

Review on Methods of State-of-Charge Estimation with Viewpoint to the Modern $\text{LiFePO}_4/\text{Li}_4\text{Ti}_5\text{O}_{12}$ Lithium-Ion Systems

Jonny Dambrowski^{1,2}

¹Faculty of Mathematics & Informatics, OTH Regensburg, Universitaets-Str. 31, 93053 Regensburg-Germany

²Energy Storage Research Department of Deutronic Elektronik GmbH, Deutronic-Str.5, 84166 Adlkofen-Germany

Abstract—The topic of the present paper is to discuss common methods to detect the state-of-charge (SOC) in lead-acid batteries and conventional lithium-ion systems and how they could fit in the needs of the LFP/LTO system. Especially those methods which are not transferable are picked out as a central theme. For the first time two concrete first approaches for monitoring the state of charge in a LFP/LTO battery system are given. Each method is carefully introduced, on common lithium ion and lead acid battery systems demonstrated, both advantages and drawbacks are analyzed and finally the applicability to LFP/LFP systems is given.

Index Terms—state of charge estimation, SOC, Electrochemical impedance spectroscopy, EIS, open-circuit-voltage, OCV, impedance based modelling

I. INTRODUCTION

SAFETY, reliability, long-life stability, high operating temperature range, and the fast charging ability, in particular a high rate charge acceptance, are the main requirements in an electrochemical energy storage devices in renewable energy systems. Neither conventional lithium-ion systems nor lead-acid batteries meet these requirements. In the first case the safety, operating temperature (and costs) are the main problems, whereas in the second case cycling stability and charge acceptance are the main obstacles. Recently, the relatively new lithium ion system, consisting lithium titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$, LTO) as anode material and lithium iron phosphate (LiFePO_4 , LFP) as cathode, is commercial available. The LTO-LFP system fulfills all the above requirements and hence it will be an appropriate candidate for grid connection in renewable energy systems.

II. METHODS OF SOC DETERMINATION

Most methods for state-of-charge (SoC) estimation in lead-acid and lithium-ion cells are based on ampere-hour counting, estimation of the open-circuit-voltage (OCV), impedance measurement, in particular the ohmic and the DC internal resistance of the cell. For each method there are advantages and also drawbacks trying to overcome by hybridization these different methods. In this paper we review these common methods an SoC determination and relate them for application to LFP/LTO cells.

A. Ampere Hour Counting

The most used method for SoC determination is the so called *ampere hour counting* (Ah-counting) or *charge balance*. That is a sign conform measurement of the amount of balanced charge which has been stored in or taken out of the cell, normed to the nominal capacity C_N . More exactly:

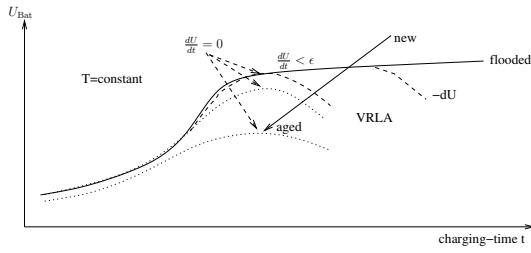
Definition 1. Let $SOC_0 := SOC(t_0 = 0)$ the SoC at the time $t_0 = 0$, then define

$$SOC := SOC(t) := SOC_0 + \frac{1}{C_N} \int_0^t i_{MR}(\tau) d\tau, \quad (1)$$

whereby $i_{MR} := i_{cell} - i_{loss}$ denotes the main reaction current, which is the difference of the cell current i_{cell} and the loss current i_{loss} , e.g. by gassing, corrosion, or other chemical reaction mechanisms.

Thus the main reaction current stores or restores, depending on its sign, the energy within the cell. Normally, the range of SoC-function is between 0 and 1, i.e. $SOC(t) \in [0, 1] \subset \mathbb{R}$. However, it is well known, that e.g. during the first cycles the actual capacity of a *new* lead-acid battery can be increased to 130% of C_N , implying the possibility of $SOC(t) > 1$. By scaling the SoC-function the unit of SoC can be given in %. During the regular operation time the aging process of the electrochemical energy storage system is inevitable, and hence the *actual capacity*, which is the capacity of the full charged battery under rated conditions, at the time *after* operation start date, will be decreased. Hence the SoC defined in (1) is dependent on the state-of-health (SoH) of the battery and thus the SoC range of an aged battery is decreased. Instead referring the balanced charge to nominal capacity C_N , it is more convenient to replace C_N in (1) by the actual capacity C_a . This SoH-independent SoC is called *relative state-of-charge*, denoted by SOC_r .

