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Smart and Accurate State-of-Charge Indication In Portable Applications

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Abstract—**Accurate State-of-Charge (SoC) and remaining run-time indication for portable devices is important for the user-convenience and to prolong the lifetime of batteries. However, the known methods of SoC indication in portable applications are not accurate enough under all practical conditions. The method presented in this paper aims at designing and testing an SoC indication system capable of predicting the remaining capacity of the battery and the remaining run-time with an accuracy of 1 minute or better under all realistic user conditions, including a wide variety of load currents and a wide temperature range. At the moment Li-ion is the most commonly used battery chemistry in portable applications. Therefore, the focus is on SoC indication for Li-ion batteries. The basis of the proposed algorithm is current measurement and integration during charge and discharge state and voltage measurement during equilibrium state. Experimental results show the effectiveness of the presented novel approach for improving the accuracy of the SoC indication.**

Keywords—Li-ion batteries; modeling; portable energy; remaining run-time.

I. INTRODUCTION

Portable electronic devices have become ubiquitous in modern society. The recent rapid expansion in the use of portable computers, personal data assistants, cellular phones, camcorders and power tools creates a strong demand for fast deployment of battery technologies at an unprecedented rate. The design of such a portable device requires many battery-management features, including charge control, battery-capacity monitoring, remaining run-time information, etc. For offering high precision each part of the system must be near to perfection.

In portable applications the request for an accurate and reliable SoC indicator system is clear. Inaccuracy of an SoC indication system can be pretty annoying, especially when a portable device suddenly stops functioning whereas sufficient battery capacity is indicated [1]. A poor reliability of the SoC indication system may induce the use of only part of the available battery capacity. For example, the user may be inclined to recharge the battery every day, even when enough battery capacity is indicated on the portable device. This will lead to more frequent recharging than strictly necessary, which in turn leads to an earlier wear-out of the battery. The effect of inaccuracy of SoC indication can be even worse when the SoC value is also used to control charging. The battery is either not fully charged or it is overcharged. In the former case, the battery will be recharged more often than needed, which will lead to an earlier wear-out. In the latter case, frequent overcharging will lead to a lower cycle life [1].

This paper deals with the important part of SoC indication in the Battery Management System (BMS). A general block diagram of a BMS is shown in Fig. 1.
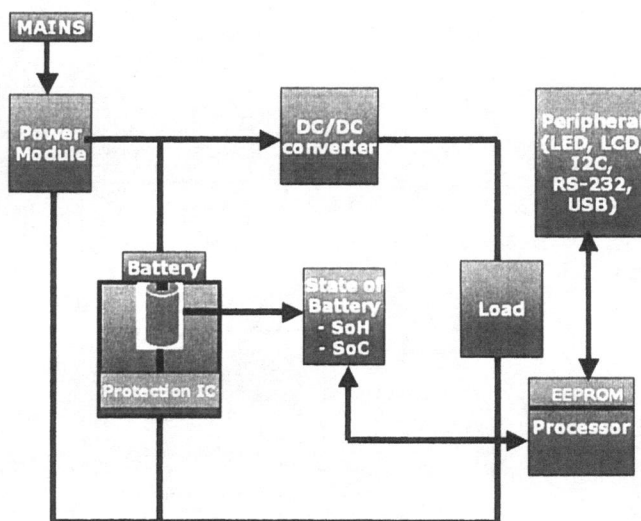

Fig. 1. General architecture of a Battery Management System [1].

The basic task of the Power Module (PM) is to charge the battery by converting electrical energy from the mains into electrical energy suitable to charge the battery (see Fig. 1). The PM can either be a separate device, such as a travel charger, or be integrated within the portable device, as in for example shavers [1]. A protection IC connected in series with the battery is needed for Li-ion batteries. The battery voltage, current and temperature have to be monitored and the protection IC has to be controlled to ensure that the battery is never operated in an unsafe region. The battery manufacturer determines the region within which it is considered safe to use the Li-ion battery. Outside the safe region, destructive processes may start to take place [1]. The DC/DC converter is used to efficiently condition the unregulated battery voltage (3 V – 4.2 V in a Li-ion chemistry) for compatibility with stringent load requirements (see Fig. 1). The basic task of the

load is to convert the electrical energy supplied by a battery into an energy form that will fulfill the load's function.

