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UNCERTAINTY ANALYSIS IN A REAL-TIME STATE-OF-CHARGE EVALUATION SYSTEM FOR LITHIUM-ION BATTERIES

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Abstract: Lithium-ion (Li-ion) is the most commonly used battery chemistry in portable applications nowadays. Accurate State-of-Charge (SoC) and remaining run-time (t_r) calculation for portable devices is important for the user convenience and to prolong the lifetime of batteries. A new SoC algorithm for Li-ion batteries that combines adaptivity with direct measurement and book-keeping systems has been developed and implemented in a real-time evaluation system.

In this paper the error sources in the real-time SoC evaluation system with possible calibration solutions are described. The goal of the SoC system is to predict the remaining run-time of a Li-ion battery with an uncertainty of 1 minute or better under all realistic user conditions, including a wide variety of load currents and a wide temperature range.

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

1. INTRODUCTION

Providing accurate SoC and t_r indication is difficult due to spread in battery and user behaviour, aging, large range of load current and temperature (application dependent) and different battery chemistries. A new SoC algorithm that combines adaptive systems with the battery Electro-Motive Force (EMF) measurement during the equilibrium state and coulomb counting (cc) [1]-[8] during the charge and discharge states, has been developed and implemented in a real-time evaluation system [1]-[5]. During the discharge state apart from the cc also the effect of the battery overpotential (η) is considered. Experimental results showed the testing ability of this SoC evaluation system and the effectiveness of the novel approach for improving the remaining run-time indication accuracy [3]. As will be shown in this paper the identification and better understanding of the error sources is useful for continuously improving the SoC and the t_r calculation accuracy.

In the real-time SoC evaluation system discussed in this paper the system's estimations are calculated in the form of a value of SoC expressed in [%] and also in the form of a t_r expressed in [min] available under the valid discharge conditions. The SoC is defined as the percentage of the maximum capacity Q_{max} of a rechargeable battery [1]-[4]. By means of the SoC calculation and battery overpotential prediction the remaining run-time available under the valid discharge conditions is indicated to the user. The predicted battery overpotential expressed in [V] can be translated in a SoC percentage value SoC_l [%] by using an SoC-EMF model EMF_m stored in the SoC evaluation system. As a result the remaining run-time [min] will be inferred from SoC [%], SoC_l [%], Q_{max} [mAh] and from the measured discharge current I_d [A]. More information regarding the remaining run-time calculation will be given in section 2.

This paper is organized as follows. The method of implementing the states of the real-time SoC evaluation system is introduced in section 2. Section 3 identifies the error sources in each state of the SoC evaluation system. The focus in section 4 is on the SoC and t_r uncertainties. Finally, section 5 presents concluding remarks and future work.

2. STATES OF THE SYSTEM

This paper presents the error sources in a real-time evaluation system for an algorithm that predicts the SoC and the t_r for a Li-ion battery. In this section a brief description of the SoC evaluation system implementation will be given. For a detailed description of the SoC algorithm the reader is referred to [1]-[4], [6], [8], [9]. The real-time SoC evaluation system operates in six different states: initial state, standby state, backlight-on state, transitional state, charge state and discharge state.

Each time the evaluation SoC system is switched-on, it starts from the initial state. The SoC in the initial state SoC_{in} is determined by means of voltage (V) and temperature (T) measurements and the stored EMF_m. Dependent on whether the battery is charged, discharged or in equilibrium, the system then switches 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. The SoC in the standby state SoC_s is determined by means of V and T measurements and the stored EMF_m. The current in the standby state I_s is only a few mA, *e.g.* 1 mA current in the SoC evaluation system described in this paper, which is lower than a limit current I_{lim} defined in the SoC evaluation system, *e.g.* 10 mA current. For this very low standby 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. From this state the system is able to switch to the charge, discharge, or backlight-on states.

