

Impedance measurements on lead–acid batteries for state-of-charge, state-of-health and cranking capability prognosis in electric and hybrid electric vehicles

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Abstract

Various attempts have been made to use impedance measurements for online analysis and offline modelling of lead–acid batteries. This presentation gives an overview on the latest and successful approaches based on impedance measurements to assess state-of-charge (SoC), state-of-health (SoH) and cranking capability of lead–acid batteries. Furthermore, it is shown that impedance data can serve as a basis for dynamic battery models for the simulation of vehicle power-supply systems. The methods and procedures aim for a reliable prediction of battery performance in electric vehicles, hybrid cars and classical automotive applications. Although, it will become obvious that impedance measurements give valuable information on the battery state, typically the information needs to be combined with other conventional algorithms or self-learning tools to achieve reliable and stable results for real-world applications.

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1. Introduction

Impedance spectroscopy is a widely used method in electrochemistry. It is also applied to batteries and many reports, devices and patents have been published. Nevertheless, the scientific community has no consistent position towards the effectiveness of impedance spectroscopy. This can be attributed to two principal reasons: (i) many promises have been made by industry and researchers about impedance spectroscopy as an ultimate solution for problems; (ii) results from impedance spectroscopy are often hard to reproduce or need very precisely defined operating conditions. This paper attempts to demonstrate that impedance spectroscopy is a beneficial tool if applied appropriately to given problems

and if combined intelligently with conventional methods and self-learning algorithms. Results from impedance measurements are valuable information and need to be processed in an overall algorithm. Pure impedance data will rarely lead to reliable results.

This study describes a multi-channel impedance spectroscope, which provides simultaneous analysis of the impedance from half-cells or cells in a block or string. This makes measurements less time-consuming and the performance of cells and half-cells can be compared directly.

State-of-charge (SoC) and cranking capability determination are master disciplines in lead–acid battery system technology. Reliable battery management systems rely on these information. The work reported here will present approaches for the determination of both parameters. Special emphasis is put on easy usage in real-world environments such as in cars.

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It is also shown how impedance spectroscopy could bring added value for the improvement of the battery cell design. Continuously measured impedance spectra on half-cells during accelerated ageing tests allow identification of ageing processes and their evolution during lifetime. In additions, impedance spectroscopy as a non-destructive measurement technique provides insights into the battery, which are not available with any other technology.

Finally, battery modelling is a key issue for the design process of appliances based on batteries. Reliable and easy-to-parameterize battery models are necessary. It has been shown by many authors that impedance measurements can be used to determine the parameters of such models. Many restrictions on the validity range occurred as especially for lead–acid batteries, the impedance spectra depend very much on the short-term charge–discharge history. To overcome this problem, a hybrid modelling approach is presented here, which combines impedance-based elements with physics-based model elements.

The different examples clearly show the potential of impedance spectroscopy, which still is by far not fully explored. Careful analysis of the application and the appropriate impedance methods combined with conventional approaches and techniques, opens up a wide range for scientifically interesting and commercially successful applications.

2. *EIS*meter for multi-channel electrochemical impedance spectroscopy (EIS)

Commercially available equipment for electrochemical impedance spectroscopy is usually optimized for small laboratory cells. Thus, these devices are restricted to relatively low currents. A typical current range is $-1 < I(t) < 1$ A, i.e., the sum of the direct current offset and the ac perturbation can never exceed 1 A [1]. For the investigation of the non-linear behaviour of automotive batteries, however, higher currents are required. Some manufacturers (e.g., Zahner–Elektrik, Germany) provide so-called boosters or power-potentiostats that allow a greater than 1 A range. This type of booster amplifies the entire output current of the impedance-measuring device. Hence, the large dc current range will also determine the achievable ac resolution, which leads to lower precision if small ac signals are imposed.

