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A REAL-TIME EVALUATION SYSTEM FOR A STATE-OF-CHARGE INDICATION ALGORITHM

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Abstract — The known methods of State-of-Charge (SoC) indication in portable applications are not accurate enough under all practical conditions. This paper describes a real-time evaluation LabVIEW system for an SoC algorithm, that calculates the SoC in [%] and also the remaining run-time available under the valid discharge conditions. With the described system the accuracy of the SoC algorithm and its validity can be determined. The final goal of the SoC algorithm is to predict 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. The basis of the SoC algorithm is current measurement and integration during charge and discharge state and voltage measurement during equilibrium state. Experimental results show the testing ability of the real-time evaluation system and the effectiveness of the novel approach for improving the accuracy of the SoC indication.

Keywords: Li-ion batteries, State-of-Charge, portable energy.

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.

Accurate State-of-Charge and remaining run-time indication for portable devices is important for the user-convenience and to prolong the lifetime of batteries. This paper describes a real-time evaluation LabVIEW system for an SoC algorithm, that calculates the SoC in [%] and also the remaining run-time available under the valid discharge conditions. With the described system the accuracy of the SoC algorithm and its validity can be determined.

The SoC is the percentage of the maximum possible charge that is present inside the battery [1]. The basis of the SoC algorithm is current measurement and integration during the charge and discharge states and voltage measurement during the equilibrium state [1-3].

This paper is organized as follows. The states of the real-time evaluation system are introduced in section II. The real-time evaluation system set-up is presented in section III. Section IV focuses on the obtained experimental results. Finally, section V presents the concluding remarks and future work.

II. STATES OF THE REAL-TIME EVALUATION SYSTEM

This paper presents a real-time evaluation LabVIEW system for an algorithm that predicts the SoC of a battery. A more detailed presentation of the SoC algorithm can be found in [1-3]. The system's estimations are presented to the user in the form of a value of SoC expressed in [%] and also in the form of the remaining run-time available under the valid discharge conditions.

The proposed real-time evaluation system operates in six different states [1-3]: *initial state, standby state, transitional state, charge state, discharge state* and *backlight-on state*. A brief description of each state of the system will be given below.

Each time the system is switched-on, it starts from the *initial state*. In this state the initial SoC is determined based on voltage and temperature measurements and the stored SoC-EMF (Electro-Motive-Force) relationship [1-3]. This initial SoC is shown to the user, as it is assumed unacceptable that the user has to wait more than say a few seconds after the real-time evaluation system has been switched-on to check the available capacity. The advantage of this method is that the EMF curve does not depend on many parameters. It does not depend on aging and only to a limited extent on the temperature of the battery, so it is a good candidate for SoC indication [1]. Dependent on whether the battery is charged, discharged or in equilibrium, the system then shifts to the appropriate state.

In the *standby state* hardly any current is drawn from the battery. This situation occurs when a battery is in equilibrium [1-3]. The mean current in this case is only a few mA, which is lower than a small mean current defined in the system (*e.g.* 2 mA mean current in a mobile phone application). For this very low mean current value, the battery voltage is very close to the EMF value, under the condition that the voltage is stable [1]. Therefore, in order to allow the system 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 and temperature measurements and the stored SoC-EMF relationship. From this state the system is able to switch to the *charge, discharge,* or *backlight-on states.*

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

In the *charge state*, a charger is connected to the battery and a positive current larger than the standby current is flowing into the battery. The SoC is determined by coulomb counting [1-4]. The stable conditions of the *charge state* are used in order to adapt the system with the aging effect [1-3]. At the end of the *charge state*, the system passes through the *transition state* to the *standby state*.

In the *discharge state*, the battery is discharged and a negative current, larger in module than the standby current, is flowing out of the battery. In addition to simple coulomb counting [1-4] also the effect of the overpotential is considered. The prediction of the overpotential yields also a remaining run-time prediction [1-3]. At the end of *the charge state,* the system passes through the *transition state* to the *standby state.*

In the *backlight-on state* the battery is discharged and a small negative current is flowing out of the battery. Because the current is still below a certain limit value the SoC can be determined based on voltage and temperature measurements and the stored SoC-EMF relationship [1-3]. The system remains in this state for about 5 seconds (an arbitrary chosen value) before it passes in the *standby state*. During these 5 seconds, all other transitions remain possible.

