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Characterizing electrochemical systems used for high-current application by measuring the short circuit current and the internal resistance

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Abstract

A method to characterize an electrochemical system like a battery for HEV or EV application is the measurement of the internal resistance. In the literature many different approaches to determine the parameters of a battery are described. The standard methods to diagnose the state of health of a battery system are typically based on tests with small currents, i.e. impedance spectroscopy, even though the information about the state of health is also required for systems which are used in a high-current application.

The method described here is focused on the measurement of the high power response in combination with a short circuit test.

Keywords: battery, battery model, electric vehicle, internal resistance, car

1 Introduction

A method to characterize an electrochemical system like a battery is the measurement of the internal resistance. In the literature many different approaches to determine the parameters of a battery are described. The method described here is focused on the measurement of the high power response in combination with a short circuit test. Based on the information of the internal resistance estimates of lifetime and of the peak-power capability are possible.

To characterize an electrochemical system many different methods are known and are used by various battery diagnostic methods. They differ by the manner of stimulation and the analysis in the time or in the frequency domain. Table 1 shows a selection of methods described in the literature.

Table1: Standard methods for characterization of electrochemical systems

Method	frequency (f) or time domain (t)	Ref.
Electrochemical Parameter Identification	t	[1]
Current-Interrupt	t	[2-6]
Periodic Current Interrupt	t	[7]
Current sweep	steady state	[8-10]
Voltage-Step Chrono-Amperometry	t	[8,11]
Current-Step Chrono-Potentiometry	t	[8,10-13]

Current-Pulse Chrono-Potentiometry	t	[2,8,11, 14-16]
High Frequency / AC Resistance	f	[4]
Electrochemical Impedance Spectroscopy	f	[1,10,14, 16-18]
Hybrid Pulse Power Characterization	t	[19]

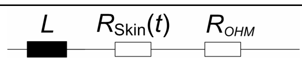
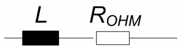
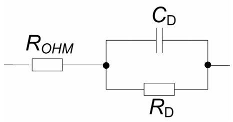
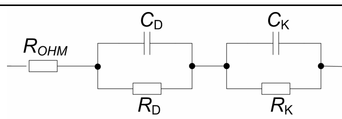
The standard methods to diagnose the state of health[1] of a battery system are typically based on internal resistance measurements with small current amplitudes, even though the information about the state of health is also required for systems which are used in a high-current application. To start an internal combustion engine, a lead-acid battery has to provide a peak current of approx. 800A (depending on cubic capacity, temperature and starting capability of the engine) and an average current of 400A for nearly 2 seconds. On closer consideration of this application it is to be asked if tests with small currents can achieve an exact estimate of the state of health.
Therefore the methods pursued here are:

- Peak-power capability estimate by analyzing the starting process of an engine
- Voltage response analysis based on a (high) current charge/discharge pulse and short circuit test

If a high-current test is used it is important to use a short test time to ensure that battery properties are not changed by the test or the battery is not damaged. The best option for a high-current test would be the diagnostic via the starting process of the engine or, for the application in hybrid-vehicles, the analysis of the measured data during an acceleration phase.

For characterizing the battery system an equivalent circuit diagram (ECD) is useful. In the literature different ECDs can be found, the necessary complexity of the model depends on the examined time domain. Table 2 shows different, quite simple ECDs with the appropriate time domains. The properties of a system, e.g. in the range of a few minutes can thus be described using the fourth ECD. A minimum sampling rate of 10 kHz respectively 0.1 ms is required for parameter determination.