Therefore, laboratory instrumentation required for high-precision impedance measurements on batteries was developed at ISEA several years ago and is still being improved. With the so-called ISEA *EIS*meter, it is possible to measure the impedances of energy-storage devices at frequencies from 6 kHz down to frequencies as low as a few microhertz with very high accuracy. Very high long-term stability of the instrumentation allows for measurements at virtually any low frequency. Technical details about the *EIS*meter as well as theoretical calculations and reference measurements concerning the accuracy of the *EIS*meter, can be found in [1].

Impedance measurements down to the micro-hertz region are very time-consuming. The duration depends on the number of sine periods per measured frequency and on the number of measured frequencies per frequency decade. With $p = 3$ periods per frequency and $N = 8$ frequencies per decade, the duration of an impedance spectrum is $T_{SPK} \approx 12/f_{min}$. Thus, a measurement down to a frequency of 30 μ Hz, for example, requires a measuring time of approximately 111 h, which is more than four and a half days.

Furthermore, results are difficult to compare when achieved in consecutive measurements. This is especially the case if impedance measurements are performed in parallel to normal operation where the state of the battery is changing continuously. To accelerate systematic measurements of impedance spectra, ISEA developed an improved multi-channel *EIS*meter (Fig. 1, [1]). It allows synchronous impedance measurements of up to 14 impedances within one string, composed of different cells, blocks or half-cells. It also provides up to four current channels for the ac current signal and dc bias. The *EIS*meter has been completely developed and implemented in hardware and software by ISEA especially for measurements on batteries over a wide frequency range. It has a flexible, modular set-up and further development of the software allows custom-made features. The multi-channel *EIS*meter uses the galvanostatic method, i.e., a sinusoidal ac current is applied to the device under test. The amplitude of the ac current is automatically controlled by the *EIS*meter to get a user-defined voltage response per cell and to make sure that the measurement is carried out in the linear part of the characteristic curve. In addition, with the dc current channels, it is possible to operate the battery at any point of the non-linear electrochemical characteristic. The *EIS*meter enables measurements of impedance in the m Ω range and can therefore be used for batteries, double-layer capacitors and fuel cells. Approximately 10 units have been built and are in operation in different labs of project part-



Fig. 1. The multi-channel impedance spectroscopy *EIS*meter (shown with industrial lead–acid batteries) is used to carry out impedance measurements on batteries, supercapacitors and fuel cells with up to 14 simultaneous impedance measurements on half-cells, cells, stacks or blocks.

Table 1
Technical data of multi-channel *EIS*meter

Four current channels	
ac current range (A channel ⁻¹)	-1...+1 (-4...+4)
Frequency range	6 kHz–1 μHz
dc current range (A channel ⁻¹)	-10...+10 (-40...+40)
Voltage range (V)	4–20 (0–20)
Fourteen voltage measurement channels	
Voltage range (V)	0–20
Resolution (μV)	7
Precision (measured on a 1 mΩ reference shunt)	
Standard deviation of Z (%)	<2
Standard deviation of φ	<1°

ners. Some technical specifications of the *EIS*meter are listed in Table 1.

With the *EIS*meter, a significant reduction of the measuring time can be achieved as well as a real parallel assessment of the impedance. The latter is of great importance, as electrochemical devices tend to change their performance with time in ways that are difficult to predict.

3. SoC determination from impedance measurements

Rechargeable batteries have demonstrated a rapid growth in many areas of battery usage. For practical purposes, prediction of the residual capacity with sufficient accuracy is required. The state-of-charge of lead–acid batteries cannot be deduced by simply measuring the open-circuit voltage, due to diffusion time constants and acid stratification effects. Determination of the SoC from a complete discharge–charge cycle is the most reliable means, but is expensive and time-consuming and leaves the batteries out of service during the testing time. An overview on conventional procedures and their limitations has been reported by Piller et al. [2].

Electrochemical impedance spectroscopy has been proposed as a fast, non-destructive and reliable alternative method to determine battery SoC [3,4]. Its objective consists of extracting one or many electrical parameters, which vary monotonously as a function of the battery SoC from the impedance spectra. These parameters must be: (i) simple to measure; (ii) reproducible; (iii) quickly accessible.