In the backlight-on state a small negative current I_b, *e.g.* 6 mA current in the SoC evaluation system described in this paper, is drawn from the battery. This situation occurs when the user activates the screen of the SoC evaluation system. Because the current is still below I_{lim}, the SoC is determined by means of V and T measurements and the stored EMF_m. The SoC evaluation 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 to the charge or discharge states remain possible.

It can be concluded from the above presented implementation method that in the initial, standby and backlight-on states the SoC is calculated by means of V and T measurements and the stored EMF_m.

The transitional state is used when the system changes from either the charge or the discharge state to the standby state. In this state a small negative current I_s is drawn from the battery. Because the battery voltage is not stable the SoC in the transitional state SoC_t is determined by means of cc. In this state it is determined whether the battery voltage reached a stable value, *i.e.* the EMF and the system is allowed to enter into the standby state. The EMF detection method EMF_d will not be discussed in this paper. For a description of this method the reader is referred to [10].

In the charge state, a charger is connected to the battery and a positive current larger than the I_{lim} flows into the battery. The SoC in the charge state SoC_{ch} is determined by means of cc. The stable conditions of the charge state are exploited to adapt the Q_{max} with the aging effect [8]. More information on the used Q_{max} adaptation method will be given in section 3.

In the discharge state, the battery is discharged and a negative current larger in module than the I_{lim} flows out of the battery. The SoC in the discharge state SoC_d is determined by means of cc. In addition to SoC_d, t_r available under the discharge conditions is also calculated during the discharge state. As a result in addition to simple cc also the effect of the battery overpotential is considered for the remaining run-time calculation. The predicted battery overpotential is translated in a SoC percentage value SoC_l [%] by using the EMF_m. As a result t_r [min] is inferred from SoC_d [%], SoC_l [%], Q_{max} [mAh] and I_d [A] as follows

$$t_r\,[\text{min}] = \frac{0.06\dfrac{Q_{\max}}{100}\left(SoC_d - SoC_l\right)}{I_d} \tag{1}$$

At the end of the discharge state, the system passes through the transitional state to the standby state.

It can be concluded from the above presented implementation method that in the transitional, charge and discharge states the SoC is calculated by means of cc. During the discharge state in addition to cc the overpotential is also predicted for the t_r calculation.

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 SoC evaluation system is shown in Fig. 1, where the backlight-on state has not been included [1], [3].