Table2: Equivalent circuit diagrams of an electrochemical system for different time domains. R_{Skin} in the µs range describes a time dependent resistance caused by eddy currents and can be explained by consideration of the so called transient skin effect [20-22]

time domain	equivalent circuit diagram
µs	
µs … 0.1ms	
0.1ms …. 0.1s	
0.1ms ... min	

To estimate the state of function as regards short, high power applications (ms range), the determination of the resistance of charge transfer across the electrolyte/electrode interface described by the Butler-Volmer equation (time domain seconds) and the resistance associated with diffusion overpotential (time domain seconds to minutes) are not necessary.
The investigations described in this paper are focused only on the purely ohmic part of the internal resistance, which consists of the electrolyte, grid, corrosion and passivation layer and the active material of the battery system and a time period of few milliseconds. The main benefit to operate in this time domain is that no further special measurement and data logging hardware is required. The microcontroller with the current and voltage measurement units used typically in charging and diagnostic devices provides the necessary performance (0.1ms…2s, 0A…1000A) to enable the analysis of the ohmic resistance. Both in conventional as well as hybrid vehicles battery sensors are used for monitoring the energy storage system. Recent developments have led to a module combining a precision shunt and an ASIC (Application Specific Integrated Circuit) which can be programmed by the customer with proprietary software to evaluate state-of-charge

[1] Here defined as nominal capacity – threshold capacity according to Meisner [23].

and ageing and communicate with the vehicles control systems via the vehicle bus. The integration of the diagnostic procedures described below into such a module will probably not lead to any major problems as the modules have been used in production vehicles for more than two years, provided that reference data for state estimation are available.

2 Method A: dynamic high-current test, exemplified for a starting process

In figure 1 the terminal voltage (bottom) and discharge current (top) and in fig. 2 the normalized diagram of voltage against current during a starting process are shown. The starting process can be split into a high current pulse (high torque) and a medium current phase. Both values are characteristic for the state of function of the battery system.

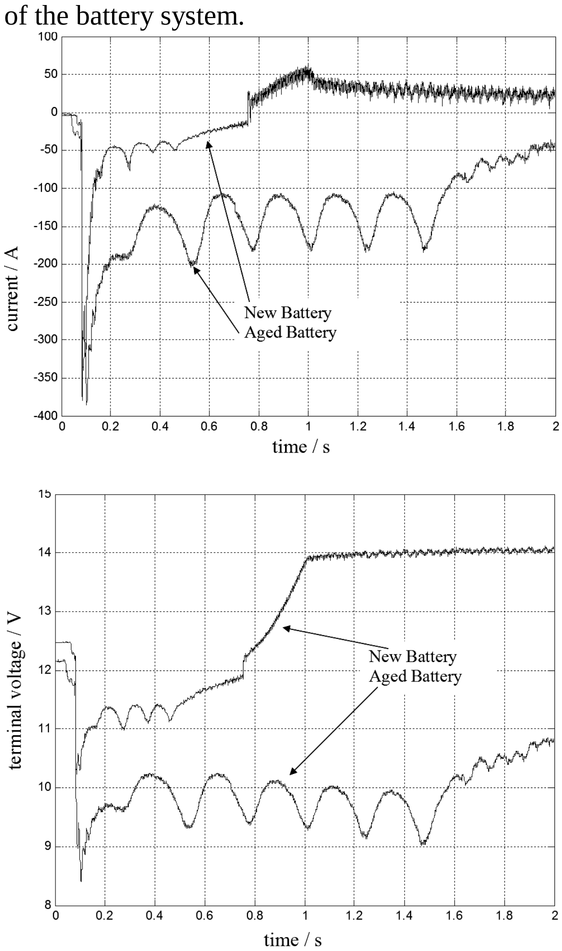


Figure1: Comparison of current (top) and voltage (bottom) during starting of an internal combustion engine (petrol engine 1124 cm³) using starter batteries with different ages.