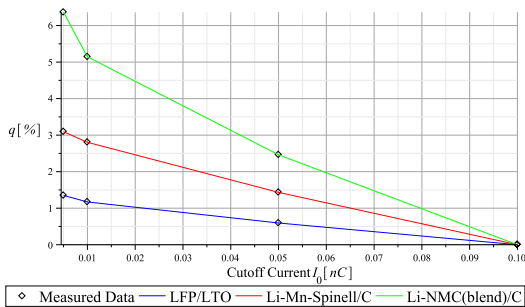
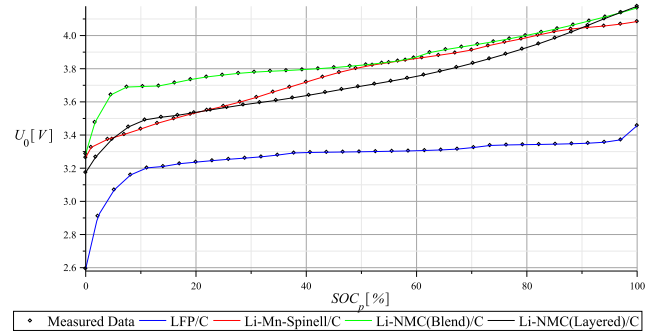
Ah-counting can be used for each rechargeable energy storage system; the algorithmic implementation on a battery management system (BMS) is simple. However, there are also drawbacks. Due current-integration errors and the current losses during recharging recalibration of Ah-counter at a certain reference point of the battery is necessary. The part of cell current flows in losses $i_{loss} = i_{cell} - i_{MR}$ cannot be directly measured, leading to divergence in the calculated and the true SoC, e.g. in NiCd or lead-acid batteries after a few cycles [2]. Thus, for calculation the SoC by Ah-counting method, the charge-factor or more complex loss-models are essential to estimate current losses.

Figure 1. SoH-dependence near $SOC = 1$ of VRLA batteries

A well chosen reference point for recalibration the Ah-counter is characterized by the following properties:

- 1) The reference point represents precisely one specific SoC, say SOC_0 .
- 2) Under regular operating conditions there are sufficient amount of events to reach the reference point, without compromising the functionality of the application.
- 3) Establishing the reference point is efficient and in particular does not stress (in the sense of ageing) the battery.
- 4) The reference point is robustly to the way which has been established (e.g. the magnitude of the charging or the cutoff current, temperature, etc.).
- 5) Establishing the reference point is invariant to the SoH.

Of course, the full or empty state-of-charge, i.e. $SOC = 1$ or $SOC = 0$, are obvious candidates for reference points for recalibration of the Ah-counter. For practical reasons we consider in the following only the full state-of-charge reference point. Establishing $SOC = 1$ for lead-acid batteries is non trivial, and is normally accompanied by a large amount of charging time, losses by overcharging (e.g. corrosion, water loss) and hence significant ageing of the battery. On the other side without periodic full charge lead-acid batteries will suffer from other ageing mechanisms (e.g. acid stratification, sulphatation). The problems are especially present at valve-regulated-lead-acid batteries (VRLA), as oxygen cycle has a strong influence on charge characteristic near the full state-of-charge, Fig. 1. Furthermore this depends intensely on temperature and SoH. Thus, the conditions 2) - 5) are not fulfilled at all. In contrast, most of lithium-ion systems the current losses establishing the full state-of-charge are very small compared to lead-acid batteries, which dramatically reduce the charging time and current losses during recharge. Thus the full state-of-charge reference point in lithium-ion batteries is much more

Figure 2. Dependence of the normalized increase q of actual capacity to the cutoff-current I_0 . The more I_0 , the more is the capacity q relative to the value with $I_0 = 0.1C$. The LFP/LTO cell is more robust to variation if I_0 .Figure 3. OCV-curves U_0 of different commercial available lithium-ion systems in discharge direction as a function of practical SoC SOC_p at $25^\circ\text{C} \pm 1^\circ\text{C}$. (Setup: $\Delta q = 3\%C_a$, $6h \leq t_{\text{relax}} \leq 12h$ such that $\Delta U_{\text{Bat}} \leq 2.5mV/h$ within $3\% \leq SOC_p \leq 97\%$.) Simplifying the representation of OCV-curves the practical SoC SOC_p is always used [1].

