A Method for Online Capacity Estimation of Lithium Ion Battery Cells Using the State of Charge and the Transferred Charge

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***Abstract*—In this paper, a method to estimate the capacity of individual lithium ion battery cells during operation is presented. When having two different states of charge of a battery cell as well as the transferred charge between these two states, the capacity of the battery cell can be estimated. The method is described in detail and validated on a battery cell with a current pulse test cycle. It is then applied to a real-life cycle; the accuracy is analyzed and discussed.**

***Index Terms*—Battery management, capacity estimation, lithium ion (Li-ion) battery, state of charge.**

I. Introduction

THE ESTIMATION of the remaining as well as the total capacity of a battery cell is an important issue both for mobile and stationary battery applications. The capacity of a battery cell is changing over its lifetime due to aging, and thus a method to estimate its capacity is necessary [1], [2]. The capacity of a battery cell can be estimated by fully discharging it and integrating the measured current (charge counting) [3], [4].

When lithium ion (Li-ion) battery cells are serially connected to a battery stack, the discharging process has to stop as soon as one cell is completely discharged [5]. The cell with the lowest capacity is usually the first one which is completely discharged and therefore limits the capacity of the whole battery. Though the capacity of this cell could be estimated by measuring and integrating the cell current, the capacities of the other cells cannot be determined with charge counting.

However, a battery stack is usually not completely discharged. For example the battery package of an electric vehicle is typically charged before it is completely empty. Hence, a battery cell is either charged or discharging stops, before it is completely discharged.

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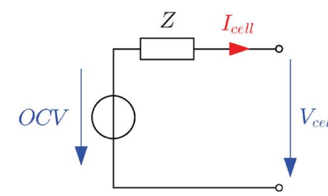


Fig. 1. Equivalent circuit of a battery cell.

In this paper, a method which allows estimating the capacity of any battery cell is presented. With this method, the cell does not have to be completely discharged. The method is explained in detail and validated by using a current pulse test cycle as well as a real-life cycle.

II. Cell Capacity Estimation Method

In this section, the proposed method for the online capacity estimation of a single battery cell is presented. The stored charge Q in a battery cell referred to the total capacity C is defined as the state of charge

$$SOC = \frac{Q}{C}. \tag{1}$$

Therefore, $SOC = 1$ when the battery cell is fully charged and $SOC = 0$ when the battery cell is completely discharged. During charging/discharging, between time t_α and t_β, the stored charge is altered from Q_α to

$$Q_\beta = Q_\alpha - \Delta Q_{\alpha,\beta} = Q_\alpha - \int_{t_\alpha}^{t_\beta} I_{\text{cell}}(t)dt. \tag{2}$$

I_{cell} is positive during discharging as shown in a Fig. 1 as a typical equivalent circuit of a battery cell. In the same manner as Q_α changes to Q_β, the SOC changes from $SOC_\alpha = SOC(t_\alpha)$ to $SOC_\beta = SOC(t_\beta)$. By using (1) for t_α as well as for t_β and (2), the total capacity of the battery cell can be calculated with

$$C = C_{\alpha,\beta} = \frac{Q_\alpha - Q_\beta}{SOC_\alpha - SOC_\beta} = \frac{\int_{t_\alpha}^{t_\beta} I_{\text{cell}}(t)dt}{SOC(t_\alpha) - SOC(t_\beta)}. \tag{3}$$

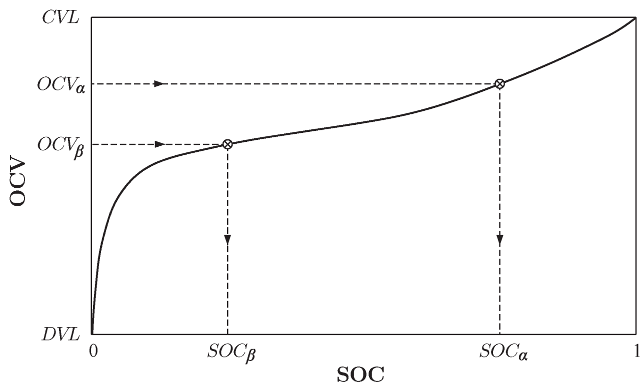


Fig. 2. Linear interpolation of the measured SOC versus OCV look up table of a Li-ion cell between charging voltage limit (CVL) and discharging voltage limit (DVL).