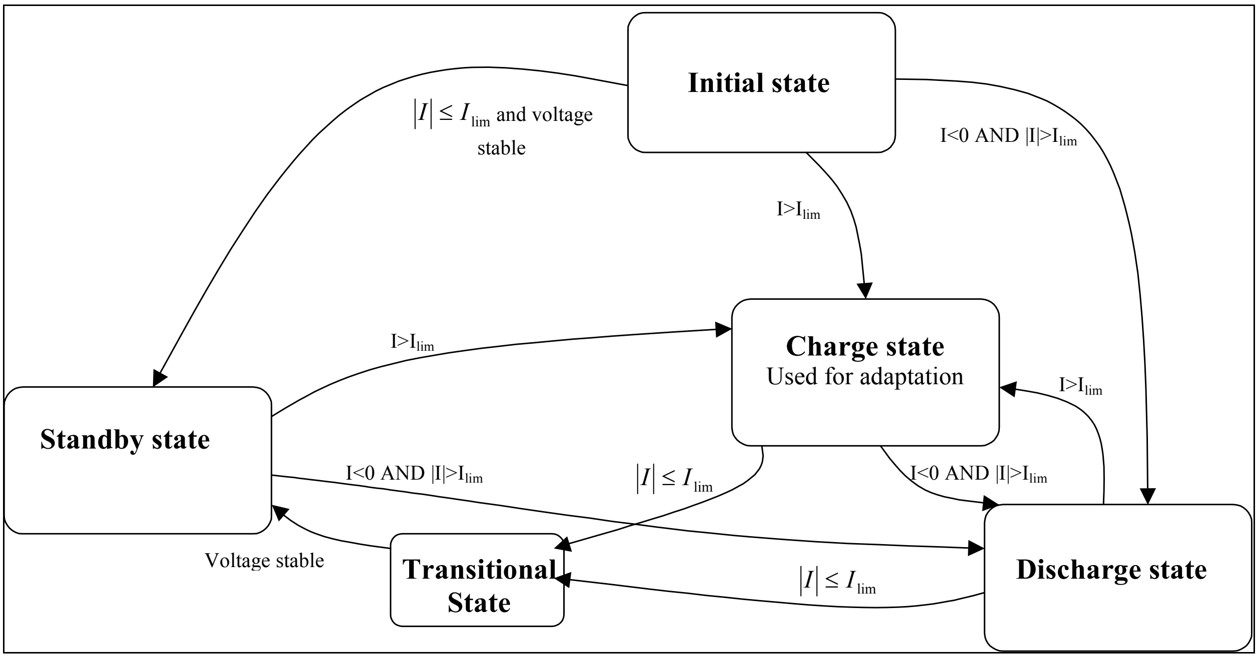

Fig. 1 State diagram of the real-time SoC evaluation system

3. UNCERTAINTY ANALYSIS

No matter which precautions are taken, there will always be a difference between the measurement result and the true (but unknown) value of a quantity. In order to enable accurate SoC and t_r calculation the error sources in each state of the SoC evaluation system must be identified and minimized. In this paper measurement uncertainty refers to a qualification of the expected closeness of the measurement result and the true value [5]. The error sources in the SoC system states will be further identified in this section.

As mentioned in section 2, during the initial state the battery SoC is calculated by means of V and T measurements and the stored EMF_m. Accurate EMF-SoC curves are obtained by measurements with a Maccor battery tester [11], and further implemented in the Battery Management System (BMS) using a physical EMF-SoC model [1]-[4]. The voltage (V_M), current (I_M), temperature (T_M) and time (t_M) Maccor measurements are considered as reference measurements. It has been observed from repeated measurements and tests that the error sources introduced by the spread, the EMF fitting and detection methods used during the Maccor measurements [10] in the EMF_m are very small and as result will be further neglected from the SoC and t_r uncertainties calculation. Also the error source introduced by the aging effect in the EMF-SoC model will not be considered in this paper for simplicity.

The implementation result of the EMF_m for a Li-ion battery in the SoC evaluation system as function of three temperatures is shown in Fig. 2.

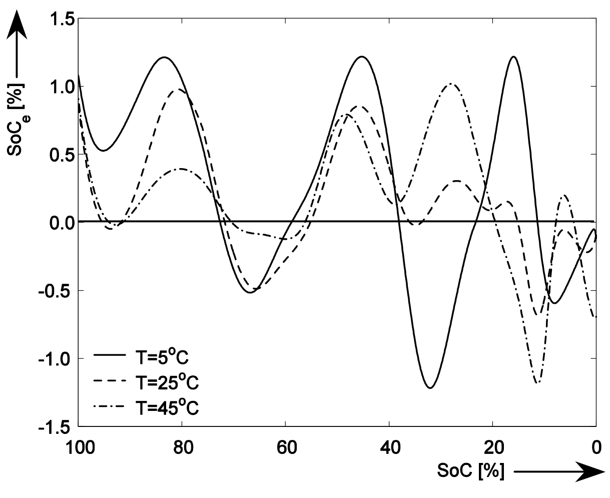

Fig. 2 Accuracy of the SoC calculation using the measured EMF curve versus the modelled EMF curve at 5°C, 25°C and 45°C. The horizontal axis shows the SoC [%] normalized to the maximum capacity [10].

Fig. 2 shows that the modelled EMF curve implemented in the SoC evaluation system reveals a good fit with the measured EMF curve obtained with the reference battery tester at 5°C, 25°C and 45°C. The SoC error SoC_e has been calculated as a difference between the true SoC value determined by means of the measured EMF and the SoC value determined by means of the modelled EMF. It can be concluded that a maximum error of 1.2% in SoC, is obtained for 5°C at different SoC levels, *e.g.* 16%, 32%, 46% and 84% SoC, respectively (see Fig. 2).