It can be recognised in figure 1 that the peak current is very similar for both batteries which can be explained as being the result of discharging the plate capacitor of the battery. The total resistance in a vehicle for starting is the sum of the resistance of a number of individual components, e.g. connections and leads with a combined resistance of ca. 7mΩ, the starter motor with a resistance of ca. 10mΩ and the battery with an resistance of ca. 5mΩ [data as given by BMW AG]. It can be assumed that the resistance of the car components (contacts, leads, starting motor) are constant and that the internal resistance of the battery will vary. A comparison of the rest voltages of the batteries already allows the identification of the weaker cell. Significant differences can be seen from the voltage drop of the aged battery which is much greater than the voltage drop of the newer battery as a result of the higher resistance of the aged battery. The voltage shows clearly the power fluctuations as a result of compression in the cylinders and the decrease of the average voltage during the starting process. This is a clear indication of a severely aged battery. The current remains nearly constant during this time and the engine does not start. Only after a number of compressions the engine reachs the minimum speed which is required for unassisted operation. The time required for starting is considerably longer when using an aged battery. As both measurements were carried out with the same vehicle under identical ambient conditions, a direct comparison between the batteries is possible.

As a consequence of the above described comparison of these measurements, different evaluation procedures can now be proposed and investigated. They are:

- Starting time
- Gradient of average voltage
- Internal resistance (in the time domain of less than 100ms)
- Load characteristics

The focus in the following section is on the evaluation of load characteristics as this procedure leads to promising results.

The load profile of the battery, a diagram showing the load current as a function of the terminal voltage, provides information on the performance capability of the battery. The voltage of an aged battery falls more quickly for a given current than the voltage of a new, better performing battery. In addition, the voltage drop is also a function of the state-of-charge of the battery so that this influence has to be taken into account properly. Diagram 2 below shows the evaluation of a highly dynamic load profile. The normalised terminal voltage is drawn as a function of the normalised discharge current. For normalising, the maximum voltage drop and the maximum discharge current are taken as reference values. The differences of the measurement points from the reference line are a measure of the performance capability of the energy storage.

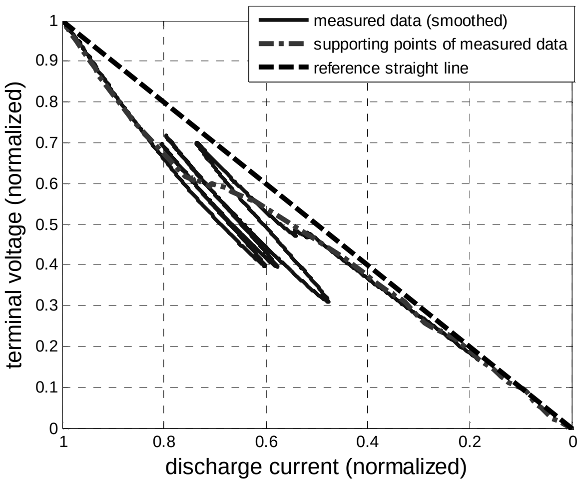


Figure 2: terminal voltage against discharge current with normalized values of an aged battery during a staring process of a combustion engine

The diagram shows the curve for a strongly aged battery. The curve for a new battery with full power capability (not shown) lies above the reference line. If there are many measurement points below a set range respectively below the reference line, then this is a clear indication for a significant loss of power capability. This evaluation procedure is particularly promising for highly dynamic load changes with high currents as in the case of starting of an internal combustion engine. This evaluation procedure will probably also be suitable for hybrid vehicle applications where the battery is subjected to currents of ±150A and more and an integral current and voltage measurement device exists.

Additionally the gradient of the supporting points of measured data can be used for the evaluation: The lower the gradient, the higher the loss of performance.

Another method of evaluation is a histogram of the distribution of measurement points (see figure 3). The diagram at the top shows the distribution for a new battery and the diagram at the bottom for a strongly aged battery. The values of the x-axis are normalised identical to diagram 2. The distribution shown on the y-axis is the frequency of the occurred current or voltage.