TABLE I
CHARGE TRANSFER MATRIX FOR N DIFFERENT SOC VALUES

	SOC_β					
	α \ β	1	2	3	$\cdots$	N
SOC_α	1	$\Delta Q_{1,1}$	$\Delta Q_{1,2}$	$\Delta Q_{1,3}$	$\cdots$	$\Delta Q_{1,N}$
	2	$\Delta Q_{2,1}$	$\Delta Q_{2,2}$	$\Delta Q_{2,3}$	$\cdots$	$\Delta Q_{2,N}$
	3	$\Delta Q_{3,1}$	$\Delta Q_{3,2}$	$\Delta Q_{3,3}$	$\cdots$	$\Delta Q_{3,N}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
	N	$\Delta Q_{N,1}$	$\Delta Q_{N,2}$	$\Delta Q_{N,3}$	$\cdots$	$\Delta Q_{N,N}$

With this equation, it is not necessary to discharge the battery cell completely to estimate the capacity, e.g., with charge counting [6]. Two accurate SOC values and the integrated current between these two values are sufficient to estimate the capacity of the battery cell.

The open circuit voltage (OCV) is a function of SOC, and when the SOC changes from SOC_α to SOC_β, the OCV does from $OCV_\alpha = OCV(t_\beta)$ to $OCV_\beta = OCV(t_\beta)$. Since the OCV versus SOC curve is monotone, it can be inverted, and therefore the SOC of a battery cell can be estimated using a look up table and the measured OCV. The linear interpolation of the measured SOC versus OCV for the investigated battery cell is shown in Fig. 2. Therefore, (3) can be written as

$$C_{\alpha,\beta} = \frac{\int_{t_\alpha}^{t_\beta} I_{\text{cell}}(t)dt}{SOC\left(OCV(t_\alpha)\right) - SOC\left(OCV(t_\beta)\right)}. \qquad (4)$$

If the SOC versus OCV curve is not available, the SOC has to be estimated differently but (3) is still applicable [7]–[10].

When a battery cell is charged or discharged and $N SOC$ values are estimated, $(N-1)\cdot(N-1)$ changes in charge ΔQ can be estimated. These changes in charge can be written in a $N \times N$ matrix as given in Table I. However, in this matrix, $\Delta Q_{n,n} = 0$ and $\Delta Q_{m,n} = -\Delta Q_{n,m}$. With this matrix, the capacity of the battery cell can be calculated using (3) and all possible combinations of two SOC values and the respective ΔQ between them. This yields a $N \times N$ matrix of calculated capacities as given in Table II. In this matrix, $C_{n,n} = 0$ and $C_{m,n} = C_{n,m}$. Thus, $(N \cdot (N+1)/2) - N$ calculations are

TABLE II
CAPACITY MATRIX FOR N DIFFERENT SOC VALUES

	SOC_β					
	α \ β	1	2	3	$\cdots$	N
SOC_α	1	$C_{1,1}$	$C_{1,2}$	$C_{1,3}$	$\cdots$	$C_{1,N}$
	2	$C_{2,1}$	$C_{2,2}$	$C_{2,3}$	$\cdots$	$C_{2,N}$
	3	$C_{3,1}$	$C_{3,2}$	$C_{3,3}$	$\cdots$	$C_{3,N}$
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$
	N	$C_{N,1}$	$C_{N,2}$	$C_{N,3}$	$\cdots$	$C_{N,N}$

necessary (number of elements in a triangle matrix minus number of elements in the main diagonal). The arithmetic mean or the median of all these calculated capacities can be used to estimate the capacity of a battery cell [11].

To show the practicability and the accuracy of this method, it is applied to determine the cell capacity of a specific battery cell in the next section.

III. VALIDATION OF THE CELL CAPACITY ESTIMATION

The battery cell used in this study is a high energy Li-ion polymer cell with a $Li[NiCoMn]O_2$-based cathode and a graphite-based anode. Two cells of this type are connected in parallel, and together they appear as a single big one. To estimate the capacity of this battery cell, the current during one complete discharge process is measured and integrated. The measured capacity of this battery cell is $C_m = 46.1$ Ah (both together). All measurements are performed at constant temperature, $T_{ambient} = 25\,^\circ$C.