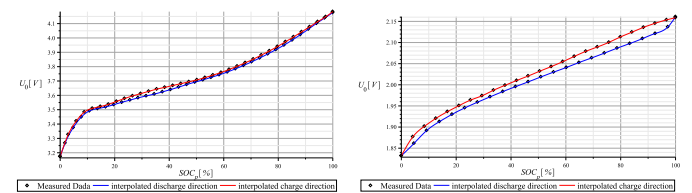
well chosen as in lead-acid batteries. Due integration errors of the current-sensor, in high-power applications a very fast and precise current-sensor technology is necessary, which increase the costs.

By the existing measurements the Ah-counter method is very suitable for SoC estimation in LFP/LTO cells. First, set the reference point to $SOC = 1$. Thus we have to show the other four conditions of a well chosen reference point in the context of renewable energy storage applications. For charging currents in the range of $0.1C - 10C$ the charging losses are below 0.1% and also negligible. By Fig. 2 it be concluded, that the reference point is robust to the cutoff-current I_0 , compared to standard lithium-ion systems. By comparable charging conditions and cell data the charging time for LFP/LTO cells from $SOC = 0$ to $SOC = 1$ succeeds $30\% - 60\%$ faster then for standard lithium-ion systems. Thus, this property and the high current charging ability of $10C$ of LFP/LTO systems compared to $5C$ for LFP/C, $4C$ for Li-Mn-Spinell/C or $1C$ for LCO/C support the condition 2) of well chosen reference point. Temperature and ageing effect will be studied in further research activities.

B. Open-Circuit-Voltage

By the open-circuit-voltage U_0 (OCV) of an electrochemical system we understand the cell voltage U_{cell} in steady-state, this means the voltage at the terminals after sufficient long relaxation time in rest. The OCV-method uses the fact, that for lead-acid batteries and most of lithium-ion battery systems the relation $f : U_0 \mapsto SOC(U_0)$ is sufficiently sensitive and approximately injective Fig.3.

Referring to a reference point, e.g. $SOC = 1$, the $U_0(SOC)$ curve is recorded by successive discharging of a specific



$$(a) U_0(1) - U_0(0.1) \cong 0.6V$$

$$(b) U_0(0.9) - U_0(0.1) \cong 0.22V$$

Figure 4. OCV-hysteresis of (a) Li-NMC(layered)/C and (b) lead-acid AGM battery at $22^\circ\text{C} \pm 2^\circ\text{C}$. OCV-method is applicable for both systems.

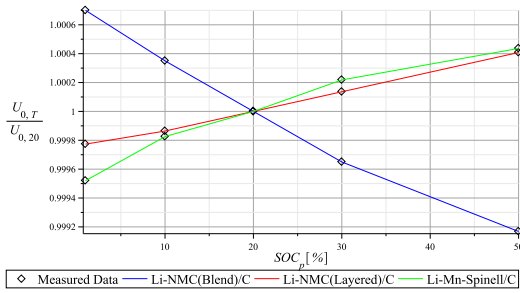


Figure 5. Measured $\alpha := \frac{dU_0}{dT}(T)$ of lithium-ion cells at $SOC = 50\%$.

amount of charge Δq . After each discharge step Δq an appropriate relaxation time t_{relax} is required such that battery voltage converge to the OCV U_0 . In this steady-state all overvoltages coming from the last preceding discharge step are relaxed. Repeat the stepwise discharge and relaxation process until the cell is completely discharged, i.e. $SOC = 0$. Subsequently start the same game in reverse direction until the full state-of-charge $SOC = 1$ is reached.

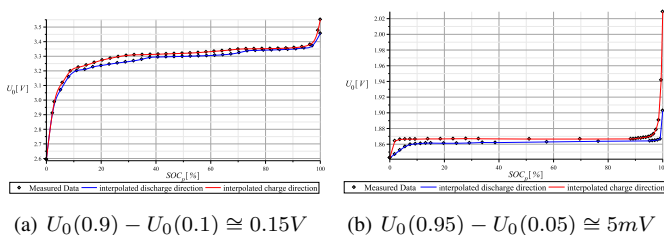
The result of such measurement, as seen in Fig. 4, is often called *open-circuit-voltage hysteresis*.

In a laboratory environment the OCV hysteresis is technical simple to generate. The discrete $U_0(SOC)$ -values can be stored in a look up table and hence it is easy to use it in a BMS. The temperature coefficient $\frac{dU_0}{dT}(T)$ in lead-acid batteries is a function of acid concentration and varies between $(0.14 - 0.23)mV/K$ ([7], Tab. 2.36 and Fig. 2.27); thus it can be usually neglected. As can be seen in Fig. 5 the temperature coefficient of some standard lithium-ion systems is in the same region as LiNMC(blend)/C, but reverse sign, or one order of magnitude smaller then for lead-acid batteries, and hence also negligible. If $U_0(SOC)$ sufficiently sensitive and approximately injective, e.g. as shown in Fig. 5, then it can be concluded, that OCV curves stable under temperature changes.