During the initial state it is considered that the battery voltage has a stable EMF value. However, when the SoC evaluation system is switched-on a current larger in module than the limit current may flow or may have just flowed into or out of the battery. As a result the battery voltage may have not been stable and an error in the SoC_i calculation might be introduced. The SoC evaluation system presented in this paper is designed with a bipolar 16-bit Analog-to-Digital Converter (ADC) for measuring the voltage (V) [12]. The absolute voltage accuracy at full-scale has a value of 1.75 mV [3], [12]. It has been observed from repeated measurements and tests that the error sources from the temperature and time t measurements from the SoC evaluation system are very small and as a result will be further neglected from the SoC and t_r uncertainties calculation.

During the standby state the battery is considered in equilibrium and the SoC is calculated by means of V and T measurements and the stored EMF_m. However, during the standby state a 1 mA current is drawn from the battery. As a result the battery voltage will not be stable and an error source in the SoC_s calculation will be introduced.

In the backlight-on state the SoC is determined based on V and T measurements and the stored EMF_m. However, during the backlight-on state a 6 mA current is drawn from the battery. As a result the battery voltage will not be stable and an error source in the SoC_b calculation will be introduced.

It can be concluded from Fig. 2 and the situations described above that the main error sources in the SoC calculation during the initial, standby and backlight-on states are the errors from the EMF_m and from the battery voltage measurement.

During the transitional state the voltage is not stable and a small current, *i.e.* I_s, is drawn from the battery. As a result the SoC_t is calculated by means of current measurements and integration, *i.e.* coulomb counting. The SoC evaluation system presented in this paper is designed with a bipolar 16-bit Analog-to-Digital Converter (ADC) for measuring the current [12]. The current is measured by measuring the voltage drop across a 20 mΩ sense resistor connected in series with the battery [3]. The absolute voltage accuracy for current measurements at full scale equals 0.06 mV [3], [12].

During the charge state a positive current is flowing into the battery. The SoC in the charge state SoC_{ch} is determined by cc. In order to translate Q_{ch} [mAh] measured by means of cc into SoC_{ch} [%], Q_{max} must also be known.

In the discharge state, the battery is discharged and a negative current larger in module than the I_{lim} current flows out of the battery. SoC_d is determined by means of cc. In addition to SoC_d, t_r available under the discharge conditions is also calculated during the discharge state. As shown in Eq. (1) the remaining run-time is inferred from SoC_d, SoC_l, Q_{max} and I_d. As a result in addition to simple cc also the effect of the battery overpotential must be considered for the t_r calculation. Accurate overpotential curves are obtained by measurements with the Maccor battery tester and further implemented in the Battery Management System (BMS) using a model inferred from physical models previously developed [1]-[4], [13]. It has been observed from repeated measurements and tests that the error source from spread in the overpotential model (η_m) calculation is very small and as a result will be further neglected from the remaining run-time uncertainty calculation. Also the error source introduced by the aging effect in the η_m will not be considered in this paper for simplicity.

Fig. 3 shows the implementation result of the overpotential model for a Li-ion battery in the SoC evaluation system, for four discharge current C-rates, *i.e.* 0.05, 0.1, 0.5 and 1 C-rate [10]. It can be concluded that the maximum difference between the measured and the fitted overpotential occurs at 0.1 C-rate discharging current and at low SoC. In this situation, at 0.56% SoC the obtained difference has a value of around –100 mV. This voltage error can be translated in a SoC_l error by using the EMF_m. In this example a SoC_l error of 0.25% can be calculated.