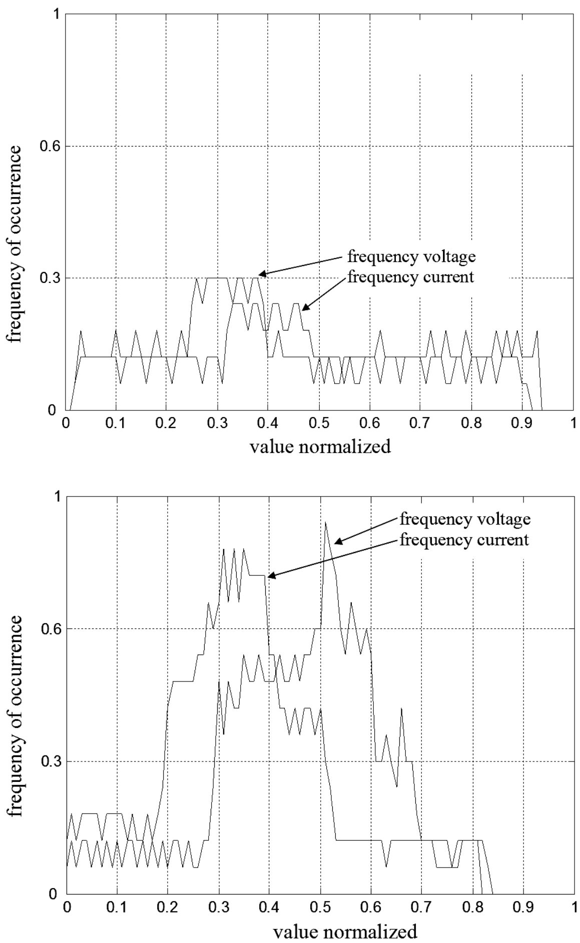


Figure 3: Distribution of the values of the terminal voltage during a highly dynamic shot load: top a nearly new battery and bottom a strongly aged battery

It can be clearly seen that the cumulative percentage as well as the distribution of the respective maximum values changes. All these procedures can be easily implemented into a diagnostic system with little effort as the source code has been developed during the term of the research project. However, the threshold values for assigning „good battery“ versus „bad battery“ still have to be determined. In addition, these procedures require recording of the total starting process (without recharging phase) in order to allow evaluating the measurement data according to the above described evaluation procedures. This should be possible at acceptable costs as microcontrollers with integrated storage are available.

3 Method B: short circuit test to determine the ohmic part of the internal resistance

A further method to characterise electrochemical systems is the determination of the ohmic resistance as a portion of the total internal resistance by means of a constant high current discharge and the evaluation of the short circuit behaviour.

In order to carry out such measurements, a highly dynamic pulse inverter (HoBIS)[2] has been developed at the Institute of Electrical Power Engineering (IEE) of Clausthal University of Technology. The inverter allows current steps of ca. 50A/µs at a maximum current of ±200A and was used for the high current tests (50A, 100A, 150A, 200A) described below. For short circuit testing, a special short circuit tester was developed with a total resistance of 2.7mΩ including leads, shunts and connections. This short circuit tester allows investigating the current and voltage behaviour of different battery technologies. Voltage was measured using a voltage divider and the current using a coaxial shunt. Data storage and evaluation was carried out using a dSPACE-System (DS1103) with a sampling rate of 20kHz.

For the results shown here, high current tests with 50A, 100A, 150A and 200A for 2 seconds, as well as short circuit tests for 1 second were carried out for lead-acid, NiMH and lithium-ion cells respectively modules were carried out. Based on the recorded current and voltage curves the ohmic resistance of the system was defined as the resistance after one millisecond ($R_{ohm}=R_{1ms}$) was determined (see figure 4). Using a shorter value is impractical and also leads only to a negligible difference.

[2] For more information see the final report EFRE-project 2005.188 “Development of a portable testing and diagnostic device for starter batteries”