Due restricted SOC range in some applications, like HEV ($30\% \leq SOC \leq 70\%$, [8]), a linear approximation of the OCV curve is sufficient.

Unfortunately the generation of a OCV-curve is normally very time consuming, due relaxation time t_{relax} has to be elapse measuring the OCV U_0 on the terminals. Depending on the electrochemical system this takes for lithium-ion cells $2h - 24h^1$ and for lead-acid batteries up to a few days. Additionally the relaxation time is a function of SoC, temperature and SoH, i.e. $t_{\text{relax}} = t_{\text{relax}}(SOC, T, SOH, \dots)$, explaining the stated wide time range on the concrete electrochemical sys-

¹Li-Mn-Spinell/C, Li-NMC/C magnitudes of $2h - 6h$, for LFP/C $6h - 24h$



(a) $U_0(0.9) - U_0(0.1) \cong 0.15V$ (b) $U_0(0.95) - U_0(0.05) \cong 5mV$

Figure 6. OCV-hysteresis of (a) LFP/C and (b) LFP/LTO at $22^\circ C \pm 2^\circ C$. OCV-method is not applicable for both systems.

tems. These dependencies are the reason for the non-triviality in experimental design of measuring the OCV-curve, which is often in practise underestimated. Thus it is not surprising, that recording a complete OCV hysteresis can take 6-8 weeks. Of course, there are several methods trying to accelerate the measurement procedure by shorten the relaxation time or low constant current profile over whole SoC range and set the OCV curve to the average voltage of the battery (terminal) voltage in charge and discharge direction. But these methods should be take with a pinch of salt, because knowing the errors of such measurement requires the existence of at least one exact OCV-curve for all relevant dependencies. Furthermore, lead-acid batteries are usually unsuitable for very low constant current (i.e. $\ll I_N$ nominal current) (dis)charge profiles and hence they will be suffer from such operation conditions.

As in most application areas the operation condition do not admit relaxation times for measuring U_0 directly the OCV method cannot be applied for SOC determination directly. In consequence additional methods, e.g. model based approaches Fig. 11, for estimation of U_0 should be considered. A precision limiting factor of OCV method are plateaus in OCV curves as seen in Fig. 3. Thus, depending on lithium-ion system and the actual SoC, as seen in Fig. 3, a precision of OCV based SoC estimation of approximately $5\% - 10\%$ is achievable. This is also consistent to literature data, e.g. [9], [10]. The OCV method cannot be used, if $U_0(SOC)$ curve is flat, that is voltage range is small to the full SOC scale, or has a significant hysteresis property, e.g. NiMh, LFP in Fig.6(a). In this two cases other or additional methods should be considered for SoC determination. For lithium-ion batteries in literature [4], [5], [6], etc. the implicit or explicit assumption of ageing invariance of the OCV curve can be often found. But this is not true. In [3] it was showed that ageing of lithium-ion batteries can rise additional errors in SoC determination in a region of $(4-8)\%$, which is not negligible. Indeed, in lead-acid batteries there also exist a well known influence of certain ageing mechanisms (e.g. water loss, acid stratification, sulfation) on the OCV curves. Thus $U_0(SOC)$ -relation are usually ageing *variant*. In consequence OCV based SoC determination ageing phenomena must be taken into account.

In fact, as can be seen in Fig. 6(b) the OCV hysteresis is, up to boundary-SoCs, flat. Within $5\% \leq SOC_p \leq 95\%$ the OCV U_0 varies only a few mV , depending on the manufacturer $5mV$ to $20mV$. Thus OCV based SoC determination in LFP/LTO is not possible. The temperature dependence of U_0 is within $-10^\circ C \leq T \leq 40^\circ C$ is linear and $\cong 0.27mV/K$.

C. Internal DC-Resistance

The notion of internal resistance of a battery by evaluation of the voltage response on a current-(dis-)charge pulsed is well known. In the following section we focuss our attention to definition and measurement of *ohmic* resistance by means of (dis-)charge current steps.