In summary, in which state the system 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 or not. The state diagram illustrating the basic structure of the real-time evaluation system is shown in Fig. 1, where the backlight-on state has not been included [1].

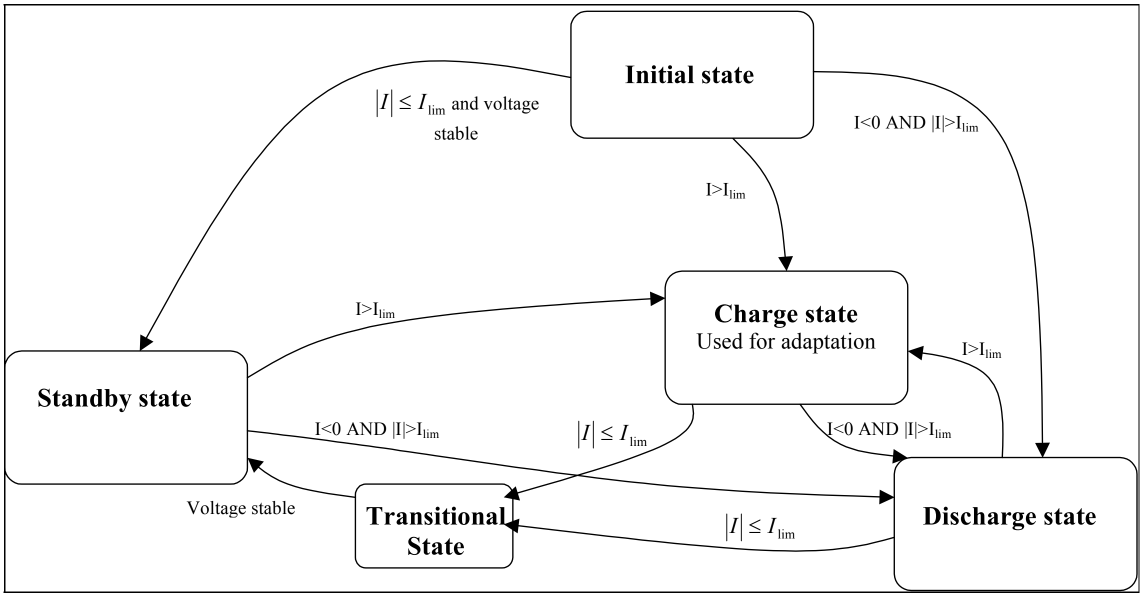


Fig. 1. State diagram of the real-time evaluation system.

III. A REAL-TIME EVALUATION SYSTEM

A performance analysis of the full SoC algorithm using a real-time laboratory set-up is necessary in order to check the accuracy of the full algorithm. A real-time evaluation system set-up has been designed containing a computer with a National Instruments (NI) Data Acquisition interface card, a SCB-68 National Instruments connector board, a 20 mΩ sense resistor, a Keithly 2420 3A Source Meter device for (dis)charging the battery, a temperature box that can keep the battery at a constant temperature between -35˚C and 65˚C, a National Semiconductor precision temperature sensor with ±1°C accuracy connected to the SCB-68 board, a Li-ion US18500G3 battery from Sony and a safety box used as a device to prevent over(dis)charge of the battery. The block diagram of the real-time operation system is given in Fig. 2, where the PC and temperature box have not been included.

The battery voltage, current and temperature have to be monitored and the safety box has to be controlled to ensure that the battery is never operated in an unsafe region. The SCB-68 board is a shielded board with 68 screw terminals for easy connection to NI 68-pin products. The temperature sensor connections are indicated as 'T'.

The voltage and current measurements are performed using a bipolar 16-bit Analog-to-Digital Converter (ADC). The ADC offset depends on the chosen voltage range. For the voltage measurements a range of +/- 5 V that respects the voltage of the Li-ion batteries [1] has been chosen. In this range the ADC has an offset value V_{off} of +/- 0,8 mV [5]. Based on (1) an absolute voltage accuracy at full scale A_{Vabs} of 1,75 mV has been obtained.

