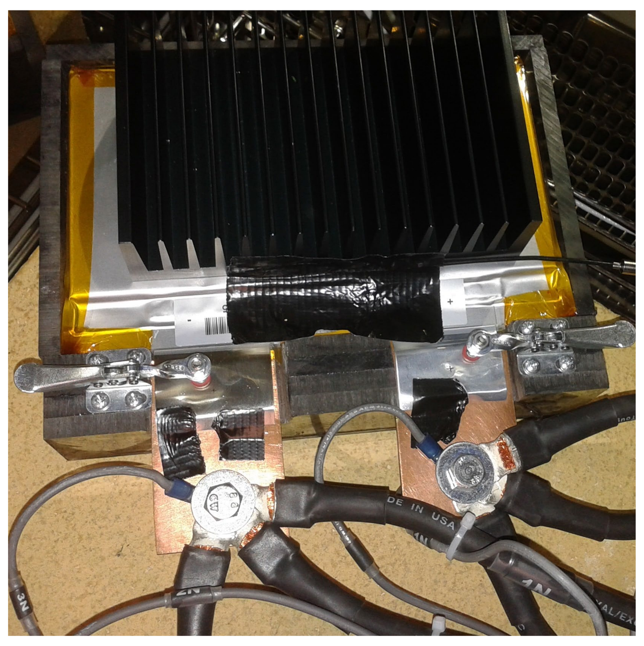

Figure 2

Connected cell holder for an AMP20M1HDA cell during testing and aluminum heatsink.

Conducted constant current tests

The available discharge times at current discharge power were measured inside a temperature chamber at 25° C ambient temperature. Figure 1 shows the constant current test method used - based on a AMP20M1HD-A cell from A123

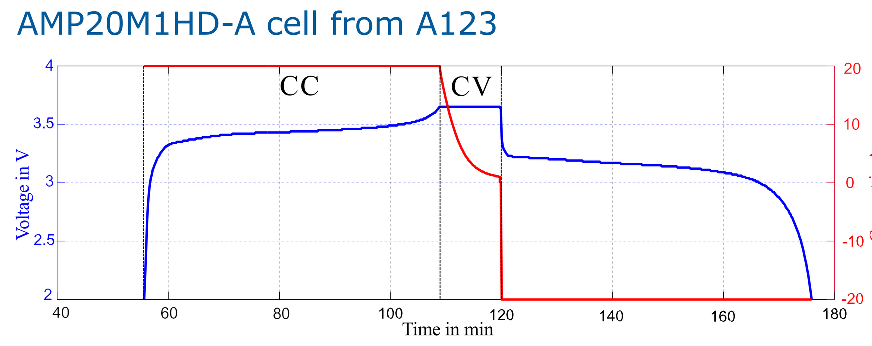

Figure 3

Figure 4 compares the calculated available energies using equation 11 with experimental data.

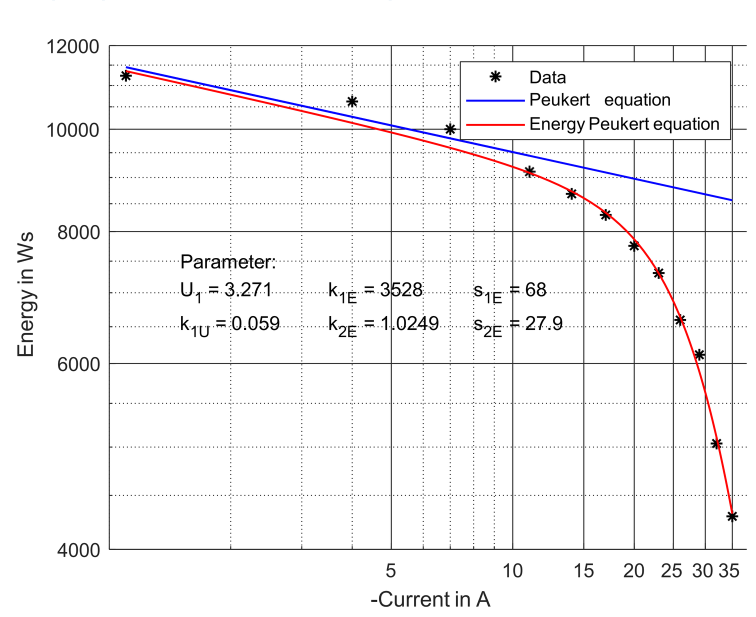

Figure 4

For lower currents the results show linear Peukert behavior. At a certain discharge energy, a disproportionate decrease in the discharge energy is detected, described by equation 11.