The battery status can be indicated in a single or a string of Light-Emitting Diode(s) (LED) or on a Liquid-Crystal Display (LCD) that indicates the SoC and the battery condition (e.g. the State-of-Health (SoH)) [1]. The processor is used to run the battery-management software, including the SoC algorithm (see Fig. 1). The communication between the BMS and other devices is another important task of the BMS. Depending on the application different systems for data exchange can be used, such as an Inter-Integrated-Circuit Bus Interface (I^2C) or some other form of a serial interface (see Fig. 1).

The battery state is used as input parameter for the portable device electrical management and additionally it is an important parameter for the user. The battery state can be used to estimate the expected lifetime of the battery. It can simply be described by two parameters: SoC and SoH. Both parameters depend on each other and influence the battery performance.

The SoC is the percentage of the maximum possible charge that is present inside the battery [1]. There are several practical methods available for SoC indication. Two of the known SoC indication methods are the direct-measurement and the book-keeping methods [1], [3].

This paper is organized as follows. The mathematical models and the states of the new proposed SoC algorithm are introduced in section II. Simulation results of the mathematical models are presented in section III. Section IV focuses on the obtained experimental results. Finally, section V presents the concluding remarks and future work.

II. A NEW SoC INDICATION METHOD

This paper presents a new method to predict the SoC of a battery that aims at eliminating the main drawbacks and combining the advantages of the direct-measurement and book-keeping methods [1]-[3]. Using this method, the system's estimations are shown to the user in each state in the form of a value of SoC expressed in [%] and also in the form of a remaining run-time available under the valid discharge conditions. The remaining run-time can be inferred from the remaining capacity in two ways, depending on the type of load [1]: for a current-type load the remaining capacity in [mAh], so expressed as charge, is divided by the drawn current in [mA] and for a power-type load the remaining capacity in [mWh], so expressed as energy, is divided by the drawn power in [mW]. In this paper only current-type loads will be considered for simplicity.

The proposed algorithm operates in five different states [1]-[3]: *initial state, equilibrium state, transitional state, discharge state* and *charge state*. A description of each state of the algorithm will be given below.

When the battery is first connected to the SoC system, the algorithm starts up in the *initial state*. In this state the initial SoC is determined based on voltage measurement and the stored SoC-EMF relationship. Dependent on whether the

battery is charged, discharged or in equilibrium, the algorithm then shifts to the appropriate state.

In the *equilibrium state* hardly any current is drawn from the battery. For example, this situation occurs when a mobile phone is in standby mode. The current in this case is only a few mA, which is lower than a small current I_{lim} defined in the system (e.g. 2 mA mean in a mobile phone application). For this very low current value, the battery voltage is very close to the EMF value, under the condition that the voltage is stable. Therefore, in order to allow the algorithm to change to this state, the condition of a stable voltage has to be met. In this state the SoC is determined based on voltage measurement and the stored SoC-EMF relationship. An advantage of the SoC-EMF curve is that it does not depend on aging and only to a limited extent on the temperature of the battery. Therefore, it is a good candidate for the SoC indication [1]. The EMF of a Li-ion battery with intercalated electrodes is modeled as a difference in equilibrium potentials of positive and negative electrodes [1],[4] correspondingly i.e.