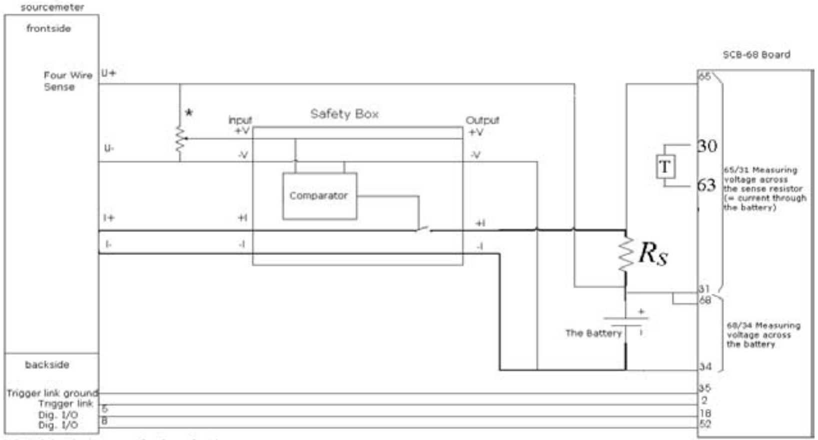
$$A_{Vabs}[mV] = 2 * V_{off} + \frac{V_{fullscale}}{2^N} = 1,75 \qquad (1)$$

where $V_{fullscale}$ denotes the full scale range of the ADC voltage and N denotes the number of ADC bits.

Typically, the current is measured by measuring the voltage across a sense resistor R_S, connected in series with the battery system. This current is integrated over time and used to determine the SoC of the battery system. The larger current levels require substantially lower R_S values and higher power dissipation ratings. In the described design an R_S value of 20 mΩ has been chosen. The low resistance value of R_S results in a very small voltage drop across the shunt that must be measured in order to determine the charge and discharge current in the battery system. Since the function of the battery monitoring system is to provide a time integration of the battery current in order to track the battery SoC, even small errors in the measurement of the current can cause large errors in the SoC measurement to accumulate over time (one of the common errors when the signals to be measured are really small is the offset of the current measurement device). For the current measurements a range of +/- 2,5 A that corresponds to an +/- 50 mV voltage range has been chosen. In this situation the ADC has an offset value V_{off} of +/- 0.029 mV [5]. Based on (2) the absolute voltage accuracy for current measurements at full scale A_{Vabs} can be calculated:

$$A_{Vabs}[mV] = 2 * V_{off} + \frac{V_{fullscale}}{2^N} = 0,06 \qquad (2)$$

In conclusion, the described LabVIEW system is able to provide all the required functions, *e.g.* the application of (dis)charge currents and measurements, in order to test the SoC algorithm.



* Switch level adjustment for the safety box

Fig. 2 Design of the real-time evaluation system [6].

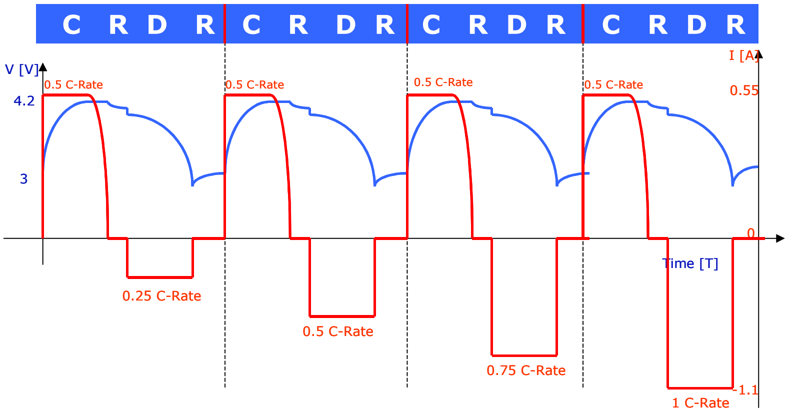


Fig. 3. Tests carried out with the real-time evaluation system.

IV. EXPERIMENTAL RESULTS OF THE SYSTEM

Set of tests has been carried out with the described set-up in order to demonstrate the SoC algorithm accuracy and validity. The tests have been limited to full charge (C)/discharge (D) cycles at different constant C-rates, see Fig. 3. A C-rate is defined as a charge or discharge current equal in Amperes to the rated capacity in Ah [1]. 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, see Fig. 3. 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 an SoC level of 100% has been assumed. Each period of charging has been followed by a rest (R) period of about 35 minutes. After this rest period a discharge step is applied until the battery voltage reached 3 V. This procedure has been repeated at different constant C-rates of 0,25, 0,5, 0,75 and 1 C-rate, respectively. All the experiments have been carried out with the same battery at 25^{0}C and 45^{0}C, respectively.