Fitting works for all examined batteries

How to describe the available energy of lithium-ion cells as function of the discharge current for high amplitudes?

As in the present work, a constant discharge energy E_{dis} is of interest and is described as follows:

$$E_{dis}(I_{dis}) = U_{dis}(I_{dis}) \cdot I_{dis} \cdot t_{dis}(I_{dis}) = \text{constant}$$

Equation 7

with U the actual voltage, I the discharge current and the discharge time t.

$$E_{dis}(I_{dis}) = U_{dis} \cdot I_{dis} \cdot k_{1E} \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k_{2E}}$$

Equation 8

Further summarized with parameter $k_t = U_{dis}(I) \cdot\ k_{1E}$ and by inserting parameter $U_1 = \frac{k_t}{k_1}$ and $k_{1U} = k_{2E} - k_1$ and modifying to a linear equation [2] one obtains a one obtains a convenient equation for the discharge voltage $U_{dis}(I_{dis})$:

$$U_{dis}(I_{dis}) = U_1 \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k_{1U}}$$

Equation 9

and by substituting into Eq. (8), finally the completely determinable equation of the discharge energy $E_{dis}(I_{dis})$:

$$E_{dis}(I_{dis}) = U_1 \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k_{1U}} \cdot I_{dis} \cdot k_{1E} \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k_{2E}}$$

Equation 10

To extend this range, the well-known Peukert bend root term [3] is applied to describe the upper operating range with

$$E_{dis}(I_{dis}) = U_1 \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k_{1U}} \cdot I_{dis} \cdot k_{1E} \cdot \left(\frac{1\ \mathrm{A}}{I_{dis}}\right)^{k_{2E}} \cdot \sqrt{\frac{1}{s_{1E}^{\left(\frac{I_{dis}}{s_{2E}}-1\right)}+1}}$$

Equation 11

and thus derive an equation over the entire discharge range for any discharge currents – called Energy Peukert equation.

Symbol explanation and results

Table 2 - explains the previously used formula symbols

Formula symbol	Description
Q_p	Battery capacity at 1 A discharge current
k	Peukert battery capacity at I = 1 A discharge Peukert exponent / Peukert similar exponent
t	Discharge time at 1 A discharge current
I	1 A discharge current
t_{dis}	Calculated discharge time
Q_{ra}	Rated cell capacity (nominal)
I_{ra}	Rated discharge current (nominal)
k_1	Peukert bend parameter - discharge time at 1 A
s_1, s_2	Peukert bend fitting parameter
E_{dis}	Actual discharge energy
U_{dis}	Discharge voltage
U_1	Fitting parameter - average terminal voltage
k_t	Intermediate parameter - discharge time at 1A
k_{1U}, k_{2E}	New Energy Peukert exponents (fitting parameter)
k_{1E}	New Energy Peukert (fitting parameter)
s_{1E}, s_{2E}	Energy Peukert bend (fitting parameter)

Table 3 - shows the results of the calculated parameters

DUT Model	U_1 in V	k_{1U}	k_{1E} in Ws	k_{2E}	s_{1E}	s_{2E} in A
HTCN26650	4.04	0.12	$15 \cdot 10^3$	1.01	153	15.0
APR18650MA1	3.27	0.06	$3.5 \cdot 10^3$	1.02	68.0	28.0
AMP20M1HDA	3.47	0.04	$79 \cdot 10^3$	1.05	94.0	306
HPNP3R220B	3.45	0.03	$89 \cdot 10^3$	1.02	287.10^3	150

References
[1] W. Peukert, "About the Dependence of the Capacity of the Discharge Current Magnitude and Lead Acid Batteries." Elektrotechnische Zeitschrift, vol. 20, pp. 287-288, 1897.
[2] D. Small, [Online]. Available: http://www.smartgauge.co.uk/peukert_depth.html, (March/2019)
[3] C. Nebl, F. Steger and H.G. Schweiger, "Discharge Capacity of Energy Storages as a Function of the Discharge Current – Expanding Peukert's equation." International Journal of Electrochemical Science, vol. 12, pp. 4930 – 4957, 2017.

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