Since high frequencies are much more attractive for quick SoC estimation, most published work focuses on the measurement of the cell internal resistance (R_i). In case of lead–acid batteries, the sulfuric acid electrolyte takes part as an active species in the electrode processes. Therefore, the associated ohmic resistance is affected due to depletion of the acid concentration during discharge, making possible the detection of SoC from the measurement of the R_i parameter. Experience has shown, however, that such a parameter: (i) displays only little variation for a SoC > 40%; (ii) is greatly influenced by the short-term battery history due to electrolyte gradients that effectively mask the SoC effect; (iii) exhibits a non-monotonous concave shape during battery charging, due

to the concomitant gassing reactions, which hinder the reliable exploitation of this parameter for SoC estimation. Satisfying results were obtained from measurements conducted at various SoCs on value-regulated lead–acid batteries only after allowing time for the system to stabilize [5]. As such conditions are available only in very few applications or in periods of little interest for the user, these methods are of little value.

Previous laboratory research performed on high-frequency impedance parameters that related to the SoC of nickel–cadmium and nickel–metal–hydride batteries [6] and lithium-ion batteries [7] had little significance because the electrolyte (which gives the major contribution to the cell ohmic resistance) does not participate in the overall electrode processes. A pronounced effect on SoC was observed on those electrical quantities extracted from the low-frequency region of the impedance diagrams, such as the impedance modulus, the phase angle and the admittance. It should be noted, however, that measurements at low frequencies are time-consuming and hence, less suitable for routine monitoring of cells in service.

We have proved that it is still valuable to explore the high-frequency impedance values by exploring the mixed inductive–capacitive dynamic behaviour of the cell instead of the real impedance part as has been undertaken in other published studies. In the 5000–10 Hz frequency region, where inductive behaviour is strongly present, the cell shows a mixed inductive–capacitive behaviour on either side of the transition frequency f_{\pm} . At this frequency, the self-impedance contribution equals the capacitive one and results in an imaginary part that equals to zero. Unlike the inductive contribution, which is usually considered as constant at various SoCs, the capacitive behaviour, depends strongly on SoC. Simply speaking, the inductive impedance is used as a probe to measure the capacitive impedance. The capacitive impedance in the given frequency range depends mainly on the double-layer capacity and is therefore a good measure of the available active surface of the electrode materials. Thus, the particular frequency f_{\pm} with pure real impedance changes with SoC. Indeed, careful examination of the experimental spectra plotted at various SoCs shows that the f_{\pm} frequency parameter varies monotonously and reproducibly as a function of battery SoC. In practical applications, it is easy to determine the transition frequency f_{\pm} with a precision of a few Hertz and the necessary hardware is simple (patent pending).

Investigation on commercial alkaline nickel–cadmium and nickel–metal–hydride batteries [8] showed a clear-cut relationship between SoC and f_{\pm} , deduced from impedance diagrams plotted immediately after intermittent charging and discharging or during battery charge and discharge. This approach has recently been extended to commercial flooded lead–acid batteries and has demonstrated this correlation by impedance measurements performed at temperatures between -18 and 50 °C. A monotonous dependence of f_{\pm} on SoC obtained on a 70-Ah automotive flooded lead–acid battery is shown in Fig. 2. The variations in this parameter are

