EXTENSIVE VALIDATION OF A NONINTRUSIVE CONTINUOUS BATTERY MONITORING DEVICE

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ABSTRACT

Several nonintrusive, continuous battery monitoring devices for lead-acid batteries in standby applications, such as uninterruptible power systems (UPS), are available today on the market. Some of them are using impedance measurements on every bloc of a battery string for determining the state of health of each bloc. The paper will present the results of an extensive validation test, comparing the results provided on the one hand by low cost monitoring devices and on the other hand by a full scale, laboratory impedance spectroscope. For the validation tests, accelerated ageing on many different lead-acid battery products have been performed. The batteries vary in terms of size (Ah), bloc voltage, battery brands and technologies. The targeted standby applications often use large batteries consisting of many single cells or monoblocs with six or twelve volts each connected in series. These batteries grow old during their utilization and show several ageing phenomena, which could lead to a reduced bridging time and, therefore, unforeseen failure of the system connected to the UPS in case of blackout. Nonhomogenous ageing of the cells or monoblocs is much more the normal case than homogenous ageing of all elements.

The scope of the investigation is a detailed analysis on impedance as a measure for the ageing. The aim is to qualify devices and procedures for the use in UPS systems and to understand, in detail, which ageing effects can be detected at which frequencies. A low cost monitoring system has been evaluated with regard to its performance to make use of the information, which is available through impedance from the battery.

The research comprises the analysis of the relation between capacity decline and change in impedance at various frequencies. The results show that certain ageing effects result mainly in an increase of the internal resistance, and detection by means of either impedance spectroscopy or even with a low cost device is reliable and efficient. For other ageing effects, only the combination of the impedance data with other data measured in the time domain (e.g. voltage) can give a full picture of the state of health for each element in a battery string when combined with the use of "intelligent" procedures and algorithms.

INTRODUCTION

Uninterruptible power supply systems (UPS) have become increasingly essential in more and more areas of applications, such as life support systems in hospitals, telecommunications, computer systems in major centers of finance, and many more. For such systems, modern VRLA batteries offer an advantage because of their robustness, their low-maintenance design, and their relatively low price. They are used as a huge battery, composed of many (mono) blocs with two, six or twelve volts each, so that a beneficial voltage level for the connected power electronics is achieved.

However, these batteries grow old during their utilization and show several phenomena, which could lead to a failure of the system connected to the UPS and, therefore, cause heavy financial losses or life imperiling situations. Especially, the ageing of a single monobloc connected in series can deviate significantly from the others. In order to avoid such failures incipiently, regular maintenance of the batteries is required. This is done today typically by regular capacity tests. In more sophisticated systems, individual cell voltage monitoring is performed to identify weak cells. An alternative is the usage of handheld diagnosis devices (Ref 18), devices applying a test signal to the battery for measuring the impedance at a single frequency. Together with analyzing the cell or block voltage, information is gained on the state of health of the cell or block. The handheld devices are typically expensive (several k$) and require service staff for measuring all cells, but the risk of a system failure between two maintenance cycles exists further on.

Therefore, a monitoring system that observes the UPS batteries permanently is an important addition to the routine maintenance, and several companies have developed components for battery diagnosis system, which observes every monobloc in the complete UPS battery at a low price per unit. One of these components, Sentinel Battery Monitor (refer to Ref. 3) defined in this article as “alternative battery monitor,” has been extensively examined, optimized and validated, and the results of this optimization process are presented hereafter. Aside from voltage and temperature, the diagnosis for every bloc takes into account its impedance at a certain frequency.

In the examination process, batteries from different manufacturers and of different sizes and types (Table 1) are aged artificially, regularly tested on their capacity, and characterized using electrochemical impedance spectroscopy.
In parallel, tests with the alternative battery monitor have been conducted and compared with the condition of the batteries measured under the previous laboratory conditions.

This paper will present both the examination findings and the test setup, focusing on the impedance based approach for state of health (SOH) determination of lead acid batteries, highlighting impedance measurement results at different points of the battery ageing.

Impedance Spectroscopy

For a deeper understanding, a brief introduction to the principles of impedance spectroscopy is given, in order to clarify the difference between the impedance measurement provided by a laboratory full-scale impedance spectroscope, and the one given by a low cost device intended for mass production. The laboratory measurements have been performed with a multichannel impedance spectroscope (hereafter referred to as “impedance spectroscope”) specially developed for the use with batteries and fuel cells (Ref 13).