Let $t_1 \in \mathbb{R}^+$ and $I_1 \neq I_2 \in \mathbb{R}$ fixed. A *current step* from I_1 to I_2 at the time t_1 is a map $I : \mathbb{R} \rightarrow \mathbb{R}$ defined by

$$I(t) := \begin{cases} I_2, & t_1 < t < \infty \\ I_1, & \text{elsewhere.} \end{cases} \quad (2)$$

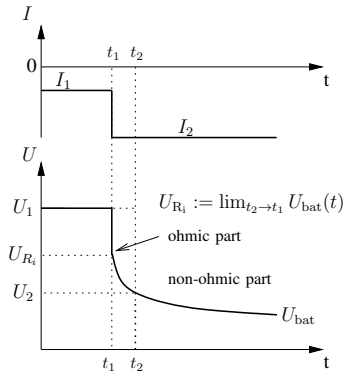


Figure 7. The definition of the ohmic resistance R_i as limit of $R_{DC}^{\Delta t}$.

Definition 2. Let $t_2 > t_1$. The *internal DC-resistance* $R_{DC}^{\Delta t}$ of a battery at time-interval $\Delta t := t_2 - t_1$ is defined by

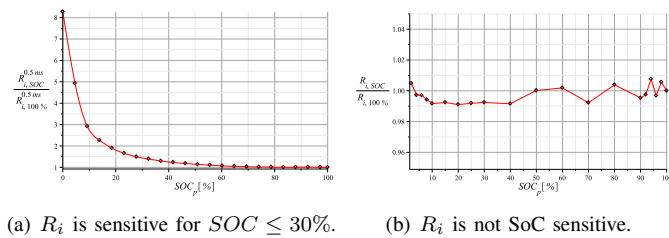
$$R_{DC}^{\Delta t} := \left| \frac{U_{bat}(t_1) - U_{bat}(t_2)}{I_{bat}(t_1) - I_{bat}(t_2)} \right|, \quad (3)$$

whereas $I_{bat}(t)$ is the current step from $I_{bat}(t_1)$ to $I_{bat}(t_2)$ at the time t_1 .

The internal DC-resistance is determined by the difference of voltage response to the current step at observation interval Δt , which is typically in magnitudes of ms to s . The *ohmic internal resistance* arises by limit consideration $\Delta t \rightarrow 0$, i.e.

$$R_i := \lim_{\Delta t \rightarrow 0} R_{DC}^{\Delta t} := \lim_{t_2 \rightarrow t_1} R_{DC}^{\Delta t}. \quad (4)$$

The notation R_i is also used for the DC-resistance $R_{DC}^{\Delta t}$, as in practical measurement the ohmic internal resistance R_i is approximated by DC-resistance for small Δt . Fig. 7 clarifies the definition of the internal DC-resistance and the ohmic resistance of a battery. Analogously to the U_0 -method the R_i based SoC determination uses the non-trivial relation $R_i \mapsto SOC(R_i)$, which means R_i is sensitive to SoC changes and the relation $R_i(SOC)$ is a injective function, as can be seen for lead-acid batteries in Fig. 8(a). The algorithmic determination of R_i is simple, and hence easy to implement in a BMS. For lead-acid batteries and most lithium-ion systems an appropriate approximation of ohmic internal resistance by $0.2ms \leq \Delta t \leq 2ms$ can be achieved, which is indeed no challenge for today's microcontroller (μC) or digital signal controllers (DSPs). It is well known, that the internal DC-resistance can be used for SoH estimation in high-power application, where ageing predominantly is determined by degradation of high-power ability of the battery. As shown



(a) R_i is sensitive for $SOC \leq 30\%$. (b) R_i is not SoC sensitive.

Figure 8. Measured $R_i(SOC)$ curve for an 12V AGM lead-acid battery and a LFP/LTO cell at $22^\circ C \pm 2^\circ C$.

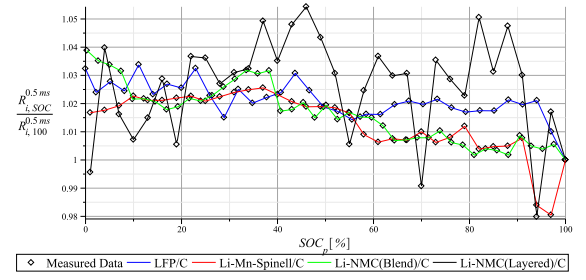


Figure 9. Measured $R_i(SOC)$ curves for standard lithium-ion cells.