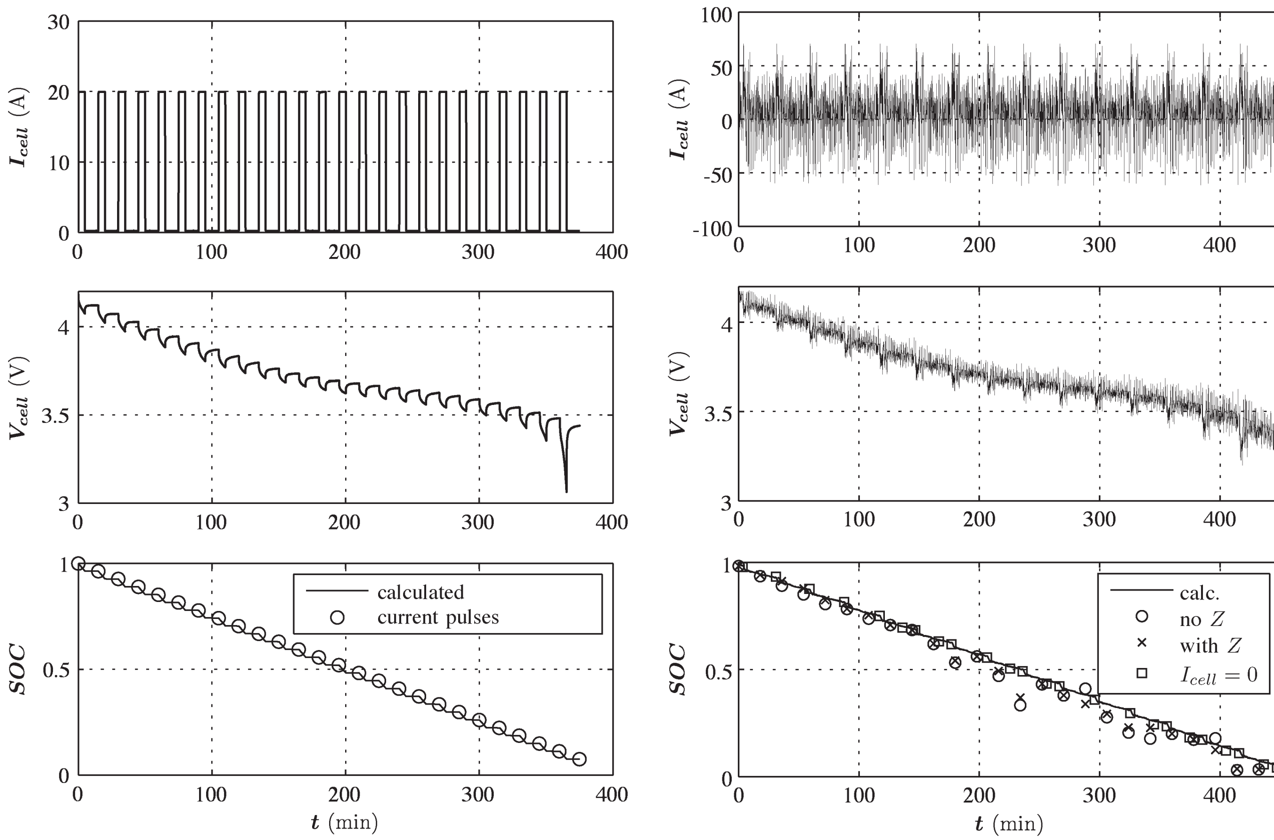
The capacity estimation method is validated using four different approaches:

- current pulses;
- FTP72, no Z;
- FTP72, with Z;
- FTP72, $I_{\text{cell}} = 0$.

A. Current Pulses

The battery cell is continuously discharged by 5-min, 20-A current pulses alternating by 10-min breaks until the discharging voltage limit (DVL) of the battery cell is reached. The current pulses, the measured voltage response, the calculated SOC using a charge counter (calculated) are shown in Fig. 3(a). After each break, the cell voltage is measured, and the SOC value is estimated using Fig. 2. Since there are 26 current pulses, 26 SOC values are estimated and marked in Fig. 3(a) (current pulses).

The cell capacity is then calculated from (3) using every possible pair of the 26 marked SOC. With this 26 different SOC values, a 26 $\times$ 26 matrix of capacity values can be calculated, and therefore $(26 \cdot (26+1)/2) - 26 = 325$ calculations are performed. In Fig. 4(a), all the calculated capacity values are shown. The best accuracy is in the area of $SOC_1 = 0.5, \ldots, 1$ and $SOC_2 = 0, \ldots, 0.5$ where the ΔSOC is large. The capacity values in ascending order are shown in Fig. 5 (current pulses), and the arithmetic mean as well as the median



(a) current pulses

(b) FTP72

Fig. 3. Applied current profile, measured cell voltage, and calculated SOC for the 20-A current pulses (a) and for the FTP72 current profile (b). The calculated SOC (continuous line) is estimated by charge counting and the measured capacity of the battery cell $C_m = 46.1$ Ah.

of all estimated capacities are given in Table III. With this current cycle, the capacity of a battery cell can be estimated with a very high accuracy.