Impedance spectroscopy has become a powerful tool in investigating, characterization and modeling of several electrochemical systems, such as batteries and fuel cells, as well as coatings and corrosion barriers (Ref 2). Due to its nonintrusive character, this measurement method has also become more and more interesting in the field of battery monitoring with respect to the determination of State Of Charge (SOC) and State Of Health (SOH) (Ref 3,4,5).

During Galvan static impedance spectroscopy, a sinusoidal current is applied to the battery under test and the corresponding voltage response is measured. Afterwards, the Fourier analysis is used to calculate the real and the imaginary part of the voltage response for a given frequency. In result, the complex impedance can be obtained by analyzing the relation between the voltage response and the excitation current in amplitude and phase angle:

$$\underline{Z} = \frac{\underline{u}}{\underline{i}} = \frac{\hat{U} \times e^{j(2\pi f t + \varphi_u)}}{\hat{I} \times e^{j(2\pi f t + \varphi_i)}} = \frac{\hat{U}}{\hat{I}} \times e^{j(\varphi_u - \varphi_i)} \tag{1}$$

By varying the excitation frequency *f*, a complete impedance spectrum can be measured, the voltage amplitude and phase being frequency dependant for a given current waveform. A typical result for a lead acid battery is given in Figure 1, as a Bode plot, for a lead acid battery, 12 V, AGM, 160 Ah, consisting of two blocs of type Yuasa "EN160-6".

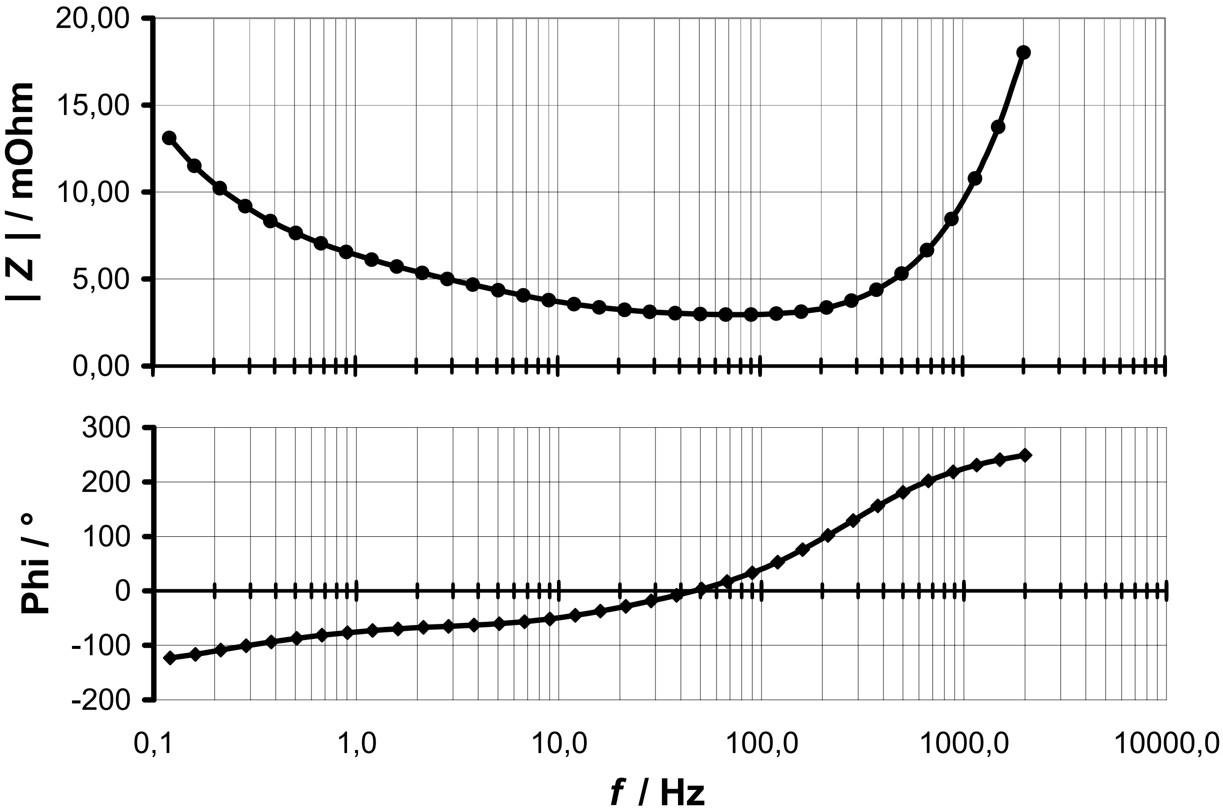

Figure 1: Bode plot of a typical impedance spectrum.

