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Methods for state-of-charge determination and their applications

Sabine Piller*, Marion Perrin, Andreas Jossen

Center for Solar Energy and Hydrogen Research (ZSW), Division 3: Electrochemical Energy Storage and Energy Conversion,
Helmholtzstr. 8, 89081 Ulm, Germany

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Abstract

State-of-charge (SOC) determination becomes an increasingly important issue in all the applications that include a battery. Former operation strategies made use of voltage limits only to protect the battery against deep discharge and overcharge. Currently, battery operation is changing to what could rather be called battery management than simply protection. For this improved battery control, the battery SOC is a key factor.

Much research work has been done in recent years to improve SOC determination. Operational conditions differ for batteries in, for example, photovoltaic applications, (hybrid)-electric vehicles or telecommunications. Hence, a given method for SOC calculation will be more suitable for a certain application than for another. The authors introduce commonly used methods for SOC determination and establish a relationship between the advantages of the different methods and the most common applications. As a main illustration, the analysis of Kalman filter technique for lead-acid battery SOC determination are presented and some results for other calculation methods as well. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: Lead-acid batteries; State-of-charge

1. Introduction

Most of us use a mobile phone, a laptop computer, perhaps a cordless shaver, maybe even an electric car for the luckiest of us. All these devices are now part of our daily life and bring a big contribution to our mobility and our freedom (even if this point is more questionable).

But besides the comfort that is gained by all these devices that use the electrical energy delivered by an accumulator, a new source of stress has appeared: will I be able to shave this morning, will the battery last until I have written the last page of my paper? In most systems that use a battery, an important point is the knowledge of the state-of-charge (SOC) of the battery or more simply: how long do I have until my device stops working?

In addition to the immediate displaying of the SOC to the user, the knowledge of the remaining battery capacity is of importance for its management. Namely, many systems are sensitive to deep discharge or overcharge because these states of extremely high or too low SOC can lead to irreversible damage in the battery.

Given the importance of knowing the SOC of a battery, another question arises: how to measure it? And before measuring the SOC, we need to know what it actually is. In a recent paper [1] the different definitions for the capacity and SOC were summarised. According to this paper, we will make reference to the SOC as: the ratio between the difference of the rated capacity and the net amount of charge discharged from a battery since the last full SOC on the one hand, and the rated capacity on the other hand. Due to this definition, the full SOC is reached when (according to DIN 43539), the battery current is not changing during 2 h at a constant charge voltage and constant temperature.

This definition leaves behind the problem of battery ageing. In fact, the capacity that can be delivered by a battery may change in the course of its life due to problems like the loss of charge acceptance of the active material on either of the electrodes, changes in the physical properties of the electrolyte or corrosion of the current conductors. In this paper, we will also not deal with the state-of-health (SOH) of batteries, which is another topic of actual research.

The paper summarises different techniques that exist for determining the SOC of a battery. Additionally, the most suitable field of application for each method is presented. The main focus is put on the lead-acid system.

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* Corresponding author. Tel.: +49-731-9530-201;
fax: +49-731-9530-666.
E-mail address: sabine.piller@zsw-bw.de (S. Piller).

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2. Methods for determining the state-of-charge

The determination of the SOC of a battery may be a problem of more or less complexity depending on the battery type and on the application in which the battery is used. Since this paper will focus on lead-acid accumulators, the SOC determination methods are described explicitly for this type of battery system, but apply partially also for the other electrochemical systems.

2.1. Discharge test

The most reliable test for the determination of the SOC of a battery — i.e. its remaining capacity — is a discharge test under controlled conditions. But such a test, which usually includes a consecutive recharge, is too time consuming to be considered for most applications. As a second drawback during testing the system function is interrupted.

2.2. Ampere hour counting (including loss calculation)

This is the most common technique for calculating the SOC. Since the charge and discharge are directly related to the supplied or withdrawn current, the idea of balancing the battery current is evident. If a starting point (SOC_0) is given, the value of the current integral (Eq. (1)) is a direct indicator for the SOC.

$$\mathrm{SOC} = \mathrm{SOC}_0 + \frac{1}{C_\mathrm{N}} \int_{t_0}^{t} (I_\mathrm{batt} - I_\mathrm{loss})\,\mathrm{d}\tau \qquad (1)$$

where C_N is the rated capacity, I_batt the battery current, and I_loss is the current consumed by the loss reactions.

Two main complications arise with this method: firstly, incorrect current measurement could add up to a large error and accurate current measurement is expensive. Secondly, not all current supplied to the battery is consumed by charging and the corresponding losses have to be taken into account. The first point can be overcome by investing money in measuring equipment, while for the second one, many different approaches have been developed. As an example, two loss calculations will be presented below. The errors can be kept low if points for re-calibration are reached, e.g. the SOC is set to one if a full charge is detected or open circuit voltage measurement (see below) is used to correct the SOC value.