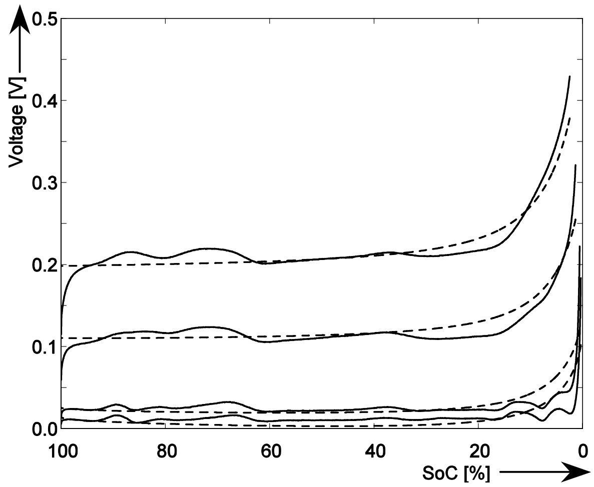

Fig. 3 Overpotential curves measured (solid) at 25°C at various discharge rates and corresponding fitted curves (dashed) obtained from the mathematical implementation. The smalest overpotential curve is obtained for the smallest 0.05 C-rate discharge current. The horizontal axis shows the SoC [%] normalized to the maximum capacity [10].

A first conclusion is that the main error source in the SoC calculation during the transitional, charge and discharge states is the error from the cc. A second conclusion regards the t_r calculated during the discharge state. It can be concluded from Eq. (1) and the situations described above that the main error sources in the t_r calculation during the discharge state are the errors from the SoC_l, Q_{max} and from the current measurement and integration.

Any battery will lose capacity during cycling. In order to enable accurate SoC and t_r calculation and to improve the SoC evaluation system capability to cope with the aging effect, a simple Q_{max} adaptation algorithm will be further presented. In this algorithm the stable conditions of the charge state are exploited in order to adapt Q_{max} with the aging effect [4], [8]. Fig. 4 shows the used update method of the maximum capacity. Apparently, for the update mechanism it is necessary for the SoC evaluation system to run through a sequence of states: standby state, charge state, transitional state and standby state. A new value of the Q_{max} follows from Fig. 4 and Eq. (2).

$$Q_{\max} = \frac{100}{SoC_{sf} - SoC_{si}} Q_{ch} \tag{2}$$

where SoC_{si} and SoC_{sf} denote the initial and final SoC_s in [%]and Q_{ch} denotes the amount of charge flowing into the battery during the charge state in [mAh]. It follows from Eq. (2) that the error sources in the Q_{max} calculation are the errors from SoC_s and Q_{ch}.

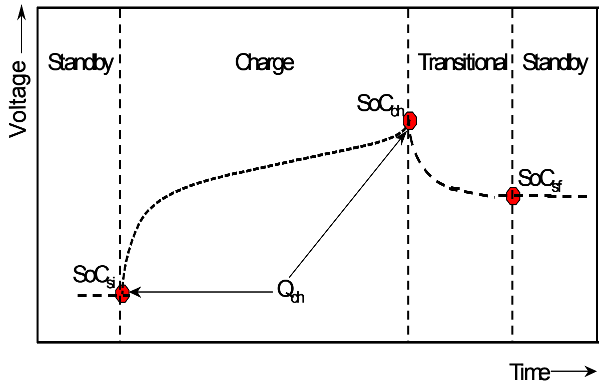

Fig. 4 Method for updating Q_{max} to take capacity loss into account [4], [8]. The horizontal axis shows the time.

In summary the SoC and t_r calculation uncertainties depend on the state for which the SoC evaluation system operates. Fig. 5 illustrates a diagram with the SoC evaluation system error sources. The single-line blocks denote the error sources from the on-line measurements obtained with the SoC evaluation system, the grey blocks denote the error sources from the used models and from the off-line measurements, the dashed and the double-line blocks denote the error sources that have not been considered and the error sources that have been neglected from the SoC and from the t_r uncertainties calculation, respectively. Finally the round blocks denote the error sources from the on-line measured variables used as input for the models calculations.