It can be seen that the impedance of the battery varies significantly with the excitation frequency. The excitation frequency ranges over 5 decades, from 100MHz up to 2KHz. Moreover, the figure shows the complex impedance, which covers also values of a few mΩ up to 20 mOhm, so the measuring device must be capable of measuring the impedance with high resolution over a great frequency range. Positive phase angles indicate inductive behavior of the device and negative phase angles capacitive behavior. According to all experiments and data analysis done by the authors in the past, no information on ageing can be achieved from the inductance of a battery.

Beside the measurement, the device must provide also the computing power for the Fourier analysis that provides the complex impedance in the end. Obviously, implementing of all these features in a low cost measurement device is hard to obtain, so the main question is, whether it is possible to maintain information about the SOH of a standby lead-acid battery with a single frequency impedance measurement or not.

BATTERY AGEING PHENOMENA

The main goal in monitoring of stationary batteries is to detect the degradation of the battery capacity in order to prevent a failure of the whole system. There are several effects, which lead to a loss of capacity with increasing age of the battery. The most common are introduced hereunder:

Premature capacity loss

This effect is very common for UPS battery systems. The batteries in these systems are discharged with a high current, which is responsible for the growth of large crystals at concentrated points of the electrodes. The effect can be increasingly severe, so that the contact between the active masses and the lead grid of the electrode is lost and the active mass at the spot cannot be used further on (Ref. 6). The effect can be reversed partially, if the battery is adequately treated / charged (conditioning) (Ref 7,9,10). However, if the battery is used in continuous cycle operation, the effect can become irreversible due to the blow-down of the lead-dioxide (Ref 6,8).

Internal short circuits

The effect described above may also lead to internal short circuits. High discharge currents and cycle operation are responsible for the formation of “dendrites” – small crystal needles, which could interface with both electrodes and therefore cause a short circuit of the positive and the negative electrode (Ref 6,10). Only in the case of a slow discharge of the cell caused by the dendrites is a detection possible. This can be seen from a decreasing open circuit voltage of an individual cell in comparison to the remaining cells. The impact on impedance in this case is small.

If the dendrites result in a severe short circuit, the battery cell will be discharged within short times, and this can be seen from the open circuit voltage again. But the time might be too short for a warning, because the cell breaks down very fast and affects the performance of the full battery string.

Another effect which could lead to internal short circuits is corrosion. This is mainly a problem with flooded batteries, where corrosion flakes from the terminals may fall on top of the electrode. A short circuit between the electrodes can occur from the corrosion flakes.

Corrosion

Temperature, voltage, and local acid concentration have an impact on corrosion of the positive plate. Corrosion effects on the negative plate also occur, but are rare and will not be discussed in detail in this paper. The corrosion rate depends strongly on the grid alloy and the quality of the casting process. The corrosion products have a lower density and therefore a higher specific volume than the underlying lead grid. The resulting mechanical stress results in a shedding of the corrosion layer and can cause a loss of active material due to the loss of contact between the grid and the active material, leading to premature capacity loss. The fall down of loose active material and internal short circuits can also be the result of these mechanical forces (Ref. 6,7,8,9,10). Moreover, the oxide layer between the grid and the active material causes a lower conductivity of the grid due to its increased resistance (Ref. 10), and the reduced cross-section of the grid due to corrosion also increases the internal resistance of the battery cell.

All of the described effects above lead to decreasing a battery’s capacity or power. Any type of diagnostic shall be aiming for an identification of these ageing effects, to take appropriate countermeasures and to quantify the loss in power and capacity.

VALIDATION PROCEDURES

This section presents the process used to systematically age and validate an impedance-based low cost monitoring device (Ref 2).

Selected battery types and brands

Table 1 shows the batteries used for the examination process, batteries coming from various manufacturers, with different voltage, sizes and technologies.