The most simple loss estimation method is to apply a constant charge factor to the battery at each recharge, i.e. a constant loss is assumed and this loss is additionally returned to the battery. Such a method is only suitable for systems that are not too sensitive to overcharge. In Ni/MH batteries, for example, a value of 1.3 is often used to assure full charge of the battery. Ni/MH batteries are not as sensitive to overcharge as are lead-acid or especially Li-based batteries. With lead-acid batteries, a charge factor of 1.05–1.2 is used, depending on the battery type. Additionally, this method implies that the charging operation is controlled.

A current-loss calculation approach for photovoltaic (PV) applications was developed by Jossen [2]. The Butler–Volmer equation is used to calculate the major losses during charging, i.e. the gassing current. Since in PV applications the currents are small, the Butler–Volmer equation could be modified and normalised to become finally that shown in Eq. (2)

$$I_\mathrm{loss} = I_0 \exp\left(\frac{U_\mathrm{batt} - U_\mathrm{N}}{K_1} - K_2 \frac{T - T_\mathrm{N}}{T\,T_\mathrm{N}}\right),$$
$$I_0 = I_0 \exp\left(\frac{U_\mathrm{N}}{K_1} - \frac{K_2}{T_\mathrm{N}}\right) \qquad (2)$$

where I_loss is the current consumed by the loss reactions; K_0, K_1, K_2 are the constants; U_batt and U_N are the battery and rated battery voltage; T and T_N are the battery temperature and temperature under standard conditions.

As mentioned above, the errors for this method can be kept low if points for re-calibration can be identified. Since in PV applications the time for recharge is limited by the length of daylight, full charge is seldom achieved. Concerning this problem, in the same publication [2] a so-called remaining charge current technique for re-calibration is presented which allows re-calibrations if the SOC is above 90%. For more details see [3].

The same loss calculation was used in a SOC algorithm published on [4]. This algorithm was developed only for PV applications, i.e. currents in the range of I_{10}, and measurement intervals of about 1 min or more. It is not designed for online use because ‘future’ data is necessary to calculate the SOC. The reference data for the linear model [5] and the Kalman filter [6] approach (both described below) was generated with this programme.

Another procedure based on Ah counting is reported in [7]. This publication focuses on discharges during the operation of electric vehicles. Three empirical gauge functions are established concerning the problems of temperature influence, maximum deviation from the nominal capacity and SOC dependence on discharge rate.

Ah counting is the most common method applied to most systems and applications. Indeed, the method is easy and reliable as long as the current measurement is accurate and enough re-calibration points are available. For example, for EV application, the method can take benefit of the regular full recharges under controlled conditions. In that field of application, the technique finds a limit in the case of high temperature effects and/or high current variations but it can be applied to all the battery systems used for the EV application. (i.e. lead-acid, Ni/Cd, Ni/MH, Zebra and lithium systems).

In the same way, because of its simplicity, Ah counting is used in most consumer applications.

2.3. Measurement of the electrolytes physical properties

In a lead-acid battery, the electrolyte takes part in the reactions during charge and discharge. The linear relationship between the change of acid density and the SOC can be used to determine the latter. This method is feasible only with vented lead-acid batteries, while methods for density measurement within VRLA batteries are not yet available. Possible applications are, therefore, in stationary batteries with liquid electrolyte. The density is measured directly or indirectly by ion-concentration, conductivity, refractive index, viscosity, ultrasonics, etc. A detailed description of the different methods is given, for example, in [8].

Problems related to this technique are the occurrence of acid stratification, water loss and the long term stability of the sensors. The first two can be avoided by electrolyte circulation and automatic water refill systems. Additionally, the measurement of the physical properties of the acid cannot be done in the pores of the electrodes where the acid is actually either consumed or produced. This means that during high current processes, slow electrolyte diffusion is a source of errors for this technique.

2.4. Open circuit voltage

Similar to the acid density measurements described in Section 2.3, the open circuit voltage relates in a linear manner to the SOC. Fig. 1 shows this linear dependence as obtained from four 12 V, 52 Ah (*C*/5) VRLA batteries of the Optima type when tested at the University of Ulm.

In applications where relatively long rest periods are common, this method is promising. Since the rest periods will only occur from time to time, the open circuit voltage measurement is usually combined with other techniques [9] to ensure a continuous indication of SOC. In such a combination, the open circuit voltage measurement can be utilised to adjust the other technique(s). The difference in the open circuit voltage for a fully charged and a flooded lead-acid cell is about 100 mV. Especially in VRLA batteries long times (several hours) are needed to reach a steady state and this can cause problems. A second point to mention is the question of what is meant by *rest period*. Often a minimal current flow is required for monitoring devices: clocks, etc. In such a case, the open circuit voltage is never reached. Finally, like with all methods which use directly or indirectly the monitoring of acid concentration, acid stratification can generate inaccurate results.

