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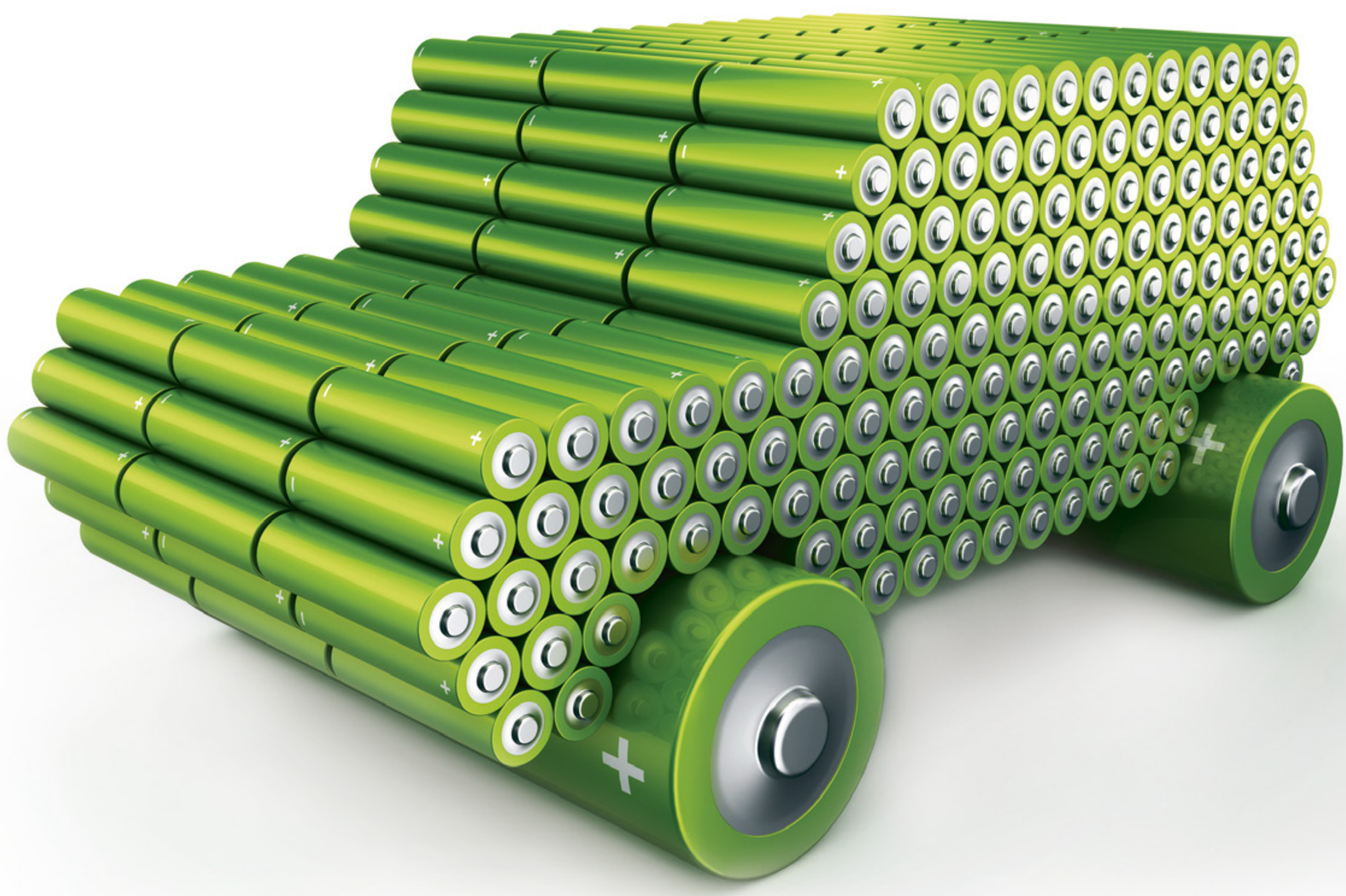
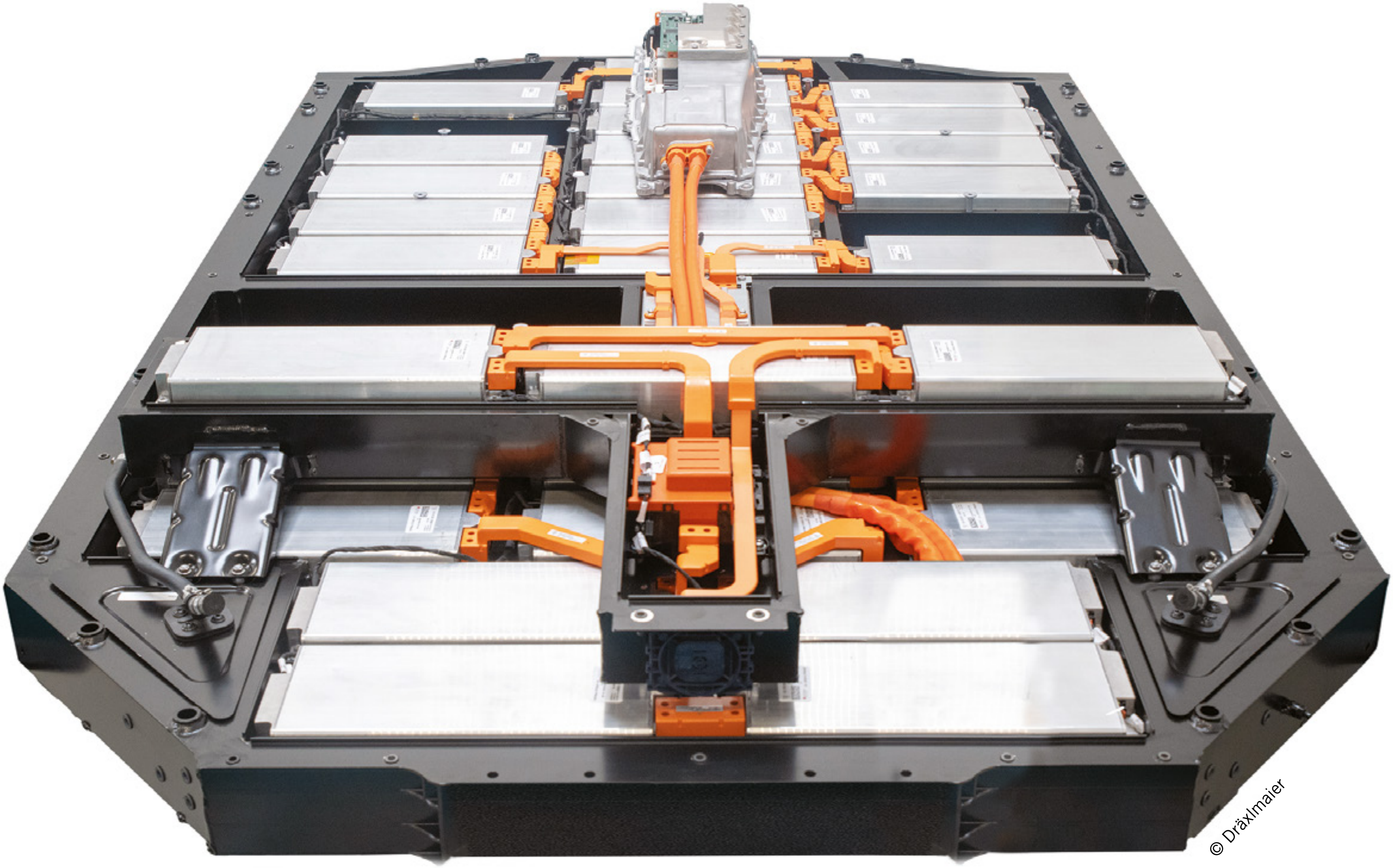