B. FTP72, no Z

The approach described in Section III-A is now repeated, but a second, more dynamic current profile to analyze the robustness of (3) is used. The FTP72 [12] driving cycle is applied to a compact electric vehicle, the power consumption of the electric vehicle is measured, and the current profile for a battery stack with 100 serially connected battery cells with a single cell voltage of 3.6 V, respectively, is estimated. Fig. 6 shows the FTP72 driving cycle, the measured power consumption, and the current profile.

This current profile is continuously applied to the battery cell until DVL of the cell is reached. Fig. 3(b) shows the FTP72 current profile applied to the cell, the voltage response and the calculated SOC using a charge counter (calc.).

In this approach, (FTP72, no Z) the internal impedance Z of the battery cell is neglected, and $OCV = V_{\mathrm{cell}}$ is assumed (cf. Fig. 1). At 26 equidistant time points, the cell voltage is measured, and the SOC is estimated using Fig. 2. These 26 SOC values are marked in Fig. 3(b) (no Z). Since the internal impedance of the cell is neglected, the SOC values cannot be estimated correctly and differ from the values, calculated with a charge counter, depending on $|I_{\mathrm{cell}}|$. The larger $|I_{\mathrm{cell}}|$ when the voltage is measured, the less accurate is the estimated SOC value.

With these 26 SOC values, the capacity of the battery cell is calculated 325 times using (3). All the calculated capacities are shown in Fig. 4(b). Fig. 5 shows all the calculated capacities in ascending order, and Table III gives the arithmetic mean as well as the median of them. Although the estimated SOC values are inaccurate and the variation of the calculated capacities from the measured capacity is very large, the median of all capacities only differs by 1.5% from the measured value C_m.

In the next section, the approach is repeated, but Z is no longer neglected to improve the accuracy of the method.

C. FTP72, With Z

In this approach, again the FTP72 current profile from Fig. 3(b) and the same 26 cell voltages are used, but now, the internal impedance of the battery cell according to the cell datasheet is taken into account. The 26 SOC values are estimated using Fig. 2 and

$$OCV(t) = V_{\mathrm{cell}}(t) + I_{\mathrm{cell}}(t) \cdot Z \tag{5}$$

derived from Fig. 1. These 26 SOC values are shown in Fig. 3(b) (with Z), and most of them are more accurate than without considering the impedance (no Z). Since only a constant, ohmic impedance and no variation over SOC of the impedance is considered, the estimated SOC values are