The Sony US18500G3 Li-ion battery has been used throughout the tests. At the time of testing, the battery was fairly new, with approximately 14 discharge/charge cycles in its history. The battery capacity has been "learned" during the charge cycles by using the method described in [3]. First, an arbitrary maximum capacity Q_{max} of 600 mAh has been programmed into the system. Then, starting from the equilibrium state and a calculated initial SoC, SoC_{Ei}, the battery is charged with 1170 mAh, 1161 mAh and 1148 mAh capacity, respectively. Each charge state was followed by a rest period in which the algorithm was allowed to enter the equilibrium state. In this state a final SoC, SoC_{Ef} value has been calculated. Based on the obtained results and (3) a new Q_{max} value have been calculated. Table 1 shows the obtained results.

$$Q_{\max}[mAh] = \frac{100}{(SoC_{E_f} - SoC_{E_i})} * Q_{chg} \tag{3}$$

TABLE 1. "Learning" of maximum capacity results

SoC_{Ei} [%]	SoC_{Ef} [%]	Q_{chg} [mAh]	Q_{max} [mAh]
0,5	100	1170	1176
1,97	100	1161	1178
2,4	100	1148	1176

As can be seen in Table 1, the correct calculated maximum capacity obtained from a full charge has a value of 1176 mAh. It can be concluded from these tests that in all of the cases the Q_{max} adaptation mechanism will generally provide us with enough accuracy in order to achieve a final accuracy better than 2 mAh capacity, or better than 0,1% SoC.

TABLE 2. Experimental results of the real-time evaluation system

C-rate	Temperature											
	25^{0}C						45^{0}C					
	SoC_s [%]	SoC_e [%]	SoC_{er} [%]	t_{r_s} [h:m:s]	t_{r_e} [h:m:s]	t_{r_er} [h:m:s]	SoC_s [%]	SoC_e [%]	SoC_{er} [%]	t_{r_s} [h:m:s]	t_{r_e} [h:m:s]	t_{r_er} [h:m:s]
0,25	100	0	0.9	04:13:34	0	00:02:16	100	0	0,4	04:13:34	0	00:01:05
0,5	100	0	0,9	02:06:29	0	00:01:06	100	0	1,7	02:06:29	0	00:02:11
0,75	100	0,5	0,5	01:24:01	00:00:25	00:00:25	100	0	2,9	01:24:01	0	00:02:22
1	100	0,2	0,2	01:02:42	00:00:09	00:00:09	100	0	3,9	01:02:42	0	00:02:28

In Table 2 the experimental results are summarised. Column 1 gives the discharge C-rates of the tests. The SoC in [%] indicated at the start SoC_s, at the end SoC_e, and the absolute error of the SoC indication SoC_{er} of the tests carried out at 25^0C, is given in columns two, three and four, respectively. Columns five, six and seven denote the remaining run-time in hours, minutes and seconds at the start t_{r_s}, and end t_{r_e} of the experiment and the absolute error in the remaining run-time t_{r_er} of the experiment carried out at 25^0C. The absolute error is calculated as the absolute difference between the indicated value at the start and the value at which the system reaches the 3-V End-of-Discharge voltage level. The same notations for the tests carried out at 45^0C are indicated in the columns 8 to 13.

Let us consider for example the 1 C-rate, 25^0C case. In this situation the SoC indicator makes a slightly optimistic estimation. At the start of discharge, the system indicated 100% SoC and 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 and the system indicated 0,2% SoC. This means that the inaccuracy of the SoC system is 0,2% in SoC and 9 seconds in remaining run-time.

It can be concluded from Table 2 that the obtained SoC indication accuracy is generally better than 2% and the remaining run-time is always better than three minutes. Further improvements will be carried out in order to improve the SoC and remaining run-time system accuracy and to achieve the goal of one-minute accuracy.

IV. CONCLUSIONS

A real-time evaluation LabVIEW system for an algorithm, which calculates the State-of-Charge in percent, as well as the remaining run-time for a portable application has been discussed in this paper. With the described system the accuracy of the SoC algorithm presented in [1-3] and its validity was proved.

As shown during this paper the real-time evaluation LabVIEW system is able to provide all the required functions, *e.g.* the application of (dis)charge currents and measurements, in order to test the SoC algorithm. Experimental results proved the validity of the real-time operation system and the effectiveness of the presented novel approach for improving the accuracy of the SoC indication.

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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