Lithium-ion Batteries

Determining the Range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Determining the Range of Lithium-ion Batteries

Fully electric or hybrid powered vehicles should offer a powerful drive, but at the same time also offer longe range. Both the correct cell selection and the appropriate algorithms in the battery management system are crucial to fulfilling and calculating these contradicting properties. Dräxlmaier has worked out a calculation model that provides a specific description of the usable battery capacity in highly dynamic driving profiles.

The range of a fully electric vehicle is defined by its built-in capacity and its consumption per kilometer. The choice of the right battery cell and the definition of the key criteria therefore take precedence. The Ragone plot gives an overview of the most important electrical properties of the battery cells. With the standard specified installation space for the High-voltage (HV) battery, the volumetric energy density is shown in relation to the power density. In **FIGURE 1**, this diagram is shown using data from two energy cells (a and b) and two power cells (c and d). With, for example, 2 W/cm³, energy cell a has significantly more energy available for the power requirement than the power cell c. In return, the latter can deliver significantly higher performance than the energy cell a.

CURRENT-DEPENDENT CAPACITY

The capacity of an accumulator, i.e. a rechargeable cell, depends, among other things, on the influencing variables of temperature and the level of the current (current intensity). These can lead to a change in the rated capacity of the cell. A change in capacity can be both reversible and irreversible. If, on the one hand, a cell is exposed to a higher ambient temperature for a longer period of time, this inevitably leads to a permanent, irreversible loss of capacity (aging). If, on the other hand, the cell is exposed to a low ambient temperature for only a single discharge cycle, the measurement results in a lower capacity than at room temperature. However, this loss is only due to the measurement condition mentioned. The loss of capacity is therefore reversible.

The relationship between the current strength and the capacity behavior is particularly complex. The so-called Peukert's law [1] is used for a more detailed consideration of this influencing variable. The phenomenological Eq. 1 approximately describes the capacity (Peukert capacity C_P) of cells as a function of the discharge current I_{cell}:

Eq. 1 $$C_P(I_{cell}) = C_N\left(\frac{I_N}{I_{cell}}\right)^{k-1}$$

Here, k is the Peukert number, which is approximately $k = 1.05$ for lithium-ion cells. For energy cells, according to the standard, the rated current I_N always uses the value for the rated capacity $\frac{1}{3}C_N$ in the unit [A]. If $I_{cell} = I_N$, then $C_P = C_N$. The Peukert effect, which is based on the law, states: As the discharge current increases, the capacity that can be drawn from the cell reduces. The Peukert equation only applies to certain discharge currents; as the discharge currents decrease, the actual capacity increases by any amount. Furthermore, the law states that the discharge current is unlimited, unlike in reality. Experience shows that the range of validity for $C_P \approx C_{ACTUAL}$ is approximately $I_N < I_{cell} < 3$ I_N. Using the equation, a time-dependent resistance (polarization resistance) can be calculated with $C_{ACTUAL} = I_{cell}\, t$ and the cell voltage U_{cell}, for which the stated range of validity must be taken into account.

CHALLENGES WITH HIGHER POWERS AND CURRENTS

In addition to the energy density, **FIGURE 1**, the capacity of a cell at higher currents is also of interest. For this purpose, the capacity of the cell a was determined in **FIGURE 1** at different discharge currents. The C rate is a measure of the load on the cell and relates the discharge current of a lithium-ion cell to its maximum capacity. The C-in-C rate stands for capacity. The reversible loss of capacity at a higher C rate (capacity limitation) can be clearly seen.

Particularly in the premium segment of fully electric series vehicles, the customer has high demands in terms of performance and short charging times. This leads to a trend of steadily increasing load on the battery. Toward high C rates, the battery is subject to ever higher currents and, as a result, a steadily increasing influence of the capacity limitation, **FIGURE 2**.

When looking at the current premium market, a classification can be made of the common load ranges of vehicles that have an output of more than 400 kW.

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The vehicles are classified into three areas, as shown in **FIGURE 3**:

- 1st area: continuous performance for constant speeds/energy consumption, range of the vehicle ($I_N < I_{cell} < 4{,}5\, I_N$)
- 2nd area: fast charging capacity of the HV battery/range of the vehicle ($6\ I_N < I_{cell} < 9\frac{2}{3} I_N$)
- 3rd area: top performance of the HV battery/acceleration, boost of