Table 1: Battery types used for validation

Designation	Type	Manufacturer	Capacity / Ah nom.
EN160-6	12 V AGM	Yuasa	160
EN480-2	2 V AGM	Yuasa	480
NPL65-12l	12 V AGM	Yuasa	60.5
18 GroE 450	2 V Flooded	Hoppecke	468
6 OPzS 600	2 V Flooded	Hoppecke	610
A412/65 F 10	12 V Gel	Exide /Sonnenschein	65
L2V425	2 V AGM USA	Exide /Marathon	425
L6V160	6 V AGM USA	Exide /Marathon	162
L6V160	6 V AGM USA	Exide /Marathon	162
Sprinter S12V500	12 V AGM Europe	Exide	21
DDm85-25	2 V AGM	Hawker	1020
6OPzS420	2 V Flooded	Hawker	450
HR 12 - 135	12 V AGM	China	135

Laboratory equipment and test set-up

For the characterization of the batteries with regard to the capacity, professional battery test equipment has been used. Test circuits for currents up to 300A are available. The accuracy of the standard equipments used for current and voltage measurement is better than +/-0.5% of the measured value, but this accuracy is improved by an order of magnitude by a dedicated calibration sequence.

For the ageing of the blocs, heated water baths are used. The batteries are covered to at least two thirds of their height by the surrounding water. The temperature during the accelerated ageing tests is set to 60°C, giving by experience a life accelerating factor close to 16.

For the impedance measurements, a multichannel impedance spectroscope developed by ISEA has been used (Ref 13). The accuracy has been validated against a commercial impedance spectroscope. The impedance spectroscope allows measurements with sinusoidal AC signals in the frequency range from 7.5 kHz down to a few µHz. In addition, DC bias currents of up to 40A can be used to define different working points of the battery. The measurements are done in the Galvan static mode, hence the AC current signal is applied to the battery and the voltage response is measured. The current amplitude is adjusted at each frequency to assure that all measurements are done in the linear region of the reactions. This allows for applying the theory of impedance measurements and assures accurate results in all working points (Ref 15).

For the validation of current and voltage, a digital oscilloscope of type Tektronix TDS714L has been used. Current measurements have been done with high precision shunts.

The validation of the monitoring and diagnostic device has been done with the setup shown in Figure 2. This setup considers the ageing of the battery under real connections, always connected to the charger. In addition, the voltage response from the battery under test (BUT) is recorded as well as the current drawn from the battery by the test device. Because the battery has a nominal voltage limit that is much higher than the voltage response, an additional conditioning of the signal is necessary.

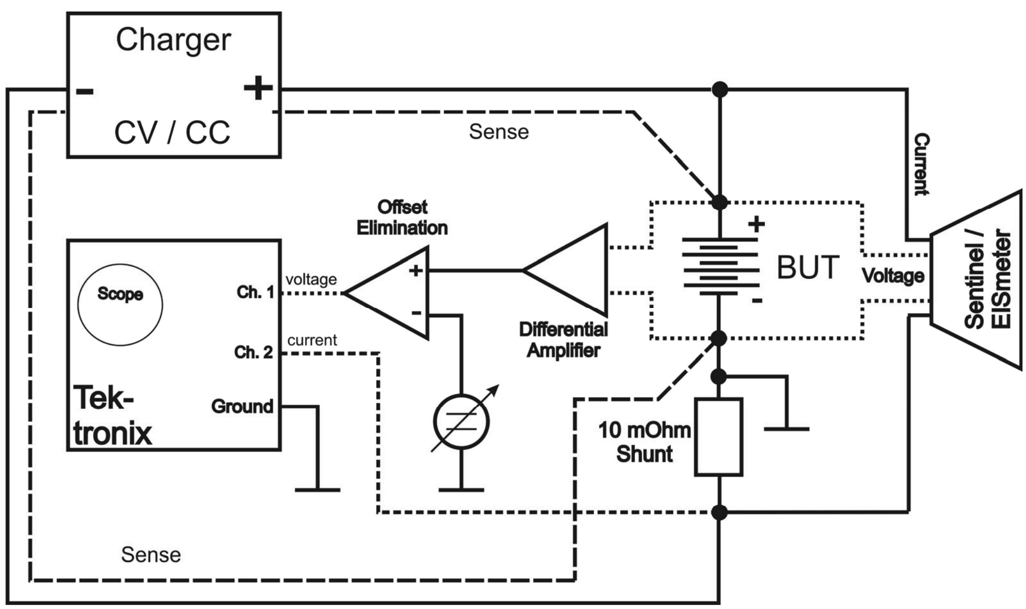

Figure 2: Test set-up for the evaluation of the monitoring devices.