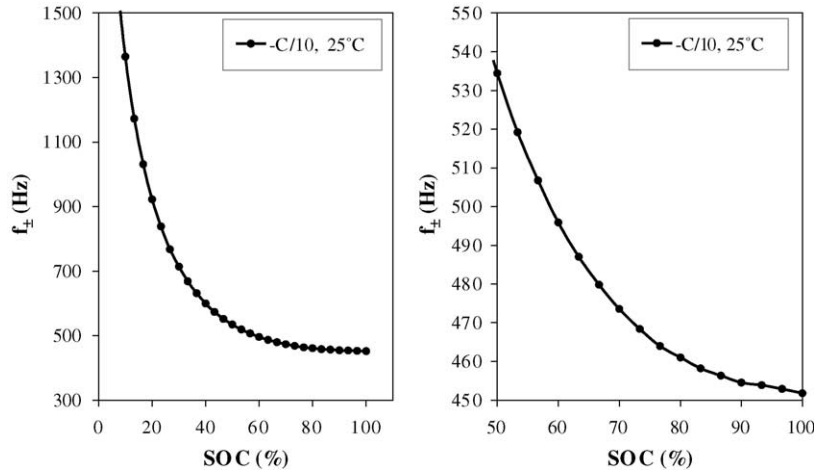


Fig. 2. Transition frequency for a lead–acid battery during discharge at C/10 as a function of SoC (left-hand figure: full SoC range, right-hand figure: magnification of SoC range 50–100%).

considerable with regard to its sensitivity to SoC changes; they are about 600 Hz at -18°C and 3000 Hz at room temperature, when the SoC decreases from 100 to 0%. Consequently, the parameter f_{\pm} can also serve reliably as a robust, sensitive and precise tool for indicating the SoC of lead–acid batteries. This assertion is being validated for other types of battery technology; e.g., valve-regulated lead-acid, lithium-ion batteries, that are of tremendously increasing importance for large-scale industrial applications. Actually, the mixed inductive–capacitive dynamic behaviour from which the parameter f_{\pm} is evaluated, is a specific feature of all electro-chemical power sources in view of their low-resistance and large-electrode capacitance.

Despite the above findings, a purely impedance-based approach will fail. As mentioned above, frequency ranges and allocation of transition frequency to SoC depend, for example, on the temperature. Therefore, it is necessary to combine the measurement of the transition frequency with some self-learning algorithms. Such an approach allows calibration of the transition frequency/SoC relation during periods where the SoC is well known, e.g., from Ah balancing.

4. Determination of cold-cranking capability

In many applications, the demand on batteries is not only to serve as an energy-storage device, delivering moderate power for a long time, but also to deliver high power for short periods. Examples of such pulse-power applications are the boost modes of hybrid vehicles, x-by-wire technologies, the idle–stop mode for mild hybrid vehicles and the cranking of internal-combustion engines (ICEs), e.g., in a conventional vehicle. It is therefore essential to have a reliable prediction of the batteries power capability. Based on this, it is possible to decide whether the vehicle can operate in idle–stop mode or if the engine has to keep on running whether to charge the battery safely. Especially for safety-relevant applications

such as steer-by-wire and brake-by-wire, it will be mandatory to give an early warning to the user when the battery leaves its safe operating area due to ageing or insufficient charging.

In a modern vehicle, these tasks are realized by an intelligent energy-management system that monitors the state of the battery and predicts its performance with respect to certain functions. Based on this state-of-function (SoF), necessary measures can be initiated [9]. As mentioned above, cranking capability is beside others, an important parameter. Any failure during cranking could cause critical situations for the driver.

ISEA, together with an industry partner developed an impedance-based approach to predict the actual cranking capability (Akkumulatorenfabrik Moll GmbH & Co. KG, [10], patent pending). A simple battery model is directly parameterized by impedance measurements during normal operation. As the procedure is made for rather high discharge currents, the non-linearity of the battery impedance is neglected. A lumped-element battery model tailored for this kind of application is shown in Fig. 3.

The elements of the model reflect the main mechanisms that contribute to the battery impedance. R_i , the ohmic resistance is determined mainly by the conductivity of the electrolyte and the electrical pathway (poles, grid, active masses). R_{ct} and C_{dl} describe the transient behaviour, which

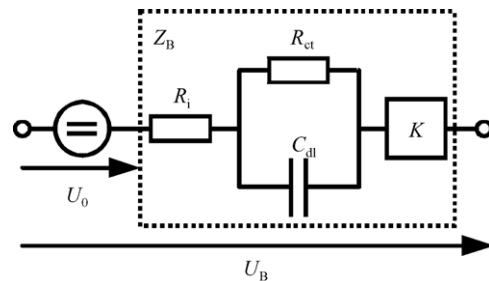


Fig. 3. Equivalent circuit of high-rate battery model.