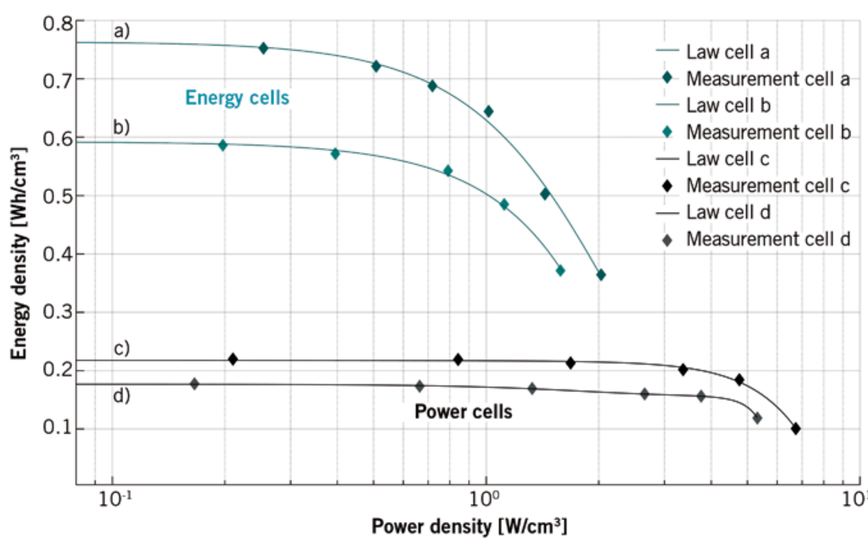

FIGURE 1 Volumetric power and energy density diagram of two energy cells and power cells (© Dräxlmaier)

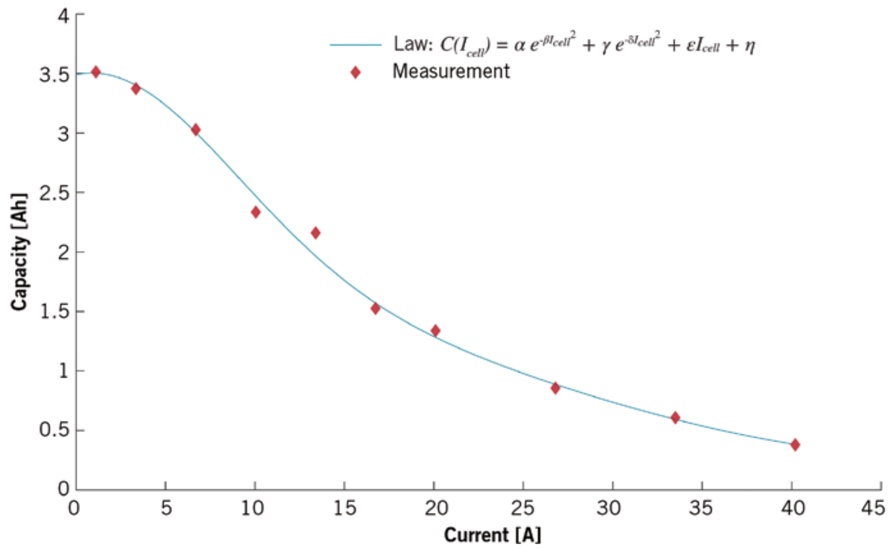

FIGURE 2 Current dependence of the actual capacity in an extended range of validity – generalized Peukert equation (© Dräxlmaier)

the vehicle ($15\, I_N < I_{cell} < 24\, I_N$). The diagram shows that current vehicles are mostly designed for special peak loads (3rd area) of more than 5C pulse load. In this performance class, the current-dependent capacity limitation plays an important role in the functional development of battery management systems.

More continuous loads occur in the areas of constant driving and fast charging. The maximum charging power is a decisive factor for many customers when making a purchase. An exact prediction of the charging time is an important criterion in order to stand out from other market participants. For an exact range prediction, consumption or C rates at constant speeds should also be taken into account. These were determined for 1st area, **FIGURE 3**, using simulations for the underlying vehicles. This primarily takes into account the loads that are not covered in cycles such as the Worldwide harmonized Light vehicles Test Cycle (WLTC), but that correspond to realistic use for high-performance vehicles. Capac-