$$U_{emf} \doteq E^{eq}_{LiCoO_2} - E^{eq}_{LiC_6} \qquad (1)$$

where equilibrium potentials of the positive and negative electrodes are modeled as follows. The equilibrium potential of the positive electrode is given by:

$$E^{eq}_{LiCoO_2} = E^0_{LiCoO_2} - J(\log(\frac{x_{Li}}{1-x_{Li}}) + U^+_j x_{Li} - \zeta^+_j) \qquad (2)$$

$$\zeta^+_2 = (U^+_2 - U^+_1) * x_{ph} + \zeta^+_1, \quad j = \begin{cases} 1 & x_{ph} \le x_{Li} \le 1 \\ 2 & 1/2 \le x_{Li} \le x_{ph} \end{cases} \qquad (3)$$

where $E^0_{LiCoO_2}$ is the standard redox potential of the $LiCoO_2$ electrode in [V], U^+_j denotes the dimensionless interaction energy coefficient in the $LiCoO_2$ electrode, ζ^+_j denotes a dimensionless constant in the $LiCoO_2$ electrode, x_{Li} is the molfraction of Li^+ ions inside the positive electrode, i.e. the SoC of the $LiCoO_2$ electrode, and $J = RT/F$, where R is the gas constant (8.314 J/(mol.K)), F is Faraday's constant (96485 C/mol) and T is the (ambient) temperature in [K]. In (3) a phase transition occurs at $x_{Li}=x_{ph}$, that results in a curvature change. According to modern literature on Li-ion materials (see e.g. [1], [5]) the main phase-transition point is located nearby $x_{ph}\approx0.75$, while there is also minor one at $x_{ph}\approx0.93$. The negative electrode is modeled symmetrically, with only a small difference.

$$E^{eq}_{LiC_6} = E^0_{LiC_6} - J(\log(\frac{z_{Li}}{1-z_{Li}}) + U^-_j z_{Li} - \zeta^-_j) \qquad (4)$$

$$\zeta_2^- = (U_2^- - U_1^-) * z_{ph} + \zeta_1^-, \quad j = \begin{cases} 1 & 0 \le z_{Li} \le z_{ph} \\ 2 & z_{ph} \le z_{Li} \le 1 \end{cases} \quad (5)$$

where $E_{LiC_6}^0$ is the standard redox potential of the LiC_6 electrode in [V], U_j^- denotes the dimensionless interaction energy coefficient in the LiC_6 electrode, ζ_j^- denotes a dimensionless constant in the LiC_6 electrode, z_{Li} is the molfraction of the Li^+-ions inside the negative electrode, i.e. SoC of the negative electrode. In the negative electrode a phase transition occurring around $z_{ph} \approx 0.25$ is modeled. Under normal operational conditions x_{Li} will cycle between 0.5 and 1, but z_{Li} will cycle between 0 and 1 [1]. Simulation results of the mathematical EMF implementation will be presented in section III.

The *transitional state* is used when the algorithm changes from either the *charge* or the *discharge state* to the *equilibrium state*. In this state it is determined whether the battery voltage is stable and the algorithm is allowed to enter into the *equilibrium state*.
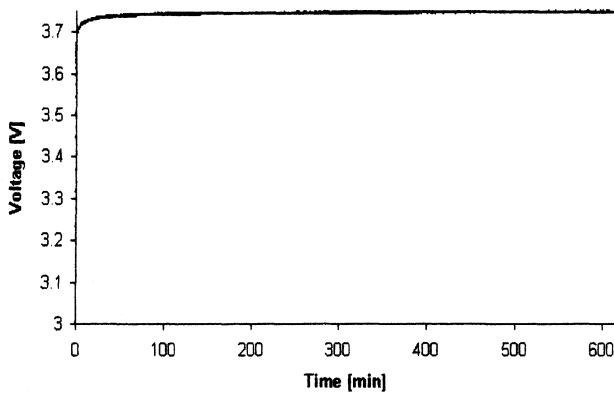

Fig. 2. Voltage relaxation after a discharge current step of 0.25 C-rate at 0% SoC and 0^0C.

Fig. 2 illustrates what happens to the battery voltage after a long discharge step. As can be seen during the transition process the battery OCV (Open-Circuit Voltage) doesn't instantaneously coincide with the EMF of the battery, but relaxes to it. Especially at low SoC and low temperature this may take a long time, see Fig. 2. The value of the OCV changes from 3 V directly after the current interruption to about 3.748 V after 615 minutes. It can be observed that the OCV is constant after about 200 minutes. The voltage after 30 minutes differs by approximately 15 mV from the voltage after 615 minutes. This means that when it is considered for this example that the equilibrium state is entered after 30 minutes, the inaccuracy into the SoC indication will be about 5%, as can be inferred from the most sensitive part of the EMF curve.