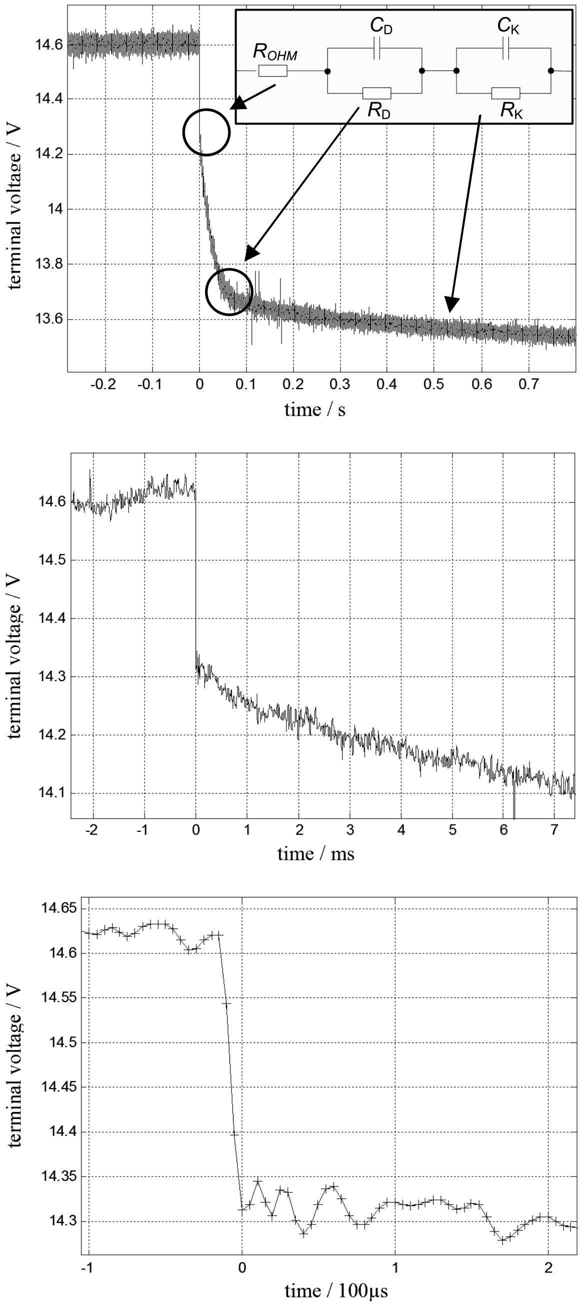


Figure 4: Voltage after a 25A charge pulse shown in a time frame of 1s (top), as well as enlarged with a time frame of 10ms (middle) and 300µs (bottom) of a 12V lead acid starter battery with a capacity of 45Ah for determining the ohmic portion of the internal resistance.

As can be seen from figure 4, the ohmic portion of the internal resistance can only be detected in a considerably smaller time frame (1µs) as the value used subsequently (1ms). Ideally the measurement value at approximately 0.1ms or even after a shorter time should be used, which, however, requires a sampling rate considerably above 10kHz. If measurement systems with such a high sampling rate are available, they should also be used for evaluating the data. The error of ca. 40mV which is introduced is acceptable as the algorithm used for evaluation does not necessarily require absolute values but can use changes of relative values.

Based on the measurements, the equivalent circuit diagrams for the time domain of more than 1 millisecond shown in table 1 can be parameterised. For determining the inductance and the skin resistance, data with a much higher time resolution are needed.

In figure 5 the calculated values of the ohmic resistance are shown for different battery technologies. The values are determined by different high current pulses including the short circuit current and a time domain of 1ms. The represented electrochemical systems (lead-acid (Pb), nickel metal hydride (NiMH) and lithium-ion (Li-ion)) have different nominal capacities, voltages and states of health.

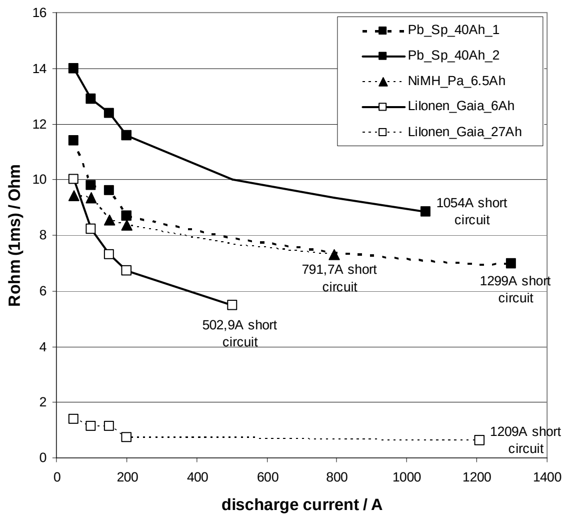


Figure 5: Internal ohmic resistance of various battery technologies; peak power capability of lithium-ion round cells made by GAIA with various nominal capacities. (Short circuit: Load resistance of 2.7 mΩ as a result of MOSFETs, shuts and cables), (Data points between 200A and short circuit current are interpolated)