4. THE REMAINING RUN-TIME UNCERTAINTY

A particular test example at 25°C for the SoC and t_r uncertainties calculation will be considered in this section. The US18500G3 Li-ion battery from Sony has been used through this test. The rated capacity of this battery type is 1100 mAh [2]. At the time of testing, the battery was fairly new, with approximately 8 cycles in its history.

At the beginning of the test the SoC evaluation system has been switched-on and the initial state has been entered (see Fig. 1). In this state a battery voltage of 3.01 V and a battery temperature of 25°C have been measured. Based on these measurements and the stored EMF_m a SoC_i value of 0% has been calculated.

After a short rest period in which the battery voltage and temperature have been continuously monitored the SoC evaluation system has switched to the standby state (see Fig. 1). In this state a SoC_s of 0% has been calculated by means of V and T measurements and the stored EMF_m.

A 0.5 C-rate positive current has been further applied to the battery and the SoC evaluation system has switched to the charge state (see Fig. 1). During this state the battery has been fully charged with the normal Constant-Current-Constant-Voltage (CCCV) charging method [1] at a 0.5 C-rate charging current. In the CV mode the voltage has been kept constant at 4.2 V until the current reached a 0.05 C-rate value. The SoC during the charge state SoC_{ch} has been calculated as follows

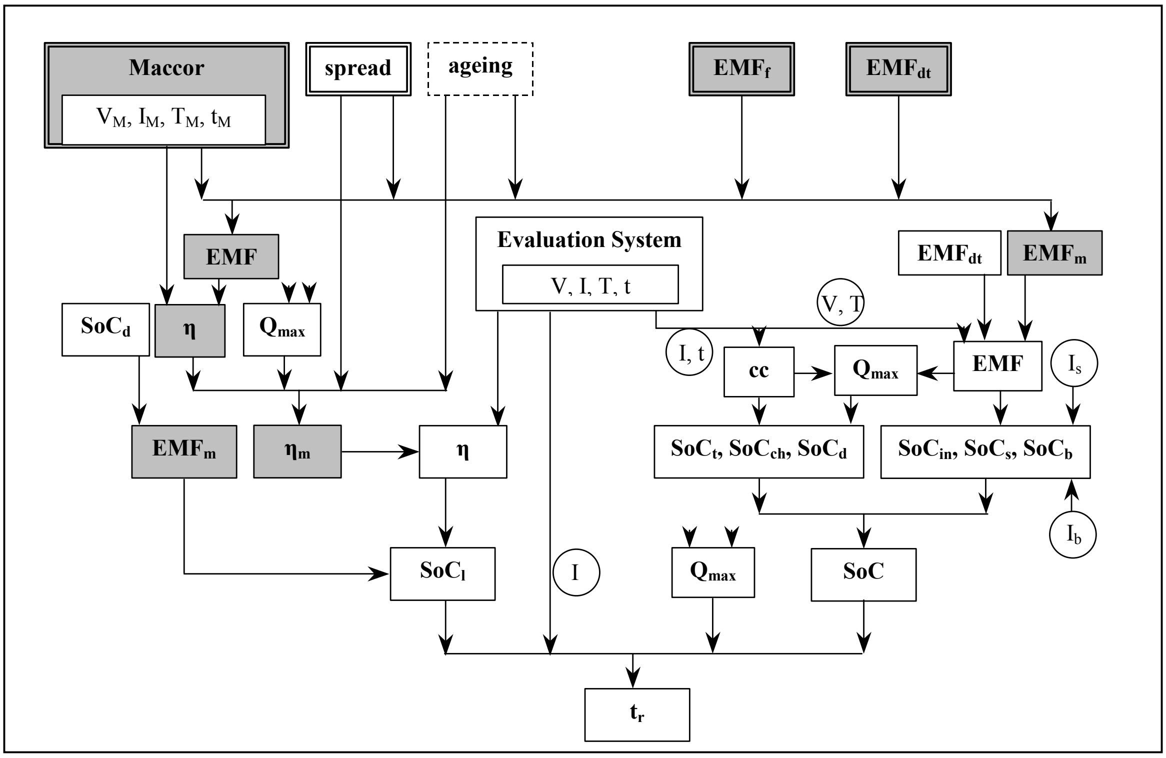

Fig. 5 Schematic representation of the error sources in real-time SoC evaluation

$$SoC_{ch} = SoC_s + 100\frac{Q_{ch}}{Q_{\max}} \quad (3)$$

During the CCCV charging a Q_{ch} of 1164 mAh has been measured by means of cc and an arbitrary maximum capacity Q_{max} of 1177 mAh has been considered in the SoC evaluation system. As a result a SoC_{ch} of 98.9% has been calculated (see Eq. (3)). However, at the end of the CV mode the SoC level in the SoC evaluation system has been defined to be 100% [10]. As a result SoC_{ch} has been calibrated and a new SoC_{ch} value of 100% has been defined in the SoC evaluation system. It can be concluded from this example that the error in SoC_{ch} is 1.1%. This SoC error has been calculated as a difference between the true SoC_{ch}, *i.e.* 100% and the calculated SoC_{ch} by means of Eq. (3). The error sources in the SoC_{ch} calculation will be further discussed. Applying the partial derivative formula on Eq. (3) and considering SoC_s in unit value for simplicity results in