In the *discharge state*, the battery is discharged and a negative current larger than I_{lim} is flowing out of the battery. In addition to simple coulomb counting [1], [6] also the effect of the overpotential is considered. As will be shown in section IV of this paper the prediction of the overpotential yields also a remaining run-time prediction. Due to this overpotential, the battery voltage during the discharge state is lower than the EMF. The value of the overpotential depends on the discharge current, the SoC, age and temperature. Especially for old cells, at low temperatures and at low SoC, due to a high overpotential the remaining charge cannot be withdrawn from the battery, because the battery voltage will drop below the End-of-Discharge voltage defined in the portable device (e.g. 3 V). This leads to an apparent capacity loss, which at low temperatures of e.g. $0°C$ amounts up to more than 5% [1]. Hence, a distinction should be made between available charge in the battery (i.e. SoC) and the charge that can be withdrawn from the battery under certain conditions, expressed in remaining run-time. As overpotentials are temperature-dependent, temperature measurements are also needed in the discharge state. The overpotential model, in which the ohmic, kinetic, diffusion and increase of the overpotential when the battery becomes empty are considered, is modeled as follows:

$$\eta = I * \left[R_{\Omega k}(T) + R_{lk}(I,T) + (R_d^0(T) + R_d^l(I,T)) * (1 - e^{\frac{-c_1 \sqrt{t}}{\tau_d(T)}}) + \frac{(E_q^0(T) + \frac{E_q^l(I,T)}{I}) \cdot (1 - e^{\frac{-c_2 Q_{in}(t)}{\tau_q(T)}})}{Q_{in}(t)} \right] (6)$$

where $R_{\Omega k}(T), R_{lk}(I,T)$ denote the linear and nonlinear contributions to the "ohmic" and "kinetic" resistance in $[\Omega]$, $R_d^0(T)$ and $R_d^l(I,T)$ denote the linear and nonlinear contributions to the "diffusion" resistance in $[\Omega]$, c_1 is a constant in $[\sqrt{s}]$, $\tau_d(T)$ denotes the "diffusion" time constant in [s], $E_q^0(T)$ and $E_q^l(I,T)$ denote the linear and nonlinear measures of the energy that cannot be obtained from the battery when the current I increases in [J] and [JA] respectively and $Q_{in}(t)$ denotes the charge present in the battery at the time t in [C]. Finally, c_2 is a constant in [1/A] and $\tau_q(T)$ is a time associated with the increase in overpotential in an almost empty battery in [s] [1]. Simulation results of the mathematical overpotential implementation will be presented in section III.

In the *charge state*, a charger is connected to the battery and a positive current larger than I_{lim} is flowing into the battery. The SoC is determined by coulomb counting. The stable conditions of the charge state are used in order to adapt the system with the aging effect [3].