Ultimately, in order to carry out state estimation using this type of measurement data, a reference measurement is required for the cell under investigation so that a resistance value can be assigned to it corresponding to its age or state of function. For the evaluation it is not necessary to carry out a complete measurement series covering many different discharge currents. It is sufficient to use one or two well defined discharge currents.

As an example the measurement data of some NiMH modules are shown, each consisting of 6 cells. In diagram 6 below, three prismatic Panasonic modules with a nominal capacity of 6.5Ah and two Sanyo modules with round cells and a nominal capacity of 6Ah are shown. An exact determination of the state of ageing of the modules had not been carried out. As a result of the identical time of use and the series connection in a Toyota Prius, a uniform ageing of the prismatic cells can be assumed.

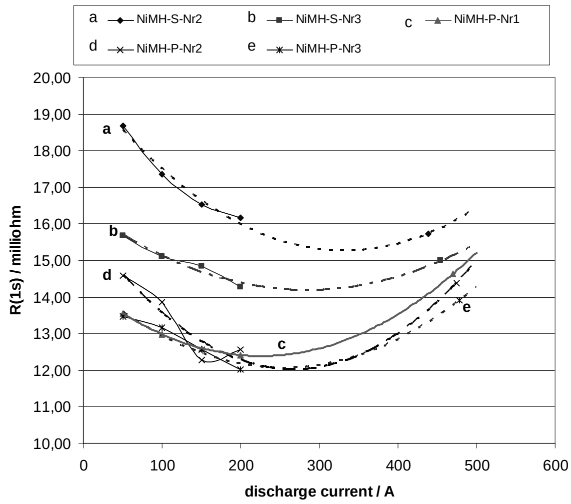


Figure 6: Internal resistance (R_{1s}) of three prismatic NiMH modules (6 cells, Panasonic, 6.5 Ah) and two modulces with round cells (6 cells, Sanyo, 6Ah)

It can be clearly seen that the value of the internal resistance falls up to a discharge current of ca. 300A but then increases slightly when the modules are discharged with the short circuit current. This behaviour has only been observed for NiMH cells and very severely aged lead-acid batteries, but not for lithium-ion cells.

In order to prevent unnecessary stressing and discharging of cells during state estimation and to avoid the difficulties of taking this effect into account for the development of the algorithm, it seems appropriate to limit the maximum discharge current to ca. 300 A, e.g., by means of a resistance. The battery voltage must not fall below a threshold value when using this procedure in the vehicle with the battery connected to the onboard power supply system so that the function of the vehicle control electronics is guaranteed.

The changes of the absolute voltage or current values during a short circuit test can also be used for state estimation. Particularly aged cells show an increased voltage drop due to their higher internal resistance.
An additional option is the extrapolation of the equilibrium voltage based on the measurement data during a one second test and the comparison with reference data so that a first estimate of ageing can be carried out. Initial steps towards the development of such an extrapolation algorithm have been carried out in a recent research project where the voltage curve after a discharge pulse at different temperatures and state-of-charge have been measured in the laboratory and an extrapolation algorithm has been developed using these data as variables. In a further investigation the connection to an ageing model has to be done which has not happened so far.
The analysis of the power output during the time of the short circuit (which in reality had 2.7 mOhm due to the resistance of shunts, switches, connectors and leads) is possible. The voltage drop is used indirectly for this evaluation, too.