Special emphasis was put on a high reproducibility of the conditions which can be found in UPS operation. The batteries are operated in float conditions, and, thus, all current is flowing only into the gassing reaction, and no current is flowing anymore into the charge reaction. The impedance significantly depends on the reactions. Therefore, it is necessary to assure for all tests these conditions. As several different configurations of the diagnostic device have to be tested at each point during the ageing test, the UPS condition must be restored for each measurement in short time. This is the reason for the high complexity of the test setup presented in Figure 2. Precautions in order to prevent distortions from the charger during the impedance measurements are provided.

The device for continuous battery monitoring

The analyzed battery monitoring device (alternative battery monitor, Ref. 3 and 17) has been designed for monitoring single battery blocs in battery strings for any system voltage level. A device is placed on every bloc, and each device is communicating with a main control unit via a specific communication bus (Ref 3). The alternative battery monitor works therefore like a battery sensor for voltage, temperature and impedance and transmits these values to the main control unit, which could be connected to the UPS controller itself. The two types of alternative battery monitor models used for the discussed performances validation are, in one hand, the unit dedicated for single cells in the range of 2 V and, on the other hand, a model for 6 or 12 V blocs.

Impedance is measured by applying a square wave discharge current to the battery and analyzing the corresponding voltage response (Ref 14). The discharge current pulse is repeated with a defined frequency. A 69Hz frequency has been chosen, in a range where a direct measurement of the internal resistance is possible and a value not coinciding with 50Hz or 60Hz harmonics frequencies, allowing an effective filtering of the effect of the ripple current. For the discussed validation tests campaign, special units of the alternative battery monitor have been engineered in a way to explore different current pulse amplitudes and frequencies.

The first task of the analysis was to check if the impedance measured and displayed by this simplified impedance measurement results in comparable data, with regard to a full scale laboratory impedance spectroscope. The differences in the principle of measurement are significant: The alternative battery monitor applies a square wave pulse instead of a sinusoidal signal, and thus the alternative battery monitor impedance is the result of a multiple frequencies excitation (current and voltage harmonics). The alternative battery monitor signal itself consists only from a discharge pulse (half-wave signal) instead of a sinusoidal charge/ discharge pulse. Also, the alternative battery monitor is not adapting the current rate to assure operation under linear conditions.

Figure 3 shows a comparison between the impedance measured by either the impedance spectroscope (full spectrum) or the alternative battery monitor. For the alternative battery monitor, three different units have been considered, with different square wave fundamental frequencies (15Hz, 69Hz and 145Hz). The alternative battery monitor only measures the modulus of the impedance and cannot analyze the imaginary part.

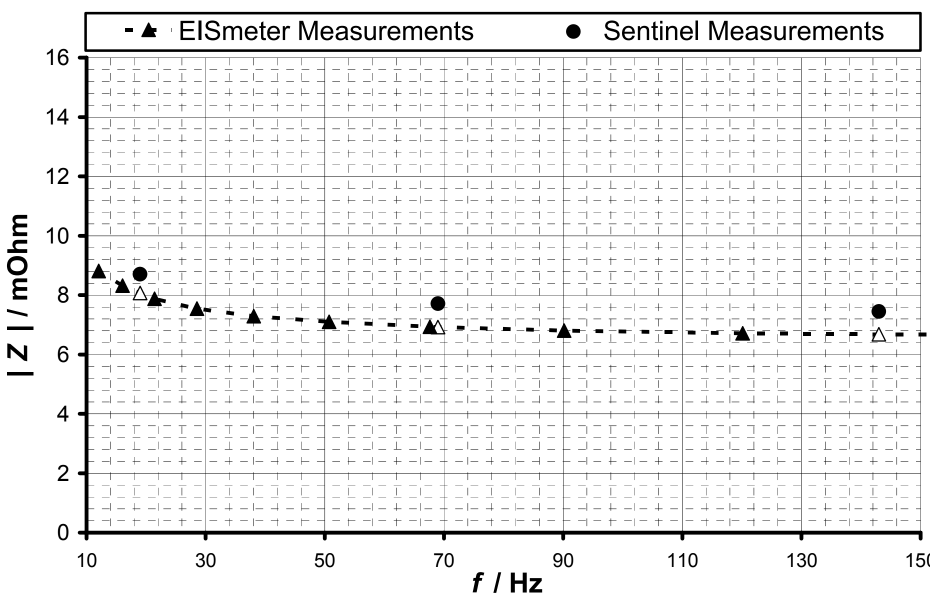

Figure 3: Comparison between impedance modulus given by the impedance spectroscope and impedance values given by the alternative battery monitor versus frequency.