2.5. Heuristic interpretation of measurement curves

The following gives a brief, non-comprehensive, selection of techniques that use the electrical discharge/charge characteristics to calculate the SOC. Some methods were developed to get data on the SOC by interpreting only parts of the discharge curves. The chosen parts are understood to be significant for the battery SOC.

2.5.1. Coup de fouet

In [10] the so-called *coup de fouet* region is used to calculate not exactly the SOC but the capacity that can be delivered after a full recharge for a discharge at a given current and temperature. The *coup de fouet* is the short voltage drop at the beginning of discharge following a full charge of a lead-acid battery. Two parameters are established, which are shown to have a linear relationship to the deliverable capacity: firstly the trough voltage, i.e. the minimum voltage during the occurrence of *coup de fouet* and secondly the plateau voltage, i.e. the maximum voltage reached during voltage recovery at the end of the *coup de fouet*. For one cell type it has been shown that the linear

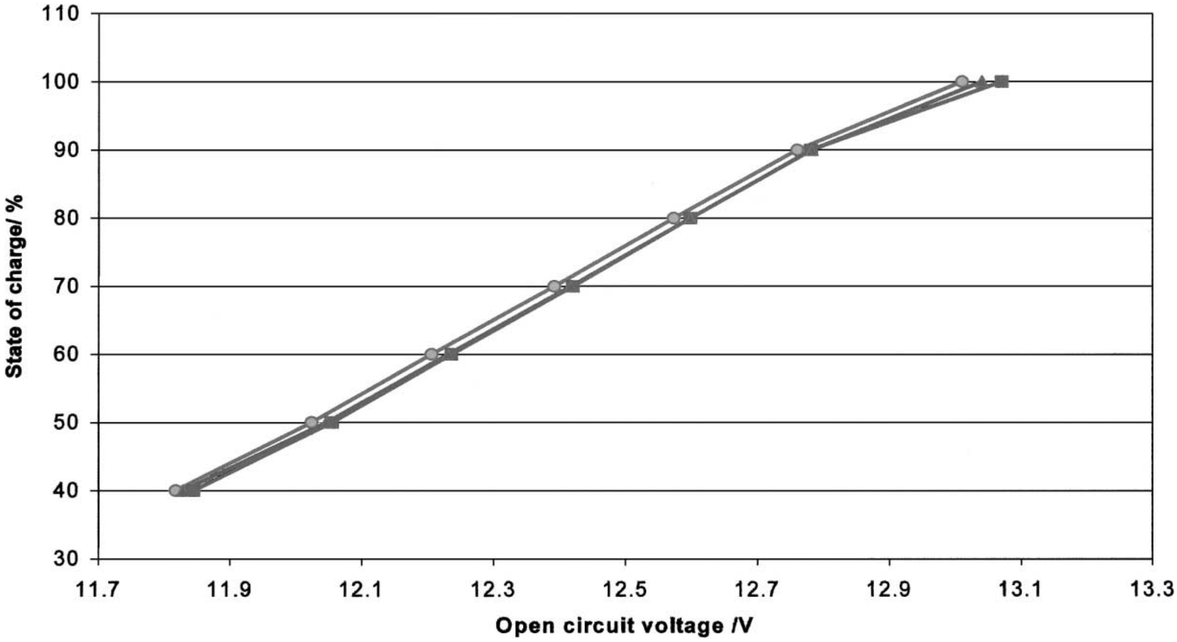

Fig. 1. Dependence of the state-of-charge on the open circuit voltage from four VRLA batteries of the same type.

equation determined by regression stays within an error limit of 12.5% for high discharge-current variations and temperature changes. Since the *coup de fouet* region occurs only after a full charge, this method can be used if a full charge is frequently reached during operations. For static discharge-currents this method is advantageous, because it gives an estimation of the actual available capacity, which depends on the discharge-current and temperature. The authors suggest this technique for batteries in telecommunication installations.

2.5.2. Linear model

In [5] a linear relationship (Eq. (3)) was established between the variation of SOC, the intermediate electrical measurements on the battery and the previous SOC value.

$$\Delta Q(i) = \beta_0 + \beta_1 U(i) + \beta_2 I(i) + \beta_3 Q(i-1),\quad Q(i) = Q(i-1) + \Delta Q(i) \tag{3}$$

where $Q(i)$ is the state-of-charge, $\Delta Q(i)$ the SOC-difference, U the voltage and I is the current measurements.