In summary, in which state the algorithm is operating depends on the value and sign of the current, which is flowing into or out of the battery and whether the battery voltage is stable. The state diagram illustrating the basic structure of the algorithm is shown in Fig. 3 [1],[3].
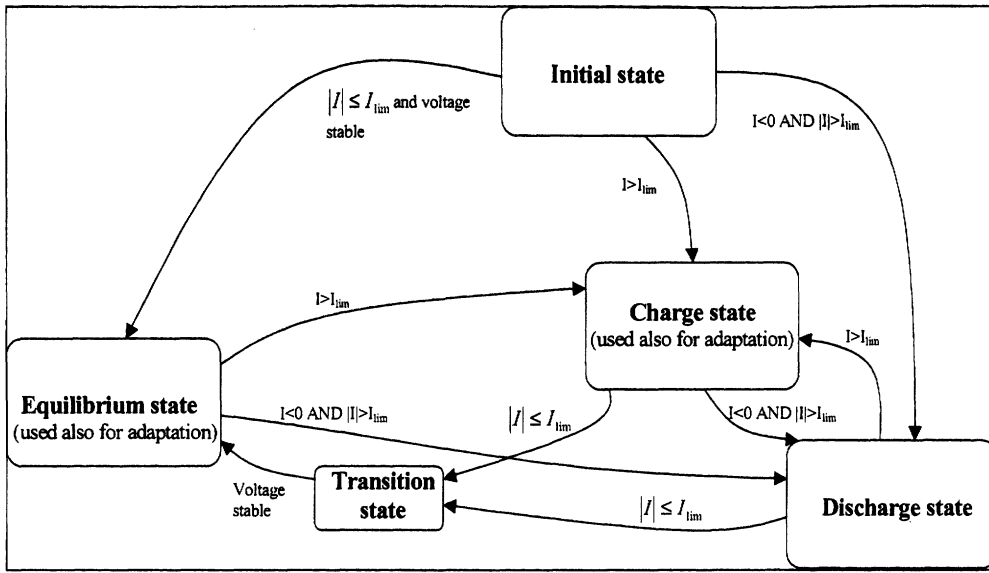
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Fig. 3. State diagram of the SoC algorithm [1], [3].

III. SIMULATION RESULTS OF THE ALGORITHM

As previously mentioned, the battery SoC is determined based on the SoC-EMF relationship during the *equilibrium state*. The results of the mathematical implementation of the EMF function in the SoC system will first be presented in this section.

The Sony US18500G3 Li-ion battery has been used throughout the experiments. The rated capacity of this battery is 1100 mAh. The EMF equations described in Section II of this paper need to be fitted to a measured EMF curve. Fig. 4 and 5 show that the fitted EMF curve used in the system fits the measured curve obtained with the Maccor battery tester very well at 25°C. In all the cases the SoC error is lower than 0.8% SoC. The SoC error has been obtained as the absolute value of the SoC difference at the same EMF voltage between the fitted curve and the curve obtained from the Maccor battery-tester measurements.
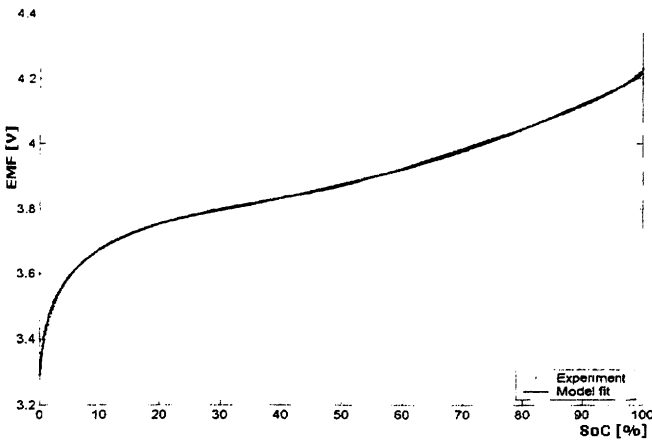

Fig. 4. EMF curve measured with Maccor battery tester and fitted EMF curve using the mathematical implementation at 25°C.
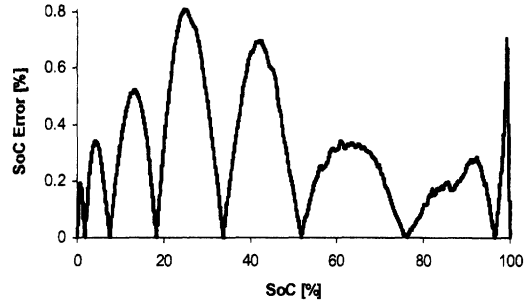

Fig. 5. Accuracy of the SoC indication using the measured EMF curve versus the fitted EMF curve (absolute values).