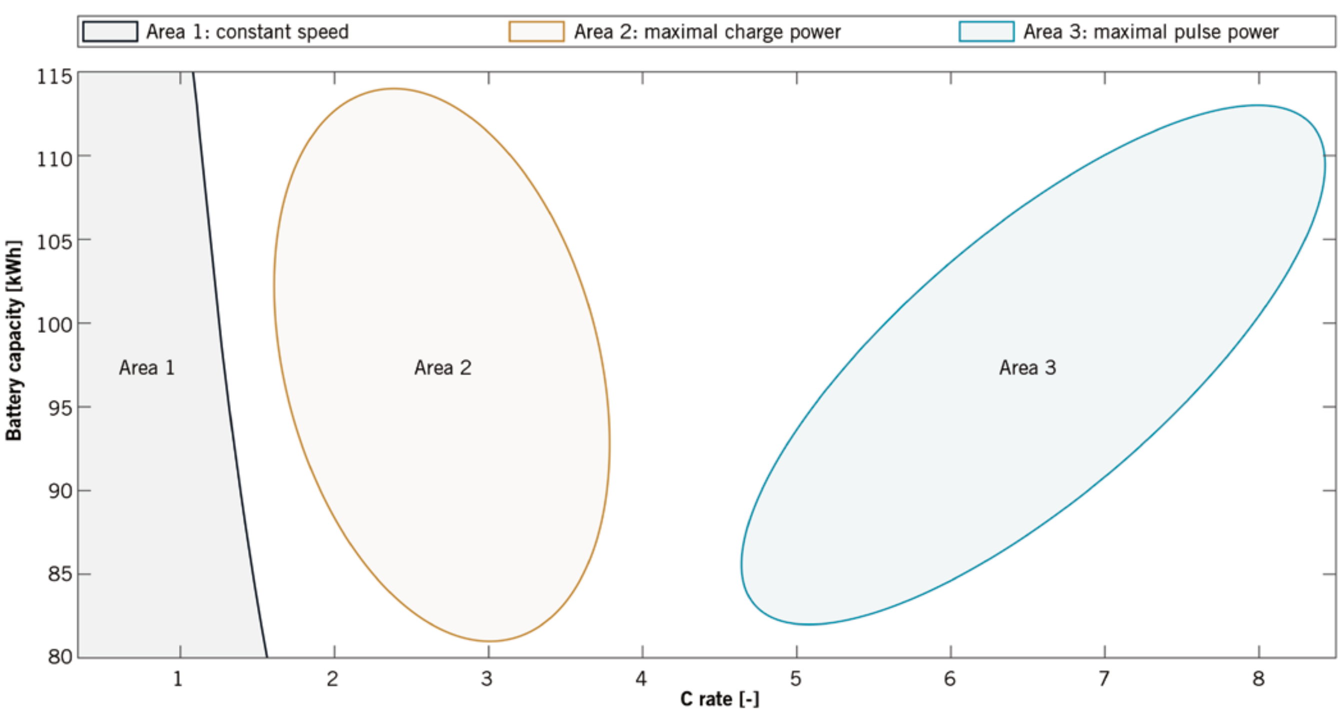

FIGURE 3 C rates for vehicles with an output of more than 400 kW, subdivided into their areas of constant driving, fast charging and peak performance (© Dräxlmaier)

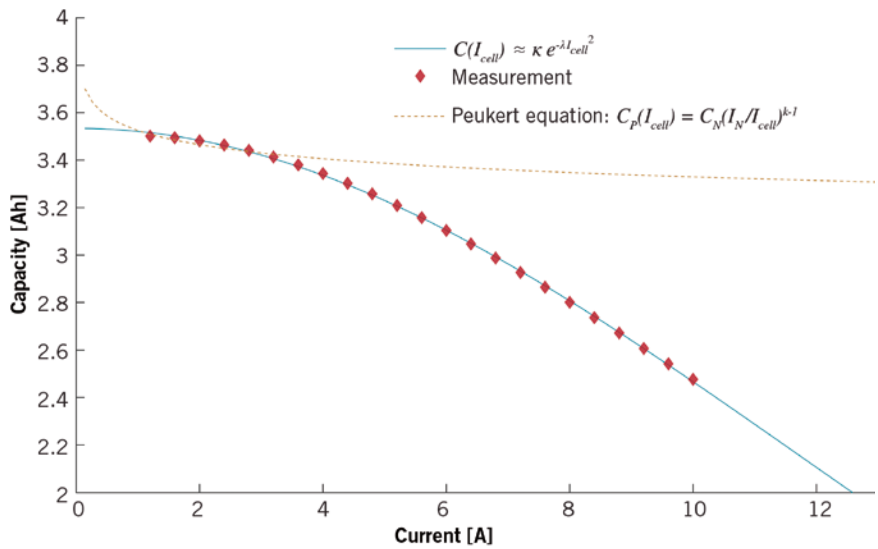

FIGURE 4 Section of **FIGURE 2**, with Peukert's law and an approximation formula for the generalized Peukert equation (© Dräxlmaier)

ity-limiting currents act in all three areas, which go beyond the definition range of Peukert's law and must be described by an generalized Peukert's law.