The factors $\beta_0, \ldots, \beta_3$ are determined from reference data by least-mean-square calculations. The model was developed for PV applications, i.e. for low currents and slow SOC changes, and is characterised by high robustness in relation to measurement errors and wrong initial conditions, as shown in Fig. 2.

It is important to note that the β-factors do not describe physical parameters.

The linear model can be applied to various battery types and to batteries at different stages in their lives. However, best results are achieved if reference data from the same battery type is used to calculate the β-factors.

2.5.3. Artificial neural network

The utilisation of artificial neural networks for SOC determination is presented in [5,11,12]. Since artificial neural networks establish a relationship between input/output data of any kind, this method can be utilised for all battery systems and for all applications, providing that training data for the net is available. In [5], an artificial neural network is presented which is trained before use, whereas in [11,12] adaptable artificial neural networks are used. If an adaptable artificial neural network is applied, other methods for SOC determination are used to provide training data at selected states of operation. Errors depend strongly on the training data and the training method. Since the training methods usually minimise functions that lead to an evenly distributed error, the error is usually no function of the SOC. However, in Fig. 3 (taken from [5]) error extremes occur at high SOCs, because the net was trained with data obtained from a battery with slightly larger capacity and better electrolyte circulation. But the SOC curves of a battery of the same type as the one corresponding to the training data show smaller and evenly distributed errors.

2.6. Impedance spectroscopy

Much research work has been carried out on impedance spectroscopy. This method is a common measurement technique to investigate electrochemical processes and has been studied for all battery systems not only for SOC but also for SOH determination. A review of impedance measurements for determination of the SOC for lead-acid and nickel/cadmium batteries is given in [13]. Fig. 4 shows a Nyquist diagram of the complex impedance of a lead-acid battery (OPzS 150) during discharge.

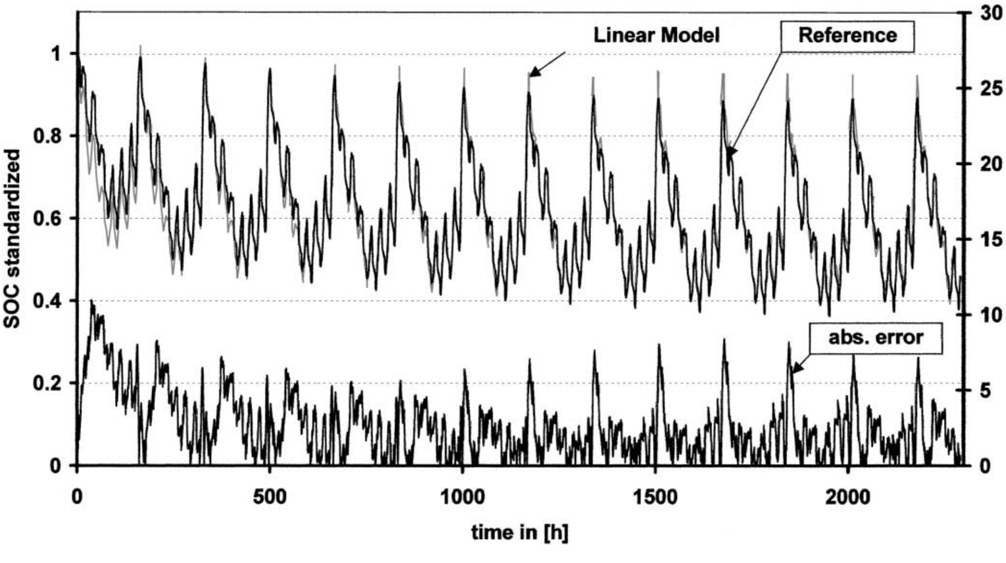

Fig. 2. SOC curves of the linear model, showing the reference and the error between the two curves.