$$\frac{dSoC_{ch}}{SoC_{ch}} = \frac{1}{Q_{\max}SoC_s + Q_{ch}}\left(Q_{\max}SoC_s\frac{dSoC_s}{SoC_s} + Q_{ch}\frac{dQ_{ch}}{Q_{ch}} - Q_{ch}\frac{dQ_{\max}}{Q_{\max}}\right) \quad (4)$$

where *d(.)/(.)* denotes the relative error in the quantity (.).

It appears that a 0.2% SoC relative error has been introduced by Q_{ch}, whereas the error introduced by SoC_s is very small and can be further neglected from the SoC_{ch} uncertainty calculation. It appears from this example and Eq. (4) that 0.9% SoC relative error has been introduced by the 1177 mAh Q_{max} value programmed in the system. As a result Q_{max} has been recalculated and a new value of 1166 mAh has been further programmed in the SoC evaluation system. The step of charging has been followed by a rest period of about 4 hours during which a small current I_s of 1 mA has been drawn from the battery.

At the beginning of the rest period the SoC evaluation system has switched to the transitional state (see Fig. 1). The SoC during the transitional state SoC_t has been calculated as follows

$$SoC_t = SoC_{ch} - 100\frac{Q_d}{Q_{\max}} \quad (5)$$

where Q_d has been determined by means of cc.

During the first two hours of the rest period a charge Q_d of about 2 mAh has been measured by means of cc, and a value for SoC_t of about 99.8% has been calculated at the end of the transitional state (see Eq. (5)). It can be concluded that after the calibration of SoC_{ch} and Q_{max} the error sources from the transitional state can be further neglected. After the two hours period the SoC evaluation system has switched to the standby state.

At the beginning of the standby state a battery voltage of 4.177 V and a battery temperature of 25°C have been measured. Based on these measurements and the stored EMF_m a SoC_s value of about 99% SoC has been calculated. It can be concluded from this example and the SoC_t value that the SoC_s calculation had an error of 0.8% SoC. At the end of the standby state a SoC_s of 98.5% has been calculated, whereas the true SoC_s had a value of 99.7%. The true SoC_s value has been calculated by means of cc. It follows from this example that the error in SoC_s amounts 1.2%. This error has been calculated as the difference between the true SoC_s and the calculated SoC_s by means of *V* and *T* measurements and the stored EMF_m. So, the error in SoC_s arises from errors in the battery *V* and *T* measurements and in EMF_m. In summary, the error in the EMF_m has the largest contribution to the SoC_s error. Further a 0.5 C-rate negative current has been drawn from the battery and the SoC evaluation system has switched to the discharge state (see Fig. 1).