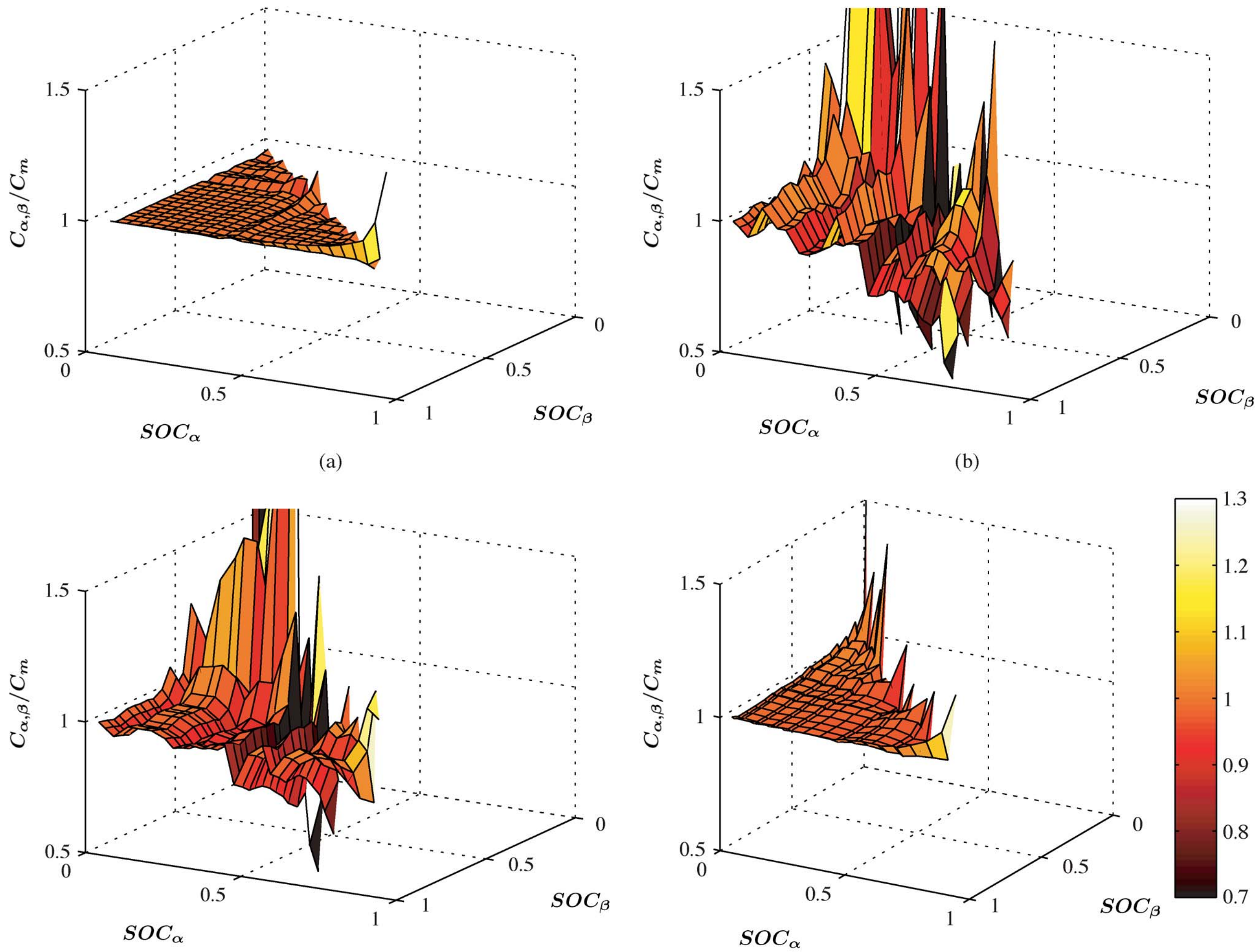


Fig. 4. Estimated capacities with respect to the two states of charge SOC_1 and SOC_2 for the current pulses (current pulses), for the FTP72 current cycle neglecting the cell impedance (FTP72, no Z), for the FTP72 current cycle considering the cell impedance (FTP72, with Z) and for the FTP72 current cycle measuring the voltage at $I_{\mathrm{cell}} = 0$ (FTP72, $I_{\mathrm{cell}} = 0$). The capacity values are based on the measured capacity of the battery cell $C_m = 46.1$ Ah. (a) Current pulses. (b) FTP72, no Z. (c) FTP72, with Z. (d) FTP72, $I_{\mathrm{cell}} = 0$.

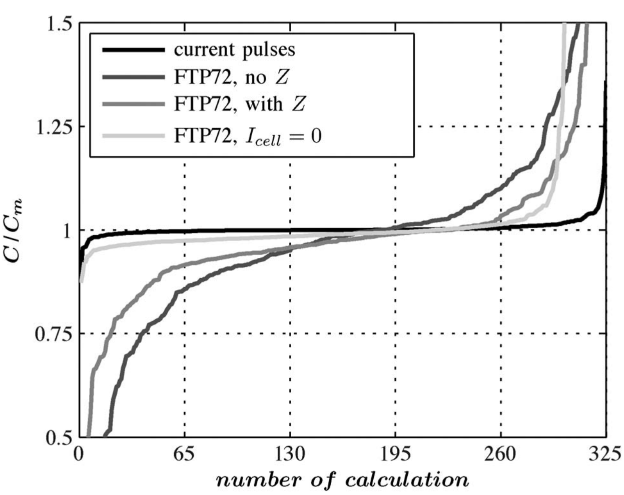


Fig. 5. Estimated capacities in ascending order for the current pulses (current pulses), for the FTP72 current cycle neglecting the cell impedance (FTP72, no Z), for the FTP72 current cycle considering the cell impedance (FTP72, with Z) and for the FTP72 current cycle measuring the voltage at $I_{\mathrm{cell}} = 0$ (FTP72, $I_{\mathrm{cell}} = 0$). The capacity values are based on the measured capacity of the battery cell $C_m = 46.1$ Ah.