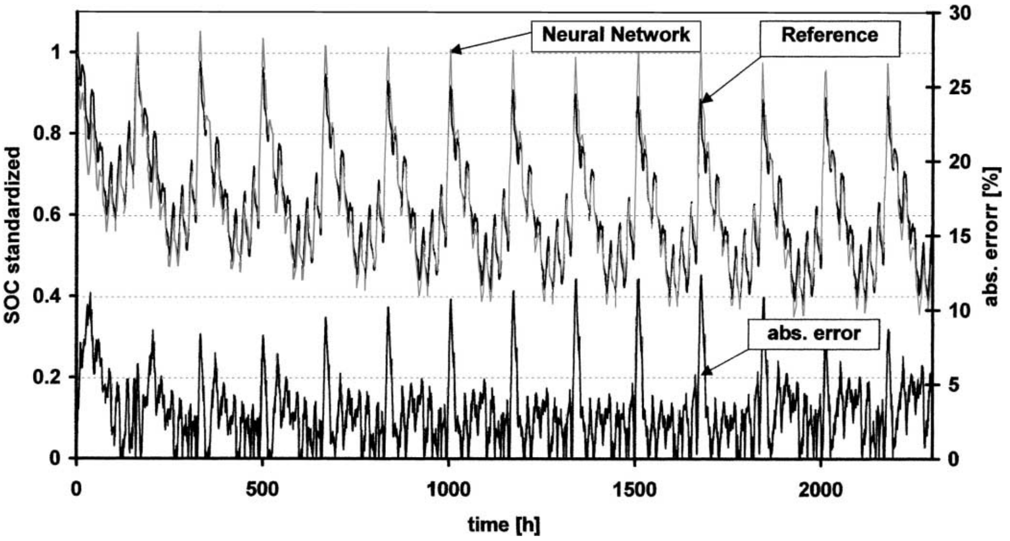

Fig. 3. SOC curves of back-propagation artificial neural network, showing the reference and the error between the two curves.

A combination of impedance spectroscopy with fuzzy logic methodology is presented in [14]. Two battery systems were investigated, a lithium/sulphur dioxide and a nickel/metal hydride system. A fuzzy model was used to establish a relationship between battery model parameters derived from impedance spectroscopy measurements and the SOC. For the lithium/sulphur dioxide cells the imaginary component of the impedance at three different frequencies was used as input for the SOC calculation and an accuracy of ±5% was achieved, for the nickel/metal hydride cells the $C2$ capacitance (also derived from impedance measurement) and the cycle number was the input and for the available reference points of 0, 25 and 100% an error below 10% was achieved.

Impedance curves are strongly influenced by temperature effects. Therefore, the best utilisation of this method is with batteries in temperature controlled environment, e.g. large stationary battery installations.

Surprisingly, in spite of the quantity of papers written on the subject, impedance spectroscopy is seldom implemented for practical SOC determination and it stays still a subject of debate. In a review [13], Huet concluded that the temperature influence is so high that practical application

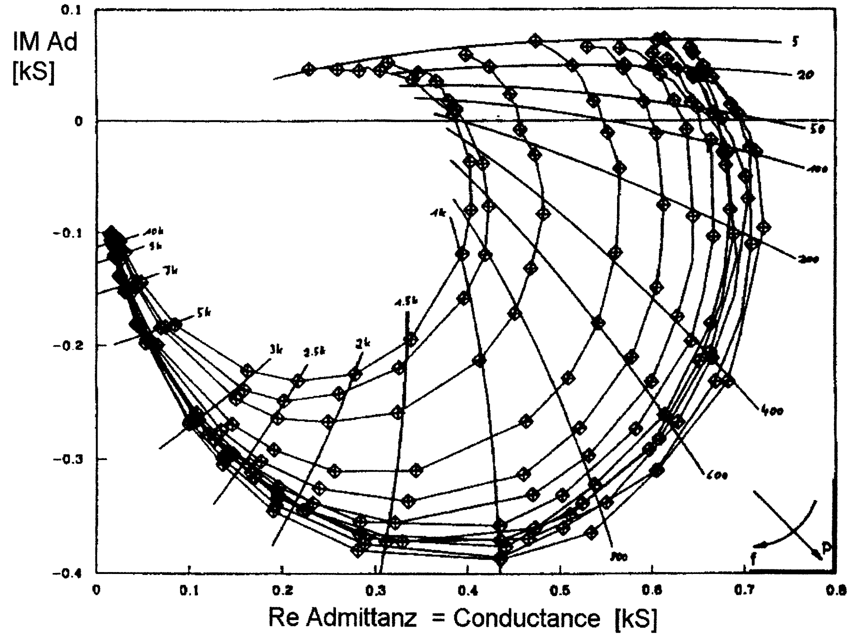

Fig. 4. Impedance measurements from a lead-acid battery (OPzS 150) during discharge (from [8]).

of impedance spectroscopy can only be made in ranges of high frequencies. This technique seems to be more suitable for lead-acid systems than for nickel/cadmium and is more promising for the determination of SOH rather than for the precise measurement of SOC.

Another review on this subject is given in [17]. Besides conventional systems (i.e. lead-acid, nickel/cadmium, nickel/metal hydride), initial measurements on lithium-ion batteries are presented. For this system, impedance spectroscopy seems to be a possible method for SOC determination.

In fact, conductance measurements at a given frequency are performed on batteries for quality control and provide information about state-of-health. They can also be used for SOC evaluation provided they are taken within a convenient frequencies range (e.g. in Fig. 4, the SOC varies only at low frequencies).

2.7. Internal resistance

Related to the impedance spectroscopy is the calculation of the internal resistance of the battery, i.e. the voltage drop divided by the current change during the same (short) time interval. The value of the resistance depends heavily upon the chosen time interval. For a time interval smaller than 10 ms, only Ohmic effects are measured. If the interval is extended, other effects such as transfer reactions or acid diffusion are involved and the resistance becomes complex. In this case it would be better to use the previously described impedance spectroscopy instead of the voltage current ratio.