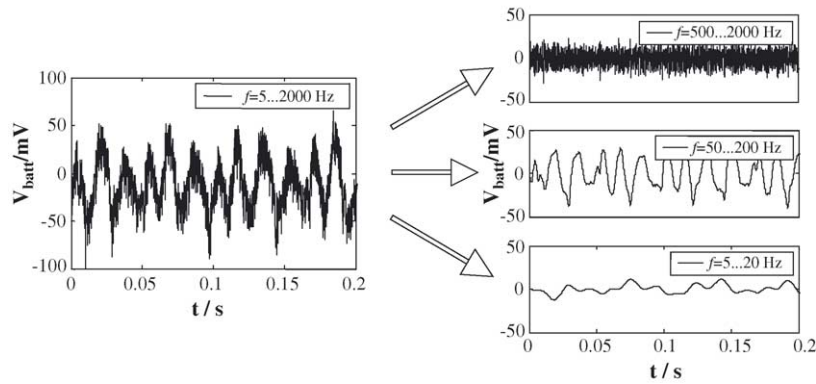


Fig. 4. Digital filters split voltage noise (left, measured in car) into different frequency ranges (right). Frequency ranges given as examples.

is caused by the charge-transfer reaction in combination with the double-layer capacitance at the surface of the electrodes. Finally, the element K describes local depletion of electrolyte in the pores.

Existing noise is used as a signal source instead of costly active excitation. No indirect and often unreliable quantities such as SoC are needed. Noise is caused by the loads and the alternator in the car. The signals occur in a broad frequency spectrum. For the analysis, they are split up with digital filter algorithms into current and voltage signals in different frequency ranges (Fig. 4). For an efficient and reliable algorithm, a good compromise between the quality of the signal (low bandwidth) and the signal strength (wide bandwidth) must be found. Details of the procedures can be found in [10].

The resulting current and voltage ripple profiles allow the calculation of the real part of the impedance for the different frequency ranges. Through intensive tests, specific frequencies have been identified to describe the battery performance (described by the voltage drop) best at a certain point of time after the start of the cranking process (Fig. 5). A complete hardware for measuring current, voltage and temperature, calculating the impedance and for analysing the cranking capability has been built and tested in the laboratory and in a car. The current measurement must have a resolution of 10 mA in a dc current range from 0.1 to 1000 A.

Once the parameters of the model are known, the voltage response on a pre-defined current profile can be calculated.

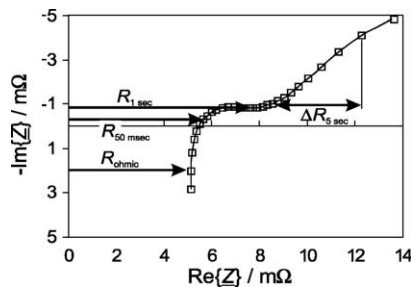


Fig. 5. Measurements at certain frequencies yield different effective resistances.

This current profile can be adapted for the desired application. For prognosis of the cranking capability, a simple test profile has been defined, which consists of a short, high-current pulse followed by a moderate cranking current for 5 s. The model predicts the voltage response immediately, 50 ms, 1 and 5 s after the start of the current pulse, as in Fig. 6. Conventionally, the cranking capability would be determined by the lowest voltage during cranking. The proposed method allows, however, a more sophisticated prognosis, e.g., if a lower voltage limit is defined for short-voltage dips (Fig. 6).

This prognosis is valid as long as the state of the battery does not change significantly between the measurement of the model parameters and the pulse load. Nevertheless, a new determination of the parameters, especially those based on high frequencies, can be made frequently during operation of the car. If the car is parked either the signals caused, for example, by the alarm device or other regularly operating devices can be used. If such devices are not available, a short start-up caused by the energy management system can make the signals available instead. No information about the temperature, the SoC or the state-of-health (SoH) is needed for the prediction of the power capability. First of all, this makes the vaguely-defined SoH parameter dispensable, because its effect on the dynamic behaviour of the batteries is directly being measured. Consequently, this short-term prognosis is especially valuable for applications such as start-stop operation. Comparison of the measured voltage drop and the

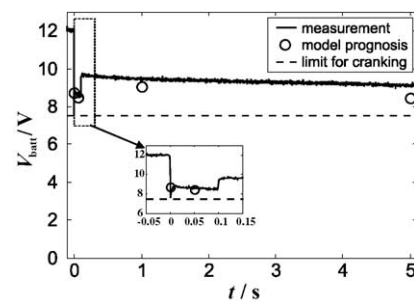


Fig. 6. Measured battery voltage and impedance-based prognosis of battery voltage during cranking pulse of 500 A for 100 ms continued by 350 A for 5 s.