TABLE III
ARITHMETIC MEAN AND MEDIAN OF ALL ESTIMATED CAPACITIES FOR DIFFERENT APPROACHES BASED ON THE MEASURED CAPACITY OF THE BATTERY CELL $C_m = 46.1$ Ah

approach	arithmetic mean / C_m	median / C_m
current pulses	0.9994	0.9991
FTP72, no Z	0.6644	0.9854
FTP72, with Z	0.9385	0.9588
FTP72, $I_{cell} = 0$	0.9963	0.9963

still inaccurate particularly when the V_{cell} is measured at a large $|I_{\mathrm{cell}}|$.

The calculated capacities are shown in Fig. 4(c), and the smoothness of the surface is better than in Fig. 4(b), in particular at the trustable area of $SOC_1 = 0.5 \ldots 1$ and $SOC_2 = 0 \ldots 0.5$. The calculated capacities in ascending order considering the impedance as shown in Fig. 5 (FTP72, with Z) have a lower variance than the calculated capacities neglecting the impedance (FTP72, no Z). Table III gives the arithmetic mean as well as the median of all the calculated capacities when considering the impedance. Though the arithmetic mean

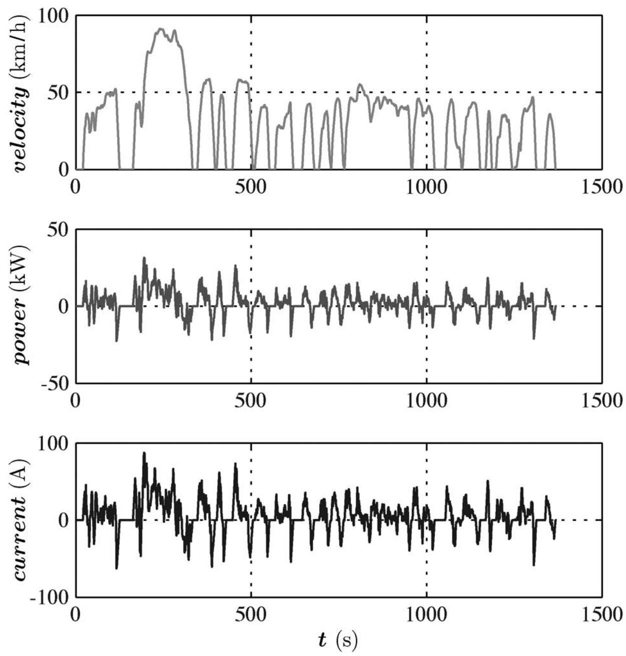


Fig. 6. Definition of the FTP72 driving cycle, power consumption of a compact electrical vehicle, and current requirement from a battery stack with 100 serially connected single cells each having a cell voltage of 3.6 V.

is now much better than without considering the impedance, the median becomes a little worse.

D. FTP72, $I_{\mathrm{cell}} = 0$

Again, the FTP72 current profile is continuously applied to discharge the battery cell until it reaches DVL, and again 26 cell voltage values are identified. However, these values are identified not at equidistant points in time as in Section III-A until III-C. The voltage values are identified when $|I_{\mathrm{cell}}|$ is below a limit of 100 mA for at least 40 s. Therefore, the internal impedance of the battery cell can be neglected, and the estimated SOC values using Fig. 2 have a high accuracy as shown in Fig. 3(b) (FTP72, $I_{\mathrm{cell}} = 0$). With these SOC values and (3), 325 capacity values are calculated and shown in Fig. 4(d). The capacity surface is almost as flat as the estimation with the current pulses. The capacities in ascending order as shown in Fig. 5 (FTP72, $I_{\mathrm{cell}} = 0$) are significantly better than the approaches with equidistant voltage measurement (FTP72, no Z and FTP72, with Z). The arithmetic mean and the median are given in Table III. The capacity estimation error is 0.37% both for the mean and the median.

IV. Conclusion

In this paper, a capacity estimation method for battery cells during operation has been presented. The capacity of battery cells can be estimated using two states of charge and the transferred charge between this two states. A specific battery cell has been discharged with two different current profiles (test cycle and real-life cycle), and several states of charge as well as the transferred charges between every two states have been used to estimate the capacity for several times. With the arithmetic mean as well as with the median of all these values, the capacity of this battery cell has been estimated to demonstrate the use of the method. With a current pulse test cycle, the accuracy is at about 99.9% compared to the measured capacity of the battery cell. With a real-life cycle, the precision of the presented method is still very high, with an accuracy of up to 99.6%, depending on the estimation of the state of charge.

Therefore, this method can be used to estimate the capacity of a battery cell with a high accuracy during operation.

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