For lead-acid batteries the change in the internal (Ohmic) resistance between full SOC and SOC = 0 is only some mΩ per cell. This kind of measurement is more useful for

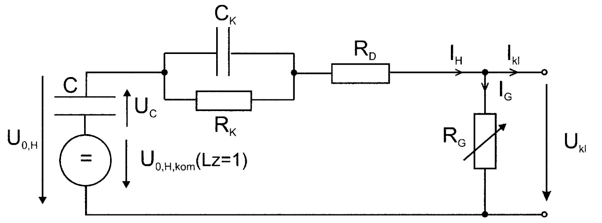

Fig. 5. Battery model for SOC determination in PV applications.

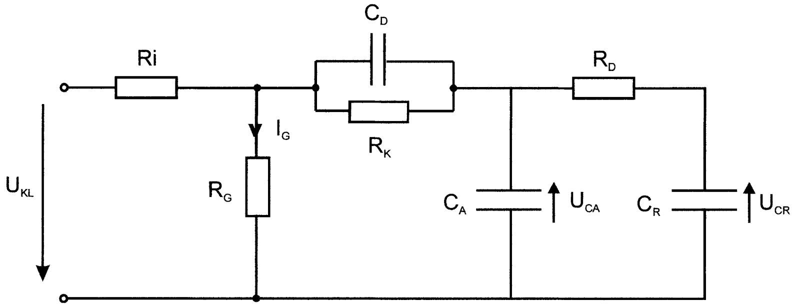

Fig. 6. Battery model for dynamic applications such as HEV and EV.

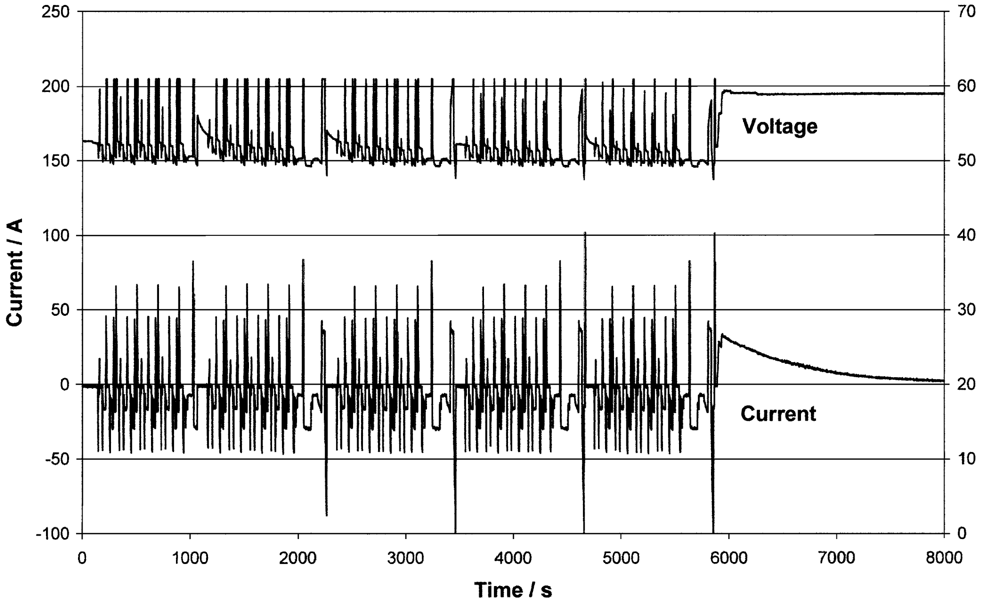

Fig. 7. Current and voltage curves measured on four 12 V lead-acid battery blocks used for Kalman filter SOC determination (simulated hybrid vehicle cycle).