in Fig. 8(a) the ohmic resistance of lead-acid batteries is a well suited SoC-indicator in the middle and lower SoC range. But for middle and higher SoCs the SoC sensitivity decreases asymptotically. In consequence R_i based SoC determination for lead-acid batteries is only restricted applicable. To overcome the low sensitivity of ohmic resistance at high SoC additional methods are necessary, e.g. neuronal network or kalman-filter theory. As shown in Fig.9 the ohmic internal resistance in standard lithium-ion systems is not SoC sensitive and also R_i based SoC determination in lithium-ion cells cannot be used. The variation of the internal resistance over the full SoC scale is only a few percent and is superimposed by measurement limitations (only in the case of Li-NMC(Layered)/C because of very low $R_i \cong 0.7m\Omega$) and minor temperature changes (within $24^\circ C \pm 2^\circ C$).

From Fig. 8(b) we conclude, that the internal ohmic resistance is not sensitive to SoC for LFP/LTO systems and hence this method is not applicable for such type of batteries.

D. Impedance Based Methods

The electrochemical impedance spectroscopy (EIS) is a prominent tool for characterizing, modelling and state diagnostic of electrochemical energy storage systems. By EIS we understand a measurement method extracting the complex (frequency dependent) impedance

$$Z(\omega) = \text{Re}\{Z\}(\omega) + i \text{Im}\{Z\}(\omega) = |Z|(\omega) \exp(i\varphi(\omega)) \in \mathbb{C}$$

of an electrochemical system, e.g. battery. Thereby denote $\text{Re}(Z)$, $\text{Im}(Z)$, $|Z|$, φ the real and imaginary part, the modulus and phase of the impedance Z , depending all on (angular) frequency ω . These magnitudes lead to well known representations of Z via Bode plot ($|Z|(\omega)$, $\varphi(\omega)$) and Nyquist diagram ($\text{Re}(Z)$, $\text{Im}(Z)$) ((Fig. 12). The EIS measurement can be done by potentiostatic or galvanostatic excitation, whereas the last one is more common in the field of electrochemical energy storage devices. In the first case the battery is excited by a voltage signal and the current response on the output is measured; and vice versa in the second case. From systemtheoretical point of view the (classical) impedance is the transfer function of a real convolution system, e.g. *battery*, that is the quotient of the Fourier transform $I(\omega) := \mathcal{F}\{i(t)\}$ of the input current signal $i(t)$ and the Fourier transform $U(\omega) := \mathcal{F}\{u(t)\}$ of the voltage response $u(t)$ of the battery, i.e.

$$Z(\omega) := \frac{\mathcal{F}\{u(t)\}}{\mathcal{F}\{i(t)\}} = \frac{U(\omega)}{I(\omega)}. \quad (5)$$

This formula (5) alone does not ensure the existence of the impedance Z . However, if the battery behaves like a stable convolution system, and if $i(t), u(t)$ integrable or of finite energy, then the existence of Z is guaranteed, as proved in [11]. Up to well chosen signal spaces the transfer function Z characterizes such systems in the sense, that the output signal can be calculated by knowing Z and the input signal.

Most measurement methods to determine impedance of a battery uses a harmonic current signals stimulus of the form $i(t) := \hat{i} \sin(\omega \cdot t)$ at given frequency $\omega \in \{\omega_{\min}, \dots, \omega_{\max}\}$, and the voltage response $u(t) = \hat{u}(\omega) \sin(\omega \cdot t + \varphi(\omega))$ is measured. If, in fact, the voltage response $u(t)$ is also harmonic with the same frequency ω , which is true for convolution systems, then the impedance at the frequency ω of such system can be calculated by (Fig. 10)

$$Z(\omega) = |Z|(\omega)e^{i\varphi(\omega)} = \frac{\hat{u}}{\hat{i}}(\omega)e^{i\varphi(\omega)}.$$

The idea behind der impedance based SoC determination is to find one ore more frequencies $\omega_0, \omega_1, \dots, \omega_k$ such that at least one impedance parameter $p_Z \in \{\text{Re}\{Z\}, \text{Im}\{Z\}, |Z|, \varphi\}$ is SoC sensitive and the map $p_Z \mapsto p_Z(\text{SOC})$ is injective.