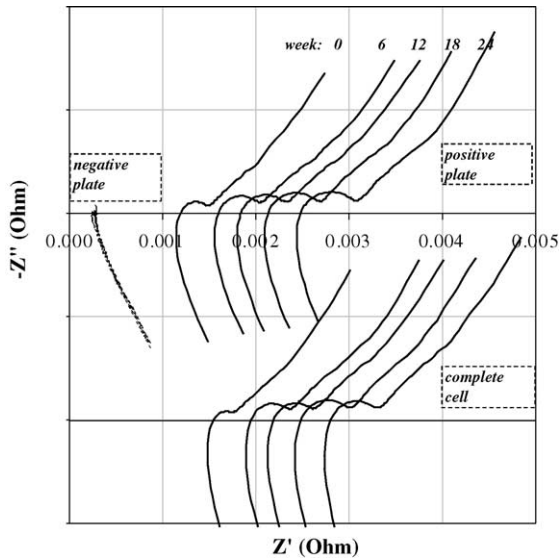


Fig. 7. Impedance diagrams for lithium-ion batteries and half-cells after storage at elevated temperature for various periods.

predicted value showed that all cases where the battery failed have been predicted correctly. Only in very few cases where the battery was still able to deliver the cold-cranking power was a failure erroneously predicted.

5. Identification of ageing effects

Electrochemical impedance spectroscopy is a method chiefly employed for investigation of electrochemical phenomena and electrical properties of batteries and battery electrodes. Since processes with different time constants are easier to identify in the frequency domain, EIS has been proposed to disclose the actual origin of battery ageing processes that are hardly recognised by traditional test methods.

In order to assess the cycle life and calendar life of lithium-ion cells, the EIS technique was applied to characterize cells subjected to accelerated ageing by means of continuous cycling and heat treatment during a couple of months. Full impedance spectra are plotted at time intervals or at different cycle numbers on complete cells and on half-cells. The impedance data are interpreted in relation to the results of regular performance check-ups. The following examples show how the major ageing effect during an accelerated ageing experiment can be identified very early and without destroying the cells.

A lithium-ion battery was stored at elevated temperature. Impedance and capacity were measured every 6 weeks. With the help of a reference electrode technique, the impedance was determined separately for the positive and the negative electrode. Already at an early stage of the evaluation, a steep increase in the ohmic and internal resistances is identified (Fig. 7). It can be noticed that change in the cell impedance is mainly due to the increase in the ohmic resistance. The shape of the half-circles and the angle of the diffusion branch remain

almost unchanged whereas the ohmic resistance is continuously increasing (lower part of Fig. 7). Analysis of half-cell impedance indicates that, while the negative impedance does not vary significantly, the major contribution comes from the positive electrode. In addition, the fact that the ohmic resistance of the negative remains unchanged implies that the electrolyte is stable over the testing period. The change in the cell impedance is therefore most likely due to the increase in the resistance of the contact area between the electrical current-collector and the positive active-mass. This result was confirmed later by physico-chemical tear-down analysis of the cells.

The example shows the potential of EIS as an in situ analysis tool to support the development process of batteries and strongly suggests its use as a specific test method for non-destructive continuous observation of the ageing degree under different operating conditions. This will undoubtedly reduce the technical effort and therefore time and costs, when impedance spectroscopy could substitute the physico-chemical post-mortem analyses. A multi-channel impedance spectroscope is necessary to allow for simultaneous measurement of half-cell potential with the help of a reference electrode. Measuring only the overall cell impedance will hardly allow identification of the reason for loss of performance.