During this state the battery has been discharged until the battery voltage reached a defined End-of-Discharge Voltage (V_{EoD}) of 3 V value at 0.5 C-rate discharging current. The SoC during the discharge state SoC_d has been calculated from

$$SoC_d = SoC_s - 100\frac{Q_d}{Q_{\max}} \quad (6)$$

During the discharge state a Q_d of 1141 mAh has been determined by means of cc. At the end of discharge a SoC_d of 0.64% has been calculated, whereas the true SoC_d had a value of 1.84%. The true SoC_d has been calculated by considering the true SoC_s of 99.7%. The error sources in the SoC_d calculation will be further discussed. Considering in Eq. (6) the SoC difference between SoC_d and SoC_s being ΔSoC_d and absolute values for simplicity results

$$\Delta SoC_d = 100\frac{Q_d}{Q_{\max}} \quad (7)$$

It follows from Eq. (7) that the absolute error in SoC_d will be a sum of the absolute errors from the SoC_s and ΔSoC_d. It has been observed from the measurements that the error introduced by Q_d during discharging has been very small and therefore has been further neglected from the SoC_d uncertainty calculation. It should also be noted that Q_{max} has been calibrated after the charge state and as a result will be further neglected from the SoC_d uncertainty calculation. In this example the relative error introduced by SoC_s in SoC_d is 1.2%.

The SoC evaluation system presented in this paper calculates also the remaining run-time available under the discharge conditions (see Eq. (1)). In order to calculate the t_r a SoC_l value is calculated at the beginning of the discharge state by means of the overpotential prediction and the EMF_m. In the example considered in this paper a SoC_l of 3.1% has been calculated, whereas the true SoC_l had a value of 1.84%. The true SoC_l has been calculated by considering the true SoC_d at the end of discharging. As a result t_r inferred from SoC_d (98.5%), SoC_l (3.1%), Q_{max} (1166 mAh) and I_d at the beginning of discharging, *i.e.* 0.55 A, is 121 minutes, whereas the true t_r was 124 minutes. This true t_r has been calculated from the true SoC_d and SoC_l values. So, in this example the t_r calculation had an error of 3 minutes at the beginning of discharging. The error sources in the t_r calculation will be further discussed. Applying the partial derivative formula on Eq. (1) and considering t_r in hours, SoC in units, Q_{max} in [mAh] and I_d in [mA] for simplicity results in

$$\frac{dt_r}{t_r} = t_r\left(\frac{dQ_{\max}}{Q_{\max}} - \frac{dI_d}{I_d}\right) + \frac{Q_{\max}}{I_d}\left(dSoC_d - dSoC_l\right) \quad (8)$$

where dt_r/t_r denotes the relative error in t_r, dI_d/I_d denotes the relative error in I_d and $dSoC_d$ and $dSoC_l$ denote the error in SoC_d, *i.e.* 0.012 and in SoC_l, *i.e.*0.0126*,* respectively.

It has been observed from the measurements that the error introduced by I_d during discharging is very small and as result has been further neglected from the t_r uncertainty calculation. It follows from Eq. (8) that the error in t_r is 0.05 hours. This calculated error corresponds well with the error obtained from the test example. It can be concluded that the main errors in t_r result from errors in SoC_d, *i.e.* 0.025 hours and SoC_l, *i.e.* 0.025 hours.

5. CONCLUSION

The error sources in a real-time SoC evaluation system have been discussed. As has been shown the main error source from the remaining run-time calculation is the error from the EMF_m.

It has been demonstrated in this paper that the Q_{max} adaptation algorithm improves the SoC and the t_r calculation accuracy even for a fresh battery. Since a battery loses capacity during cycling it can be concluded that the Q_{max} adaptation algorithm will increase substantially the SoC and the t_r calculation accuracy. In the near future we plan to improve the EMF_m accuracy and to study the influence of the aging effect in the SoC and in the t_r calculation accuracy.

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