It can be concluded from Fig. 5 that the maximum error in SoC is obtained at around 25% SoC. This low SoC error (0.8%) corresponds to a low capacity value, which can still be removed from the battery (around 8.8 mAh). As can be calculated from (7), even for a fresh cell, at 25°C and at an *e.g.* 0.5 C-rate mean discharge rate C_{dschg} this implies around 1 minute of remaining run-time t_{rem}.

$$t_{rem}[min] = \frac{SoC[\%]}{100} * \frac{1}{C_{dschg}} * 60 \qquad (7)$$

Therefore, it can be concluded that the produced error due to the EMF implementation will generally provide us enough accuracy in order to achieve a final accuracy of 1 minute of the remaining run-time indication.

During the *discharge state*, apart from simple coulomb counting, also the effect of the overpotential is considered [3]. Based on the mathematical implementation of the overpotential described in Section II and the measured EMF, the measured and fitted overpotential at four different discharge current rates as a function of the relative SoC are illustrated in Fig. 6. The measurements have been carried out at 25°C.
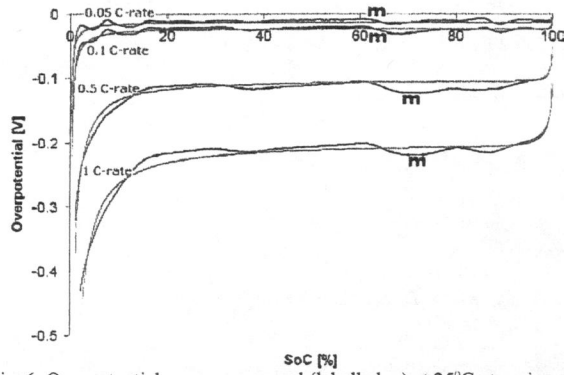
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Fig. 6. Overpotential curves measured (labelled *m*) at 25°C at various discharge rates (Maccor battery tester) and corresponding fitted results obtained from (6).
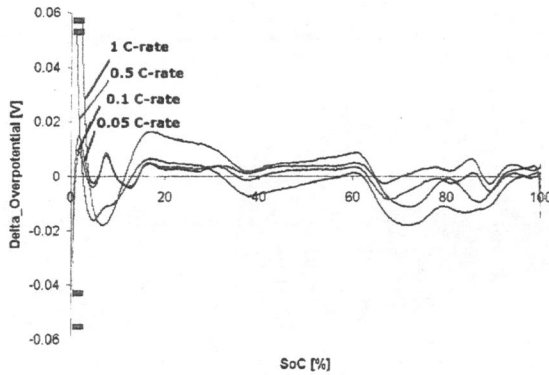

Fig. 7. Accuracy of the fitted overpotential curves versus the overpotential curves measured with the Maccor battery tester.

It can be concluded from Fig. 7 that the maximum difference between the measured and the fitted overpotential is obtained for the 0.1 C-rate discharge current at low SoC. In this situation, at 0.5% SoC the obtained difference has a value of around -55 mV. This voltage error corresponds to a low capacity value (SoC = 0.25% or 2.5 mAh), which still can be removed from the battery. Even for a fresh cell, at 25°C and at an *e.g.* 0.5 C-rate mean discharge rate this means that the SoC system will indicate around 18 seconds more remaining run-time than in the real case, see (7). In the majority of the cases a very good fit (under 10 mV difference) between the two curves is obtained.

It can be concluded that the produced error by the overpotential implementation will generally provide us enough accuracy in order to achieve a final accuracy of 1 minute of the remaining run-time indication.

IV. EXPERIMENTAL RESULTS OF THE ALGORITHM

Even though the EMF and the overpotential functions achieve good accuracy results, a performance analysis of the full SoC algorithm using a real-time laboratory set-up remains necessary in order to check the accuracy of the full algorithm.

In [3] the SoC indicator presented in this paper has been tested together with the bq26500 gas gauge IC by Texas Instruments to make a comparison. Using the *V*, *T* and *I* measurement inputs the bq26500 runs a book-keeping algorithm to calculate the SoC [8]. In conclusion, our indicator performs better for small and high discharge C-rates. However, our indicator made a slightly optimistic estimation whereas the TI indicator made a consistently very pessimistic estimation. Our aim is to predict the remaining run-time exactly or slightly pessimistically, which would be an important advantage in comparison with the TI gas gauge.