The two values are very consistent with a slightly higher value for the alternative battery monitor, most likely due to the fact that the alternative battery monitor combines multiple frequencies in the generated square pulses. This delta could easily be compensated by an adjusted alternative battery monitor calibration process during production. In any case, for batteries diagnosis, the absolute value of the impedance is not of great relevance. Indeed, the monitoring is continuously done with these types of device, typically starting at the beginning of the lifetime. Hence, the changes in the impedance are a measure for the ageing, and this is what is needed for the diagnosis.

Preparation of aged batteries and references

In total, 13 batteries from different manufacturers (Table 1), with various capacity and electrode technologies, are used for the evaluation tests. Some of them are exposed to accelerated ageing tests in order to evaluate the diagnostic devices at different stages within the lifetime. The ageing was performed by means of high temperature ageing in a water bath. This type of ageing procedure was chosen because it mainly accelerates corrosion and drying out of VRLA batteries. These are the most important ageing effects in UPS operation. The ageing was interrupted in regular intervals to perform capacity tests as reference data and to perform the diagnosis measurements with the battery monitoring device. The results from the monitoring device are compared with the capacity decline of the batteries. Table 2 gives an overview of the test procedure for a battery.

Table 2: Description of the test procedure for one battery

1	Cooling down the battery for 24h to room temperature and charging under float charge conditions with 2.23 V/cell
2	Recording of impedance data with impedance spectroscope and alternative battery monitor with various frequencies, pulse forms and current rates under float charge conditions
3	Capacity test of the battery with 2 I_{10} down to a voltage of 1.7 V / cell;
4	Recharging the battery: 1.) constant current (Rate 2 x I_{10}) up to a voltage level of 2,45 V / cell 2.) constant voltage (2,45 V / cell) as long as the current is above 0.2 x I_{10} 3.) constant current (Rate 0.2 x I_{10}) until 112% of the discharged capacity has been recharged.
5	Capacity test of the battery with 10 I_{10} down to a voltage of 1.6 V / cell;
6	Recharging the battery: 1.) constant current (Rate 2 x I_{10}) up to a voltage level of 2,45 V / cell 2.) constant voltage (2,45 V / cell) as long as the current is above 0.2 x I_{10} 3.) constant current (Rate 0.2 x I_{10}) until 112% of the discharged capacity has been recharged.
7	Return the battery back into artificial ageing for typically 6 weeks at 65°C and float charging conditions at 2,23 V / cell

After a period of accelerated ageing, the battery is taken out from the hot water bath. During the artificial ageing, the battery is stored under float charge condition at elevated temperature. According to several similar studies (Ref 5,6,7,8), the temperature has a great influence on the ageing behavior of the battery. In general, an increase of 10K in temperature is assumed to halve the lifetime of the battery. Therefore, an artificial ageing cycle of 6 weeks at a temperature of 65°C could be regarded as 22 months at 25°C. Expecting an average lifetime of 10 years for a stationary lead-acid battery, 5 cycles will be needed until the battery is at its end of lifetime. After the interruption of the accelerated ageing, the impedance of the battery is measured as well, with the laboratory instrument as with the alternative battery monitor. The batteries are always kept under float charge conditions, so it is always connected to a constant voltage source. After finalizing the battery diagnostics, the battery is discharged with a constant current of 2 I_{10} to evaluate the actual capacity. After an intensive recharging (see table 2 for details), a second capacity test with 10 I_{10} has been performed to see the capacity at medium and high rate discharge currents. The battery is returned to accelerated ageing after it has been recharged completely.

PERFORMANCE VALIDATION OF BATTERY DIAGNOSTIC DEVICES

Figure 4 shows the behavior of the battery's capacity within the course of the accelerated ageing test. The left hand bars show the results of the capacity tests at 2 I_{10} and the right hand bars are the capacities measured with 10 I_{10}. The data are normalized to the rated C_{10} capacity.