The current-dependent capacity for very high discharge currents and a constant cell temperature according to **FIGURE 2** is described in Eq. 2:

Eq. 2 $$C(I_{cell}) = \alpha\, e^{-\beta I_{cell}^2} + \gamma\, e^{-\delta I_{cell}^2} + \varepsilon\, I_{cell} + \eta$$

For the data in **FIGURE 2**, isothermal measurements were taken at a cell temperature of 25 °C. Since the measurements are not completely isothermal, especially at high currents, errors occur when determining the parameters $\alpha, \beta, \gamma, \delta, \varepsilon, \eta$. Measurement inaccuracies (current, voltage, time) can also be assumed. Overall, there is a Root Mean Square Error (RMSE) = 0.03 for the measurement.

The battery current usually undergoes anisothermal measurement in the field. To determine the range, the parameters must therefore be determined in the laboratory as a function of the cell temperature.

Eq. 2 describes the general current-dependent capacity and represents a generalization of the Peukert equation (Eq. 1). To show this mathematically, the Peukert equation has to be developed in a Taylor series according to the valid discharge current $I_N < I_{cell} < 3I_N$ and compared with the corresponding Taylor series by the function $C(I_{cell})$. This is shown graphically in **FIGURE 4** by means of a section of the entire measurement in **FIGURE 2**. The best fit with the Peukert equation (Eq. 1) gives the value $k = 1.025$ for the Peukert number.

An application of the generalized Peukert's law $C(I_{cell})$ (Eq. 2) is the analysis of the Ragone diagram, **FIGURE 1**. The current-dependent capacity can only be approximately converted into the power-dependent energy because the cell is discharged with a constant power for the Ragone plot.

Almost identical values were found for the parameter $\beta = \delta$ in all the energy cells examined. In addition, in the Ragone plots for the energy cells there was no significant contribution to the linear portion, i.e. the parameters $\varepsilon = \eta \approx 0$ can be set approximately.

For small C rates ($6\, I_N < I_{cell} < 9\, I_N$), the actual capacity can be approximately described by Eq. 3:

Eq. 3 $$C(I_{cell}) \approx \kappa\, e^{-\lambda I_{cell}^2}$$

With the Ragone plot for energy cells, the energy density can also be described as a function of the power density with the specified simplifications in the form of an exponential function; indeed, the use of energy cells is also recommended for applications with low C rates. Eq. 3 can be transformed into Eq. 4:

Eq. 4 $C(I_{cell}) = t\, I_{cell}$ and

$$t\, I_{cell} = \kappa\, e^{-\lambda I_{cell}^2}$$

Application of the logarithm on both sides:

$$\log(t) = -\lambda I_{cell}^{\;2} - \log(I_{cell}) + \log(\kappa)$$

The two unknown parameters κ, λ can then be determined online using the familiar least-squares fitting method. Note is that according to Eq. 2, $\alpha \neq \kappa, \beta \neq \lambda$.

The simplified, generalized Peukert equation (Eq. 3) thus enables the calculation of the actual capacity $C(I_{cell})$ in a larger area of validity (compared to the traditional Peukert's law) with temperature, tolerance and age-dependent parameters κ, λ. In addition, an age-dependent rated capacity can be calculated with $I_N = C_N$, from which the State of Health (SOH) results.

Eq. 3 can be solved for the current using Lambert's function and further converted into an equation for a time-dependent resistance (polarization resistance). If the software also allows the use of computationally intensive, numerical methods, the complete inversion of Eq. 2 would alternatively be possible in order to calculate the capacity from a limit current measurement in addition to the polarization resistance, or vice versa. This relationship is already used phenomenologically in the battery status detection for starter batteries in order to determine the capacity of the battery from a cold start.

SIMULATION OF THE RANGE AND STATE OF CHARGE

Both the C rates of a single cell and the resulting voltage are shown in **FIGURE 5**. The underlying driving cycle is derived from a speed run on the Nordschleife of the Nürburgring (Nürburgring cycle). A negative C rate means that the battery is charged by recuperation while driving.