Nevertheless, it is still recommended to verify the results at the end of the tests by tear-down analysis. The combination of both methods results in a precise determination of the major ageing effects and their evolution during the test period. The latter is possible because of the fully non-invasive nature of impedance spectroscopy. Development processes of new batteries can be accelerated by using this technique.

6. Impedance-based battery models

Simulation-based development methods are increasingly employed to cope with the complexity of modern power electronic systems. For these methods, suitable sub-models of all system components are mandatory. Compared with the sub-models of most electric and electronic components, however, accurate dynamic models of electrochemical energy-storage devices are rare. Fast computing and small parameterization efforts are favourable. Batteries show several characteristics that make a simple modelling with high precision nearly impossible. Batteries are not stationary, they are highly non-linear and their dynamic behaviour depends on different parameters such as temperature, SoC or short-term history.

Given the above issues, electrochemical impedance spectroscopy is a unique tool for the development and parameterization of battery simulation models. Small-signal excitation and evaluation of the system response enables accurate investigations at nearly any working point. Reasonably good simulation models can be achieved without having proper information about the chemical composition, as well as the inner geometrical design of the device. The computing time

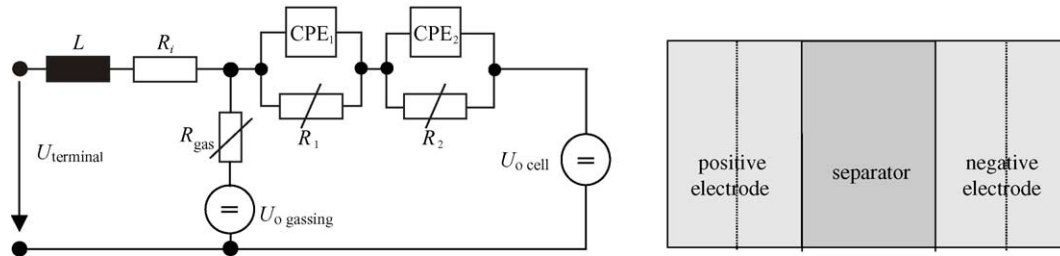


Fig. 8. Equivalent circuit of impedance-based battery model (left-hand), and schematic representation of battery cell as a basis for electrolyte transport model (right-hand).

for the simulation is very short compared with physics or chemically-based models.

Several authors have published different approaches and concepts on impedance-based battery models [11–19]. Impedance-based simulation models for various energy-storage devices (double-layer capacitors, lithium-ion, nickel–metal-hydride or lead–acid batteries) have been developed by ISEA [1,20]. These models are mainly used for the simulation of highly dynamic battery operating conditions (e.g., modern automotive power nets) and consist of elements that are related to physico-chemical processes [22]. Although the highly dynamic behaviour is represented very well by this technique, long-term effects are better modelled in the time domain. A combination of both approaches results in highly precise hybrid models.

To achieve stable and coherent impedance data, two factors are important: (i) a dc-bias current must be applied to allow evaluation of the non-linear region of the electrochemical reactions; (ii) the SoC may not change by more than 5–10% during measurement of the complete impedance spectrum [22]. It is clear, however, that these two requirements are contradictory for low frequencies. Therefore, the frequency range is limited and hence it is impossible to carry out measurements in the very low frequency range. Consequently, dynamic effects that govern long-term discharge behaviour of the battery are not accessible for impedance methods. In particular for lead–acid batteries, the electrolyte transport processes are not covered by the purely impedance-based

battery model if the acid concentration becomes inhomogeneous. Therefore, the lead–acid battery model has been extended with a basic electrolyte transport model to expand the model validity.

The following sections illustrate a hybrid modelling approach, which combines the impedance-based model and a basic electrolyte transport model. An equivalent circuit for a complete battery cell can be obtained by a series connection of two Randles circuits ([23]; Fig. 8, left-hand).