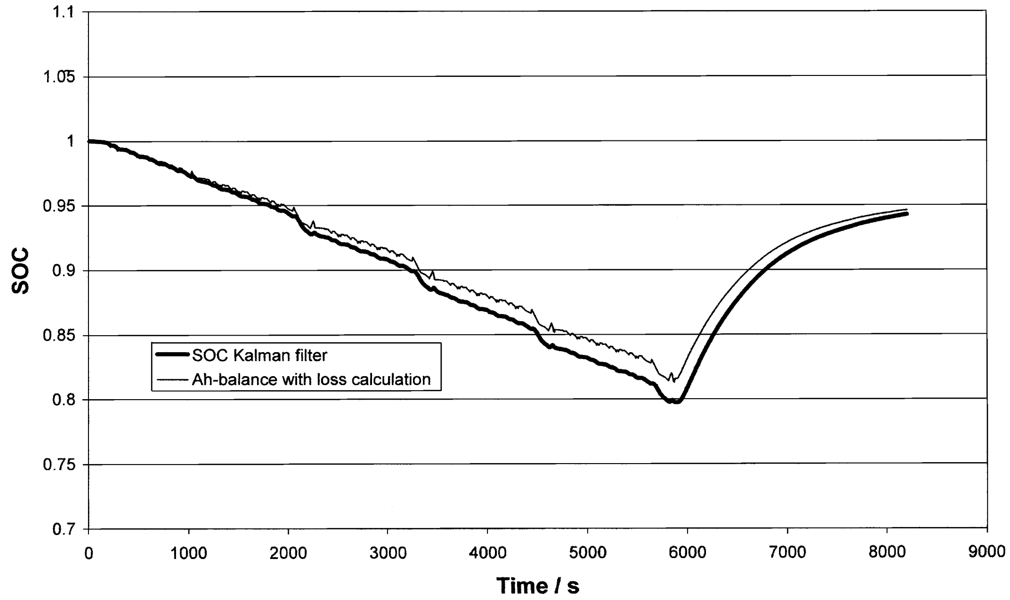

Fig. 8. SOC curve calculated by the Kalman filter technique compared with Ah balance with loss calculation.

providing statements on the state-of-health of the batteries. It can also provide some information about the SOC provided the battery is not fully charged [18].

2.8. *Kalman filters*

A Kalman filter is an algorithm to estimate the inner states of any dynamic system. In our case, the battery is the dynamic system and one of the inner states is the SOC. The estimation is based on a model of the dynamic system. At the ZSW, Kalman filters with two models are specially investigated. The first is a model based on [15], which is seen as appropriate for PV applications and the second one is a more dynamical model, being a simplification of the battery model in [16]. The models are shown in Figs. 5 and 6.

Technique	Field of application	Advantages	Drawbacks
Discharge test	All battery systems Used for capacity determination in the beginning of life	Easy and accurate, independent of SOH.	Offline, time intensive, modifies the battery state, loss of energy
Ah balance	All battery systems, most applications (consumer, PV, EV).	Online, easy, accurate if enough re-calibration points are available and with good current measurement.	Needs a model for the losses. Sensitive to parasite reactions. Cost intensive for accurate current measurement Needs regular re-calibration points
Physical properties of electrolyte (density, concentration, colour)	Lead, possibly Zn/Br and Va	Online Gives information about SOH	Error if acid stratification. Low dynamic. Problem of stability of sensors in electrolyte. Sensitive to temperature and impurities.
Open circuit voltage	Lead, Lithium, Zn/Br and Va	Online, cheap	Low dynamic, error if acid stratification and needs long rest time (current =0) for lead system. Problem of parasite reaction (e.g. Sb poisoning by lead)
Linear model	Lead PV, possibility for other battery systems ? (not tried yet)	Online, easy	Needs reference data for fitting parameters
Artificial neural network	All battery systems	Online	Needs training data of a similar battery
Impedance spectroscopy	All systems	Gives information about SOH and quality. Possibility of online measurement.	Temperature sensitive, cost intensive.
D.C. Internal resistance	Lead, Ni/Cd	Gives information about SOH, cheap. Possibility of online measurement. Easy	Good accuracy, but only for low SOC
Kalman filter	All battery systems, PV, dynamic applications (e.g. HEV)	Online. Dynamic	Needs large computing capacity. Needs a suitable battery model. Problem of determining initial parameters

Fig. 9. Summery of the different techniques for determination of state-of-charge, presented with their field of application, advantages and drawbacks.

The results for the SOC determination from the Kalman filter using the first model (Fig. 5) where presented in [5]. It was shown that the errors could be kept below 10% for data of a 12 V, 125 Ah flooded lead-acid battery, which was cycled on a typical PV regime over a period of 2.5 years.

To apply the Kalman filter technique for data of a higher dynamic, e.g. for a hybrid electric vehicle (HEV), the second battery model (Fig. 6) has to be used. Since field data of HEVs are not available, the results presented are obtained using measurements performed on four 12 V, 52 Ah (Optima Yellow Top) batteries by means of synthetic hybrid cycles, generated with the simulation tool FAHRSIM [19]. Fig. 7 shows the current and voltage evolution over time. The results of the SOC calculation with this data and the dynamic model is shown in Fig. 8. Because no other reference exists, the Kalman SOC is compared to the Ah balance with the above described loss calculation based on [2]. In total, only about 10 Ah were taken from the batteries. Both SOC curves are very similar, the maximum difference is 2% at the lowest SOC. Other cycles showed comparable results.