Due different time constants of chemical and electrochemical processes within the cell, different ω -intervals in the impedance spectrum (IS) can be related to specific internal processes, as seen in Fig. 11. This enables not only a characterization of batteries by its IS, but also an EC based modelling approach for simulating the dynamic behaviour of batteries. An example of such EC battery model is shown at bottom in Fig. 11. By nonlinear optimizations routines, e.g. Levenberg-Marquardt algorithm, the parameter of such EC models can be estimated, and hence the OCV U_0 can be extracted. In particular, the long relaxation time t_{relax} , which is necessary to reach the OCV on the terminals can be avoided, making the OCV method accessible for practical application, if the $U_0(\text{SOC})$ relation, e.g. in form of a look up table, is available. Furthermore, the impedance based modeling approach by ECs provides the possibility to determine SoC dependencies in the model parameters, which can also be used for SoC determination. Finally, the EIS is often sensitive to degradation phenomena (ageing) within the battery, e.g. formation of passivation layer. Thus the impedance spectroscopy is an important tool for the development of ageing invariant SoC determination methods.

There are also drawbacks in using EIS method. For short, these are mainly validity, interpretation and reproducibility of

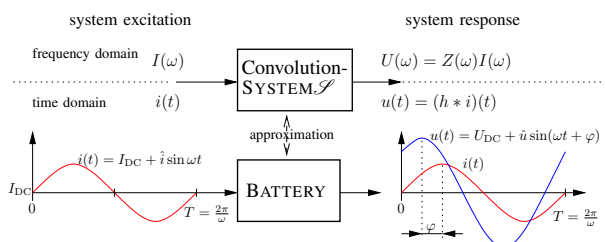


Figure 10. On definition of the impedance of an electrochemical device in terms system theory, and the transmission to a the most used concrete measurement method, the *sinus-sweep* method.

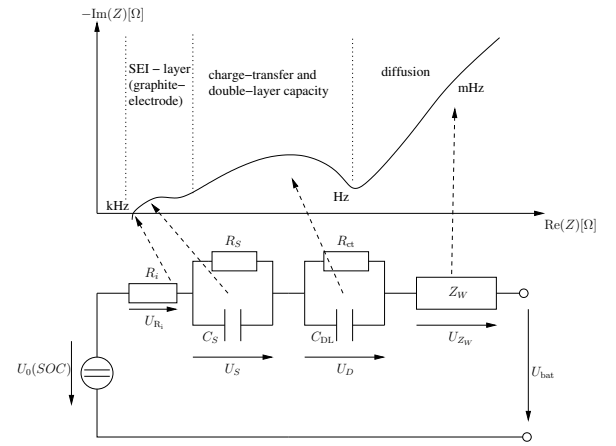


Figure 11. Schematic view of an impedance-spectrum (Nyquist plot) of a lithium-ion battery on top, and the relations to electric-circuit (EC) model at the bottom, consisting an SoC dependent ideal voltage source $U_0(\text{SOC})$, the ohmic resistance R_i , two parallel RC-devices, the first $R_s C_s$ comprises the passivation property of the graphite-electrode by the solid-electrolyte-interface (SEI), the second the charge-transfer R_{ct} and the double-layer capacity C_{DL} , and finally the Warburg element Z_W for diffusion processes.

EIS measurement data. As noted above, for the existence of the impedance certain system requirements are necessary, in particular this includes the linearity and the time invariance. In consequence the design of an EIS measurement has to be consider these systemtheoretical assumptions to obtain valid impedance measurement data. Unfortunately this is in practise a common underestimated problem. Hence automatic validity tests of EIS measurement data are necessary. A first approach in a pure mathematical treatment is given in [11]. For instance the current-voltage (Butler-Volmer) characteristic in batteries are nonlinear, also transportphenomena, e.g. diffusion, are nonlinear processes. As usually, nonlinear system will be local linearized, that means, the EIS is restricted to the small signal range around a certain working point, e.g. a specific SoC. In particular due SoC drift, especially at low frequency, time invariance of the system *battery* during EIS measurement is not feasible. Thus, smooting this effect the data has to subjected to a certain transform, a so-called drift compensation. EIS measurements at low frequencies $\omega < 0.1 \text{ Hz}$, where diffusion is predominantly present, are time consuming and hence often not operable in practical application. The impedanc spectrum

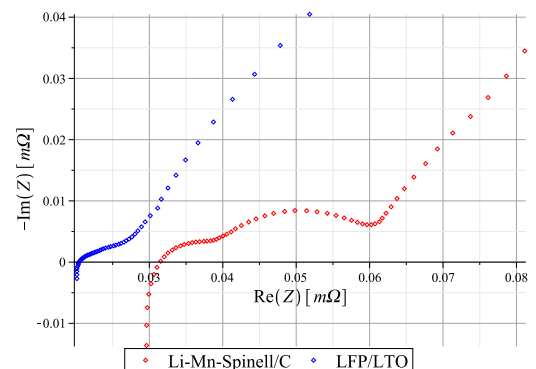


Figure 12. Nyquist plot of a LFP/LTO cell at $\text{SOC} = 90\%$ and Li-Mn-Spinell/C cell at $\text{SOC} = 10\%$, both at $23^\circ\text{C} \pm 1^\circ\text{C}$.