A few modifications [22] have been made to the purely impedance-based, lead–acid battery model, namely: generalized capacitive elements (CPE: constant phase element); a generalized dc-voltage source (considering the open-circuit voltage); a parallel current path for the side-reactions. For the model extension presented here, the generalized dc-voltage source, which depends only on the SoC of the battery, has been replaced by a voltage source using the actual acid concentrations in both electrodes as the basis. The acid concentrations are calculated by means of the transport model. To minimize the computing speed, a simplified spatial resolution with only three elements (positive electrode, negative electrode, separator) has been chosen (Fig. 8, right-hand side).

The measured and the simulated battery voltage is shown in Fig. 9 for a load profile that represents a battery application in a stop–start (engine idle–off) passenger car with high loads. The battery is an automotive value-regulated lead–acid (AGM) type ($U_N = 12$ V, $C_{20} = 44$ Ah). It can be expected that this profile will cause significant acid concentration gradients

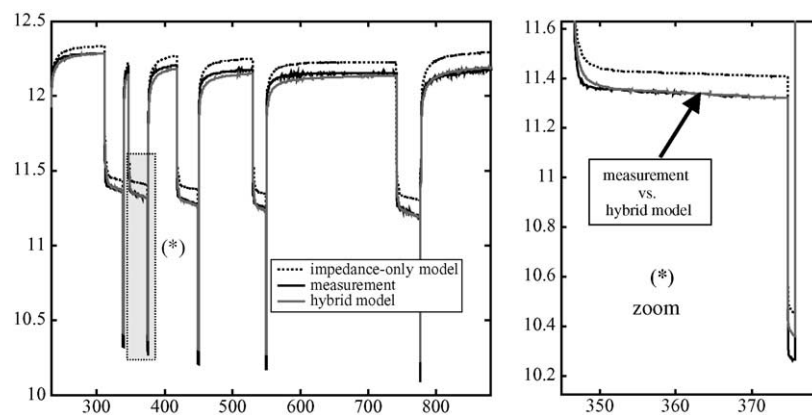


Fig. 9. Measured and simulated voltage responses.

within the electrodes. The dotted lines in the diagrams illustrate that the validity of the purely impedance-based simulation model is restricted to small variations in SoC. The hybrid model, which includes the new transport model (solid grey line), fits the experimental battery voltage significantly better. Both the voltage under load and the relaxation of the battery voltage during rest periods can be simulated more accurately. This remarkable improvement of the validity range of the model can be reached despite the fact that spatial resolution of the transport model and thus, numerical efforts is restricted to a minimum.

The procedure developed at ISEA allows parameterization of the battery models with a minimum knowledge of details of the battery and is therefore easy to apply [20]. A detailed presentation of the hybrid model approach is given in [21].

7. Summary

Impedance measurement is a powerful tool for prognosis of the state-of-function of lead–acid batteries. Approaches to determine SoC, cranking capability, ageing effects and parameters for dynamic modelling have been presented. All approaches are developed in close co-operation with industry partners. Therefore, they are very much application-oriented and tested under severe operating conditions.

It becomes obvious that impedance spectroscopy is a powerful tool, if applied appropriately. This can be achieved through combination of different methods to obtain certain information reliably and under any conditions. Impedance spectroscopy requires battery-operating conditions to be very precisely defined for the delivery of reproducible results, which might occur under real operating conditions only rarely. Therefore, it is necessary to identify appropriate specific moments for the impedance measurement. Furthermore, algorithms to interpolate the state-of-function between these specific moments are necessary. Based on today's hardware platforms for battery and energy management systems, implementation of additional algorithms is no longer a problem. Combinations of impedance-based models and models in the time domain assure model validity over a wide range of time constants, self-learning algorithms allow for reliable SoC determination and automatic adaptation for different battery types and aged batteries, and electrochemical tear-down analysis enables correlation of impedance measurement results with ageing effects.

In any situation, it is very necessary to analyse the specific benefit that impedance spectroscopy can give to a given problem, and how the technique can be incorporated into a

valuable algorithm. Solving problems with impedance spectroscopy is never simple, but offers great opportunities when used adequately.

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