The tests presented in this paper have been limited to full charge/discharge cycles at different constant C-rates. The battery has always been fully charged until 4.2 V with the normal Constant-Current-Constant-Voltage (CCCV) charging method [1] at 0.5 C-rate in CC mode. In the CV mode the voltage has been kept constant at 4.2 V until the current reached a 0.05 C-rate value. At the end of the CV mode a SoC level of 100% has been defined. Each step of charging has been followed by a rest period of about 35 minutes. After this rest period a discharge step until the battery voltage reached 3 V at different constant C-rates of 0.1, 0.25, 0.5, 0.75 and 1 C-rate, respectively has been applied.

The Sony US18500G3 Li-ion battery has been used throughout the tests. At the time of testing, the battery was fairly new, with approximately 10 discharge/charge cycles in its history. The battery capacity has been learned during the first charge cycle by using the method described in [3]. A maximum capacity of 1176 mAh has been obtained. All the experiments have been carried out with the same battery and at 25°C.

An important advantage of the presented SoC indicator is that based on coulomb counting during the *charge state* and based on coulomb counting and the overpotential function for the *discharge state* a remaining run-time indication is provided.

In Table 1 the experimental results are summarized. Column one gives the discharge C-rates of the tests. The remaining run-time of the SoC indicator in hours, minutes and seconds predicted at the start (t_{r_s}) and indicated at the end (t_{r_e}) of the tests, is given in columns two and three, respectively. Columns four and five denote the absolute error in the remaining run-time t_{r_er} and the SoC indication at the end of the experiment. The absolute error of the remaining run-time indication is calculated as the absolute difference between the t_{r_s} and the time at which the system reaches the 3-V End-of-Discharge voltage level.

TABLE 1. MEASURED RUN-TIME AND SOC ACCURACY FOR THE SOC SYSTEM.

C-rate	t_{r_s} [h:m:s]	t_{r_e} [h:m:s]	t_{r_er} [h:m:s]	SoC_e [%]
0.1	10:34:41	0	00:03:51	0
0.25	04:13:34	0	00:02:10	0
0.5	02:06:29	0	00:01:00	0
0.75	01:24:01	00:00:25	00:00:25	0.5
1	01:02:42	00:00:09	00:00:09	0.2

Let us consider for example the 0.5 C-rate case. At the start of discharge, the system indicated 2 hours 6 minutes and 29 seconds remaining run-time. After 2 hours, 7 minutes and 29 seconds the battery reached the level of 3 V, which means that the inaccuracy of the SoC system is 1 minute. For the 1 C-rate situation the presented SoC indicator makes a slightly optimistic estimation. At the start of discharge, the system indicated 1 hour, 2 minutes and 42 seconds remaining run-time. After 1 hour, 2 minutes and 33 seconds the battery reached the level of 3 V, which means that the inaccuracy of the SoC system is 9 seconds. It can it can be concluded from Table 1 that we generally achieved our goal of providing a final accuracy of 1 minute of the remaining run-time indication.

V. CONCLUSIONS

A new State-of-Charge (SoC) indication algorithm has been presented, which calculates the SoC in percent, as well as the remaining run-time for a portable application.

A particular method used for the presented SoC indication scheme is the EMF method. The advantage of this method is that the EMF curve does not depend on many parameters. The main drawback of the EMF method is that it does not provide continuous indication of the SoC. Therefore the proposed SoC system also uses coulomb counting and overpotential prediction.

As has been shown in this paper significant improvement of the fitting results compared to [1], [3] of overpotential function have been obtained. These improvements give a prediction of the remaining run-time generally better than one minute.

In the near future, we plan to reduce the required rest period for the EMF determination and to predict this value already during the transitional state. Also, more tests at different conditions (*e.g.* different temperatures, C-rates and aged batteries) will be carried out in order to improve the accuracy of the novel presented method of SoC indication.

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