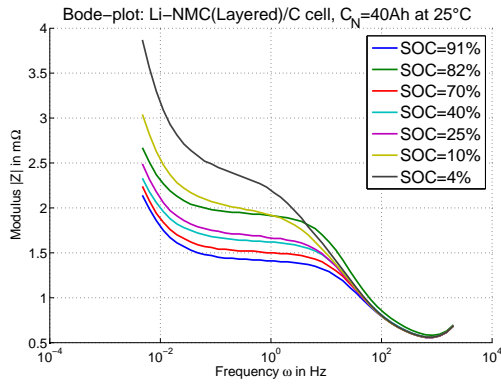


Figure 13. $|Z|$ is SoC sensitive, but violates the injectivity of $|Z|(SOC)$.

is sensitive to temperature and middle/short time history such that reproducibility is possibly compromised, in particular in the case of EIS measurements far away from the steady-state, e.g. using dc-current offset. EIS measurement devices are usually very expensive because of the high precision requirement and thus are designed for laboratory environment.

In spite of the fact, that for most of lithium-ion system the IS is sensitive to SoC variation, as seen in Fig. 13, the injectivity is violated and hence impedance based SoC determination is a priori not applicable. However, in the case of LFP/LTO Fig. 14 shows that the function $|Z| \mapsto SOC(|Z|)$ is over a wide ω -range approximately injective. In Fig. 15 the $|Z|(SOC)$ relation for a fixed frequency ω is depicted for Li-NMC(Layered)/C (red curve) and LFP/LTO (blue curve). It can be seen the modulus of the impedance varies 30% over the full SoC scale and decreases approximately monoton. This result was measured for more than one manufacturer and hence it is first approach to impedance based SoC determination in LFP/LTP systems. In contrast Li-NMC(Layered)/C system violates injectivity and hence there are impedances $|Z|$ relates to more than exactly one SOC.

III. CONCLUSION AND OUTLOOK

The object of this paper was to review some well known and also common used methods for SoC estimation in lead-acid and conventional lithium-ion batteries with viewpoint of applicability to LFP/LTO systems. Analyzing these methods it can be concluded: (1) due flatness of $U_0(SOC)$ curve the OCV

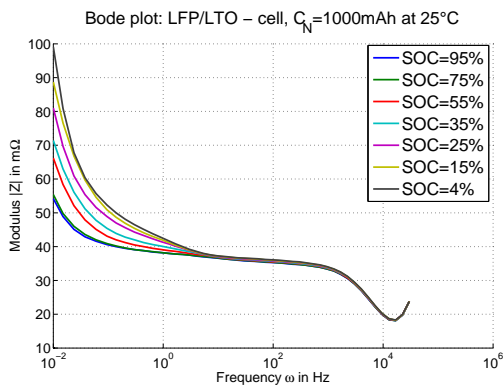


Figure 14. $|Z|$ is SoC sufficiently sensitive for lower frequencies and $|Z|(SOC)$ is approximately injective.

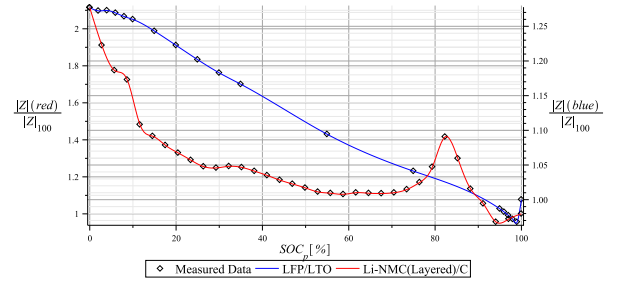


Figure 15. Measured $|Z|(SOC)$ relation at $\omega = 0.1 Hz$

method is not suitable in LFP/LTP systems, (2) the analogous argument holds for the ohmic resistance R_i , (3) Ah counting seems to be highly suitable compared to standard lithium-ion systems or lead-acid batteries, (4) also the impedance based approach to SoC determination of a LFP/LTO cell can be used. Of course, these methods have to be refined in further research activities, in particular hybridization possibilities have to take into account.

ACKNOWLEDGMENT

I'm very grateful to the company DEUTRONIC ELECTRONIC supporting this research project.

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