These are first results with dynamic data and SOC determination using the Kalman filter technique. At ZSW further work will be carried out to confirm the suitability of this method for high dynamic applications.

3. Conclusion

The paper has given a short overview of the existing techniques for the evaluation of battery SOC. Emphasis was given to the lead-acid system even though many techniques are also suitable for other systems. Fig. 9 summarises this overview.

The most used technique at this time for all systems is Ah counting because it is the most direct and transparent method and quite easily implemented. It also gives satisfyingly accurate results for short-time applications, especially if used in the range of low to medium SOC. The determination of SOC by the means of impedance spectroscopy, including ac and dc inductance measurements, is still a subject of debate because of its temperature sensitivity and the difficulty of its online implementation. New promising methods are:

- The linear model that is impressive for its simplicity and because it delivers satisfying results for photovoltaic applications.
- The Kalman filter that gives perspectives for high dynamic usage (HEV, EV).
- The artificial neural network that can be implemented for any battery and battery system provided enough training data can be supplied.

References

[1] D.U. Sauer, G. Bopp, A. Jossen, et al., State-of-charge — what do we really speak about? INTELEC, 1999.

[2] A. Jossen, Betriebsführung photovoltaischer Anlagen mit Energiespeichern, Dissertation, Universität Stuttgart, 1994.

[3] A. Jossen, H. Döring, J. Garche, Ladezustandsbestimmung von Bleibatterien an zwei ausgewählten Beispielen, 10, Symposium Photovoltaischer Solarenergie, Staffelstein, 1995.

[4] ZSW (Hrsg.) & ISET & ISE, Referenzdaten zum Test von Verfahren zur Ladezustandsbestimmung von Bleibatterien, CD-ROM, 1999.

[5] Ch. Ehret, S. Piller, W. Schroer, A. Jossen, State-of-charge determination for lead-acid batteries in PV-applications, in: Proceedings of the 16th European Photovoltaic Solar Energy Conference, Glasgow, 2000.

[6] S. Piller, A. Jossen, Kalman-filter zur Ladezustandsbestimmung von Bleibatterien in PV-Anlagen, 14, Symposium Photovoltaischer Solarenergie, Staffelstein, 1999.

[7] J. Alzieu, H. Smimite, D. Glaize, Improvement of intelligent battery controller: state-of-charge indicator and associated functions, J. Power Sources 67 (1997) 157–161.

[8] H.-P. Hönes, Elektrochemische Energiespeicher in photovoltaischen Anlagen, Dissertation, Universität Stuttgart, 1994.

[9] M. Rothert, B. Willer, C. Schmitz, et al., Verschiedene Ansätze zur Ladezustandsbestimmung, Forschungsverbund Sonnenenergie Workshop Elektrochemische Speichersysteme für regenerative Energieversorgungsanlagen, May 1999.

[10] Ph.E. Pascoe, A.H. Anbuky, Estimation of VRLA Battery Capacity Using the Analysis of Coup de Fouet Region, INTELEC, 1999.

[11] D. Kray, D.U. Sauer, Neuro-Methoden zur Prognose und Fehlererkennung durch Analyse vor Daten aus Monitoring-Systemen, Internationales Sonnenforum, Köln, 1998.

[12] M. Stoll, Ein Schätzverfahren über den inneren Zustand geschlossener Bleiakkumulatoren, VDI Fortschritt-Berichte, Reihe 21, Nr. 167, 1994.

[13] F. Huet, A review of impedance measurements for determination of the state-of-charge or state of health of secondary batteries, J. Power Sources 70 (1998) 5949.

[14] A.J. Salkind, C. Fennie, P. Singh, et al., Determination of state-of-charge and state-of-health of batteries by fuzzy logic methodology, J. Power Sources 80 (1999) 293–300.

[15] W. Burkner, Verfahren zur Ladezustandsbestimmung von Blei-Batterien in Photovoltaikanlagen, IfE Schriftenreihe, Heft 27, Lehrstuhl für Energiewirtschaft und Kraftwerkstechnik, Technische Universität, München, 1994.

[16] R. Gretsch, Ein Beitrag zur Gestaltung der elektrischer Anlage in Kraftfahrzeugen Habilitationsschrift, Friedrich-Alexander-Universität Erlangen, Nürnberg, 1978.

[17] S. Rodrigues, N. Munichandraiah, A.K. Shukla, A review of state of charge indication of batteries by means of ac impedance measurement, J. Power Sources 87 (2000) 12–20.

[18] A. Jossen, H. Döring, J. Garche, Ladezustandsanzeiger für elektrochemische Akkumulatoren, UECT, 1995.

[19] H. Kabza, C. Koerner, P. Seger, A. Wagener, FAHRSIM: A Versatile Simulator for Drivetrain Modeling and Analysis, EVS 17, Montreal, 2000.