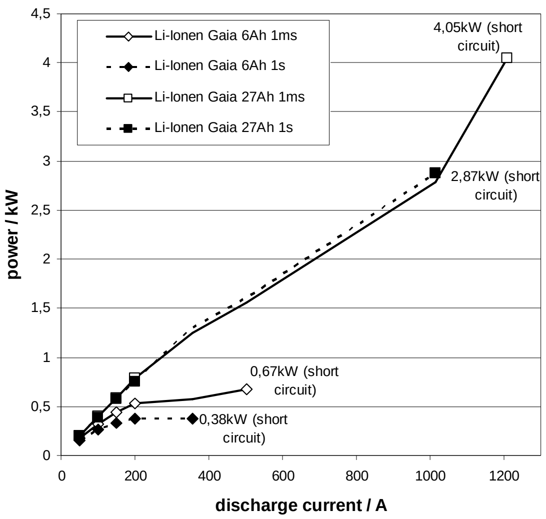


Figure 7: Maximum peak-power capability during a discharge time of 1ms and 1s (Data points between 200A and short circuit current are interpolated)

Figure 7 shows the maximum peak power during a discharge of 1 ms respectively 1 second of two lithium-ion cells (27 Ah respectively 6 Ah nominal capacity). The cells are from GAIA Akkumulatorenwerke GmbH with a nominal voltage of 3.6 V. LiNiCo based cathode material and according to the data sheet have a maximum 10 second discharge current of 865A (27Ah cell) respectively 1000A (6Ah cell).

4 Summary and outlook

For the diagnostic of a battery system using the internal resistance the voltage behaviour during the time of high power discharge and the discharge current have to be considered. By measuring the short-circuit current it is possible to get information about the peak-current and the resulting peak-power capability of the energy storage system. For systems which are used in high-power applications like starting processes of internal combustion engines and hybrid-vehicles the characterization via a short-circuit test is an impressive method to optimize the estimation of the state of health of electrochemical systems. In order to obtain reliable information on the state of the system, a number of measurement points are required. For instance, using three specified times of measurement at t=0.1ms, t=50ms und t=1s (see figure 4) it may be possible to generate a mathematical function for interpolating or extrapolating the values for the equivalent circuit diagrams shown in table 2.
As a result of the development of hybrid vehicles in particular, the question of what suitable methods for estimating state of charge and ageing arises. Estimating state-of-charge is less challenging for the development of algorithms. Ah-counting methods in combination with reference curves of equilibrium voltage versus state-of-charge for recalibration are used which offer sufficient accuracy according to today’s state of the art. New materials for lithium-ion cells, for example iron phosphate show a very flat curve of equilibrium voltage versus state-of-charge which make the application of such algorithms for estimating state-of-charge more difficult or may even prevent their use. Methods based on impedance spectroscopy which are widely used in laboratories have only limited use in vehicles as the impedance of the total on-board power supply system has to be account for the measurements. In addition, impedance spectroscopy is based on small signal excitation whereas of course in the vehicle there are mostly currents with high amplitudes so that reference data are not derived on the same basis. As a general principle cells used in dynamic high current applications should also be characterized in this way – also as the current profiles and measurement data are provided by the vehicle operation and do not have to be generated and evaluated by additional electronics.
The procedures described in this paper can be modified directly for the requirements of future hybrid vehicles and electric vehicles.

For the evaluation of starting processes a procedure for state estimation was proposed in detail which requires a high current profile as input. In further work, the results obtained so far have to be transferred to the current profile in the intermediary circuit of an electric or hybrid vehicle. The procedure described in chapter 3 can only be implemented in existing vehicle architecture by carrying out some modifications to it. An electronic switch as well as a current sensor has to be fitted in the on-board power supply system near the high voltage battery or starter battery. It is important to stress again that during a short high rate discharge current pulse of the battery under investigation, the voltage must not fall below a given threshold value so that the function of the vehicle electronics is not impaired at any time. For diagnosing a high voltage battery in a hybrid or electric vehicle, this restriction is of little importance as the vehicle electronics is supplied from the low voltage battery. The initial investigations of the approach presented here have shown promising results for transfer to electric or hybrid vehicles.

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