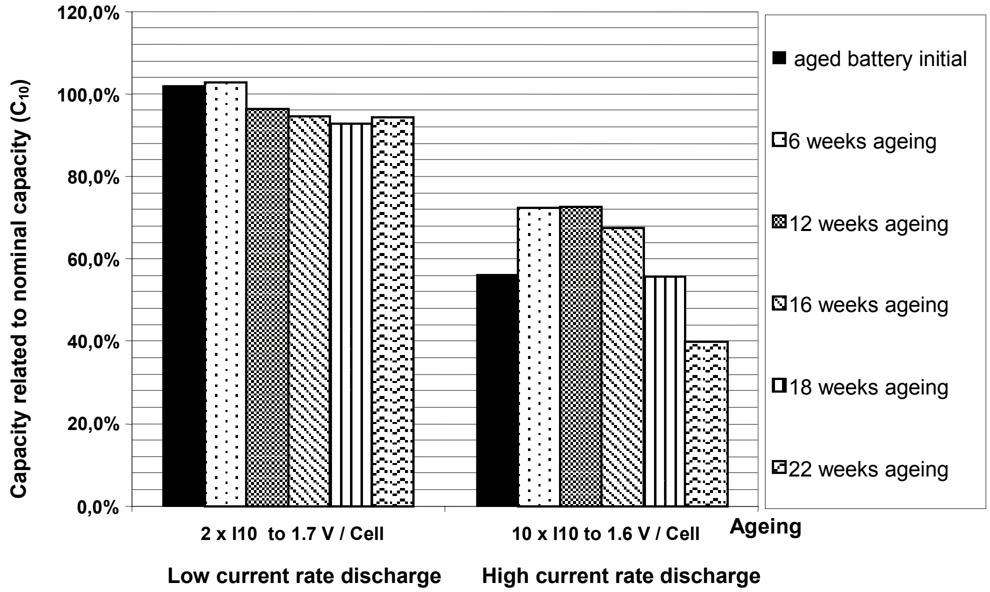

Figure 4: Development of the battery capacity in dependency of the ageing time.
(The left hand group of bars shows the capacity for the $2xI_{10}$ discharge rate; the right hand bars, the capacity at $10xI_{10}$. All capacities are normalized to the nominal C_{10} capacity.)

The battery shown here as an example is made of two AGM blocs, "EN160-6" from Yuasa, connected in series, with 160Ah and 12 volts. In the figure, the capacity in relation to the nominal capacity of 160Ah is shown. It can be seen, that the capacity increases at first, before it falls due to its age. This is a typical behavior for lead-acid batteries (Ref.12).

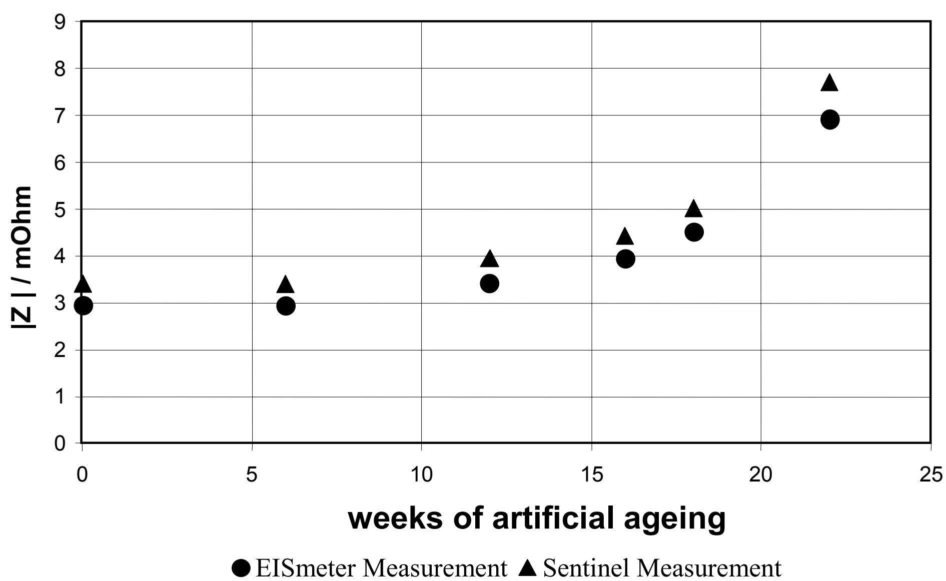

Figure 5: Alternative battery monitor and the impedance spectroscope readings versus ageing time.

Figure 5 shows the readings of the alternative battery monitor in comparison to the impedance measured with the impedance spectroscope within the course of the accelerated ageing test. Again, the readings from the alternative battery monitor are in good agreement with the impedance spectroscope. This validates the sensitivity of the alternative battery monitor. Even though the measurements are done with a low cost device, the results are equivalent to a full size laboratory impedance spectroscope.