In **FIGURE 6**, the turquoise curve shows the course of the State of Charge (SOC) if the rated capacity of the battery is taken as a basis. If this result is compared with the voltage curve in **FIGURE 5**, it is unclear whether the output of the HV battery system is ultimately sufficient for the Nürburgring driving cycle. The SOC (turquoise curve) based on the actual capacity according to Eq. 2, on the contrast, provides the correct result.

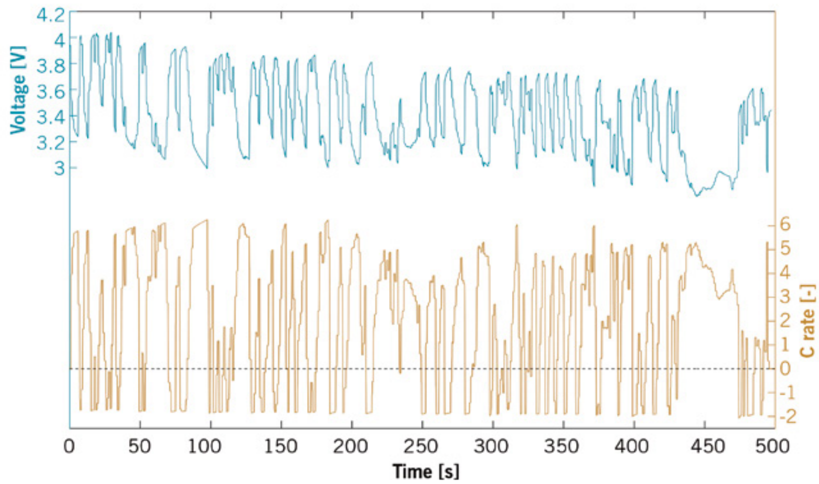

FIGURE 5 C rate and resulting voltage (scaled to cell) for Nürburgring driving cycle (© Dräxlmaier)

CONCLUSIONS

The upward trend for vehicles set to be released in the coming years will continue for the premium segment, towards higher capacities and top performance in order to meet the increasing demands in terms of range and driving behavior. The expanded Peukert's law presented here is intended and able to provide improved information about the battery condition and the range of the vehicle in this area with very high current rates.

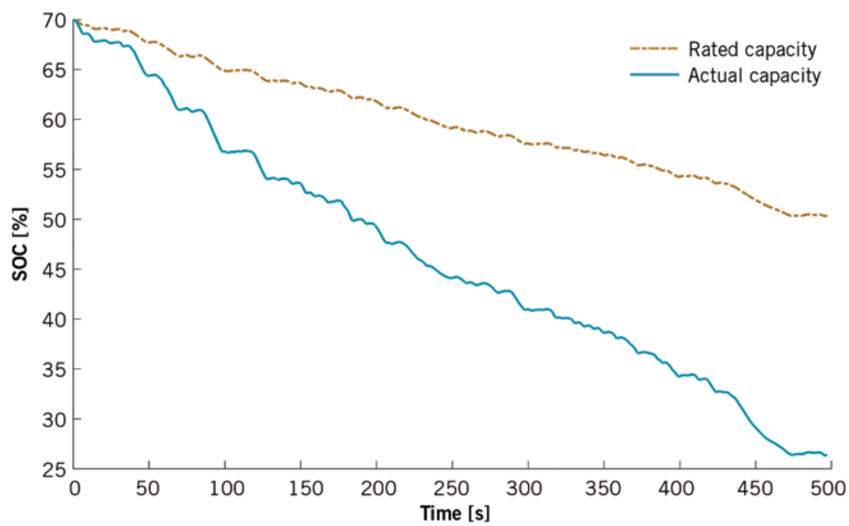

FIGURE 6 Time curve of the SOC for the Nürburgring driving cycle (the state of charge is related to the rated capacity (brown curve) and the actual capacity (turquoise curve)) (© Dräxlmaier)

REFERENCE

[1] Peukert, W.: Über die Abhängigkeit der Kapazität von der Entladestromstärke bei Bleiakkumulatoren. In: ETZ Elektrotechnische Zeitschrift 18 (1897), pp. 287-288

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