Furthermore, Figures 4 and 5 show two aspects of the investigation findings:

1. With continuous artificial ageing time, the capacity at high current rates decreases.
2. While the capacity decreases, the measured impedance is increasing.

The readings given by the alternative battery monitor for a certain combination of frequency and current rate are correlated with the measured capacities. These results are presented in Figure 6.

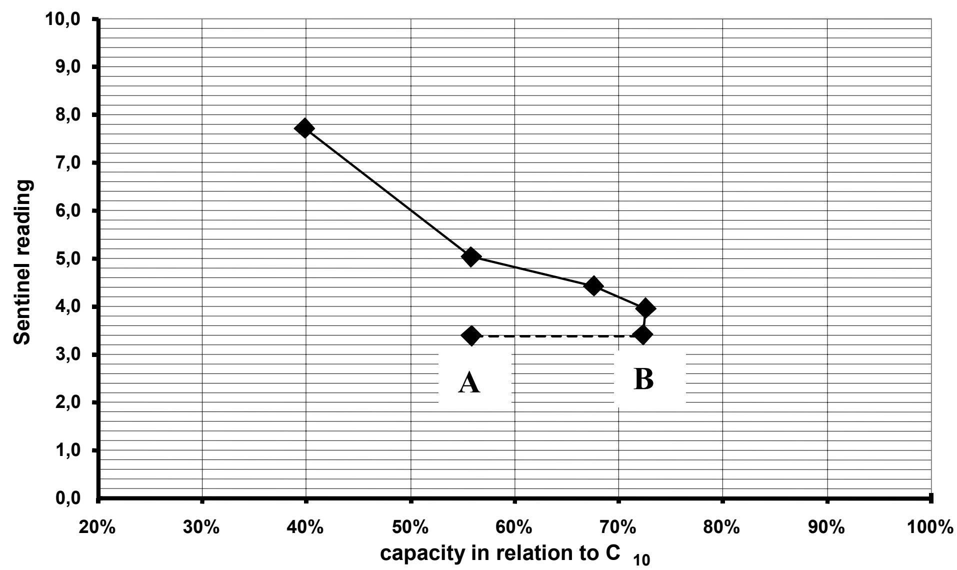

Figure 6: Correlation between capacity measured at 10 I_{10} and the alternative battery monitor readings for the battery (2 x 6 V AGM "EN160 – 6" by Yuasa)

The results show a clear correlation between impedance and capacity decline, after the formation of the battery is completed (point A to B corresponding to the capacity increase due to the formation completion). However, the relation is not linear, and this is a general characteristic of impedance-based diagnostics for lead-acid batteries. Impedance is a good measure for changes in the internal resistance, but some type of ageing processes in the active masses are not visible in the fully charged states under float charge conditions.

CONCLUSIONS AND OUTLOOK

The validation of the alternative battery monitor highlights the possibility for a qualitative determination of the effective discharge capacity of a standby lead-acid battery, showing an evident relationship between impedance variation and capacity loss.

The measured impedance values are close to the readings of a professional impedance spectroscope. In any case, the trending shown by both spectroscope and alternative battery monitor are very consistent and the determination of the battery's impedance for monitoring use is possible with this low cost device.

These conclusions are corroborated by the measurements presented in this paper, but are also valid for the other battery types as presented in table 1. While the ageing of the first type of battery started more than 12 months ago, tests are still on going for some of the battery types and will only be ended either when the capacity will reach 50-80% of their reference level or, in some cases, when the battery is completely damaged.

Post mortem detailed analysis are also part of the project and a significant work on the collected data has still to be done, showing case by case nuances to be taken into account when analyzing a battery SOH.

Additionally, the combination of impedance data with other collected parameters (bloc and string voltages, temperature, and current) will further be investigated to support the determination of other battery parameters giving more information on the battery ageing status:

- Provide information about the kind of capacity loss.
- Determine the kind of ageing processes which took place in the battery.
- Improve the today good quantitative relationship between the usable capacity of the battery and the impedance measurement.

A very clear picture about the State of Health of each cell and, therefore, the full battery can be achieved by using all information that is available from a continuous monitoring device, including the voltage and the impedance of each cell or module, and the current flowing into the string: all data have to be evaluated and compared among all cells, and changes in time monitored by a suitable algorithm.

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