

The Impact of Microcycles on Batteries in Different Applications

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Abstract

In most applications batteries are subjected to a complex current profile which is determined by the charging unit and the loads. Microcycles, a frequent change of the direction of the battery current, are the norm in all applications where charging and use of the battery to supply loads take place simultaneously, or reactive power is needed. That is the case in many different applications, from autonomous PV Systems to vehicles with generators or with feed back of braking power. The effect is particularly strong in systems incorporating loads with varying power such as single phase AC loads or loads with simple on/off control algorithms. Current pulses are usually in the range of up to a few hundred Hertz. The impact on different types of batteries caused by this has not yet been thoroughly investigated.

To investigate the impact of microcycles it was necessary to build at first a test unit. The test equipment had to fulfil as main requirements the generation of rectangular pulses for charging and discharging, frequencies in the range from 0.01 to 15.000 Hz and currents from 2 to 200A. In addition a special mode called “zero Ah control” was realised.

The results of laboratory tests on flooded lead acid batteries show that batteries lose capacity and require longer time and more power for charging if they have been subjected to microcycles. These effects are reversible in a laboratory environment but usually not reversible in field environments in particular autonomous PV or electric vehicle systems.

Models to explain these results are still under investigation. However, it is clear that the unequal current distribution in the electrodes caused by the ohmic resistance of the electrodes and the polarisation of the electrochemical reaction play a major role. Therefore the observed effects are probably not limited to lead acid batteries.

Concluding the work so far there is a need to take a *much closer look at the fluctuation of battery current for future designs* of electrical systems which use a battery as power source or sink.

Keywords: Flooded battery, lead acid, state of charge, battery charge, photovoltaic,.

1 Introduction

There are a few papers which show that fast fluctuations of battery currents with a frequency of 50 Hertz or higher have an impact on the performance and lifetime of batteries. Symons [1] reports that the voltage of small sealed lead acid batteries decreases drastically during discharging with 500 Hz current pulses compared to a constant current discharge with the same average current. Krämer [2] reports the shedding of active material during conservation charging with a thyristor controlled charging unit. Battery manufacturers usually require that the current ripple in the intermediary circuit of an uninterruptible power supply system is restricted to 5 Aeff/100 Ah. In [3] the effects of higher current ripple on the battery have been measured and show that the battery lifetime is reduced to one year when the current ripple is 100A/100Ah at full state-of-charge. This phenomenon cannot be explained only by the heating effects caused by such a ripple.

Fast variations of battery current, and in particular a fast change of the direction of the battery current, are normal operating conditions in all applications where energy generation and consumption take place simultaneously. In this paper *microcycles are defined as fast and continuous change of battery current with a change of direction*. This frequency dependent on the loads and generator. A base

frequency of approx. 100 Hz seems to be typical of such installations. In PV systems it was shown by simulations based on measurements of systems installed in the Pyrenees that the energy throughput of a battery per year increases by more than approx. 30 % [4]. When analysing the battery current in a car, the Ah throughput caused by microcycles with a frequency proportional to the motor speed causes an Ah throughput of approx. 2Ah per hour of operation during motor idling (see figure 3).

The growing body of evidence that fast current pulses have an impact on battery life and the growth of power electronic controlled loads with their pulsed current drain (see for instance GSM telephones for a particularly striking example) makes it necessary to focus on these operating conditions of batteries.

2 Test equipment

In the framework of the Research funded in part by the European Commission a test equipment called High dynamic battery impulse converter named **HoBIS** (**H**ochdynamischer **B**atterie **I**mpuls **S**tromrichter) was developed.

2.1 Definition of requirements

There are products on the market which claim to improve battery capacity and increase battery lifetime by introducing pulses with a frequency of 8 - 12 kilohertz. A thorough investigation of the effects of current pulses has to be able to investigate such claims. For this reason, it was considered necessary to built the test unit with the capability to produce 15 kHz pulses. As gas evolution experiments could also be relevant, it must be possible to investigate large batteries which produce high amounts of gas even under normal operating conditions. For this reason, 200 A were considered necessary. Short high current pulses require very fast change of current as otherwise the current cannot reach its maximum value during a pulse. For this reason, 100 A/μs have been chosen as target.

Table 1: Summary of requirements.

1. Current: charging/discharging	2 ... 200 A
2. Voltage level:	1 ... 20 V
3. Frequency:	0, 0.01 ... 15.000 Hz
4. Adjustable duty cycle	0, 0.1 ... 0.9, 1
5. „zero Ah“ charging	The total amperehour throughput to be limited to less than 1 Ah/24 hours of microcycling operation under any or all of the above operating constraints
6. constant current and constant voltage charging characteristics	The constant current or voltage during charging can be maintained either by adjusting the current amplitude or the duty cycle of pulse duration with a variable frequency.

2.2 Design concept

Figure 1 show the equivalent circuit diagram. Two current sources each with a total inductance of 4 mH at 200A and of 8 mH at 20 A were used, one for charging, the other one for discharging the battery. The inductances are necessary to generate high dynamic current pulses and to smoothen the ripples to get a “good” DC current during the pulses submit pulse increase. This is important especially at low currents. The current is either passed through an IGBT in a short circuit mode or is passed through the battery. The DC current is rectified by means of a 6-pulse rectifier from the three phase mains connection. The resulting 300 Hz ripple can be as high as 50%, if the current is low. Therefore a suction circuit tuned to 300 Hz had to be installed. Below 2A the current can no longer be controlled properly as the phase control angle becomes too small.

2.4 Measurements

The measurements of currents and voltage have to be averaged if pulse charges are used.

2.4.1 Voltage measurement

For current pulses longer than a few seconds, it is necessary to define when the voltage should be measured: during current through the battery or without current (resistance-free voltage). When high currents are used, the voltage difference can be considerable and a definition of the correct moment for measurements is important. For short pulses and DC currents the average over one second is calculated by sampling the measurement signal at 1 kHz.

2.4.2 Current measurements

The current in the charging circuit, discharging circuit and the current through the battery are measured independently. The battery current is averaged over one second, or at lower frequencies than 10 Hz over the last ten periods. The other two current measurements are carried out as an average over one second and the sensor signal is sampled with a frequency of 1 kHz.

2.4.3 Zero Ah Measurement

The requirement to keep the state-of-charge of the battery unchanged, allowing less than 1 Ah charge/discharge for every 24 hours at high current charge and discharge pulses cannot be achieved by exact current control. as the accuracy would have to be +/- 40 mA at 200 A maximum current. This would mean an accuracy of less than 0.02 %. Other effects are even more difficult to compensate. The average voltage drop across a shunt is measured using a capacitance and a resistor in series connection to smooth the signal. If the total charge during a charging pulse is equal to the total charge during the discharge pulse, the average voltage drop across the shunt is zero and the voltage measured across the capacitance will also have zero. By modifying the duty cycle of the current pulses the potential is kept at zero throughout. The system is recalibrated automatically every hours by switching off the current to get the new Offset. The calibration is necessary because of temperature drift.

3 Effect of microcycles on lead acid batteries

Batteries have been tested with 100 Hz microcycles which simulate the simultaneous charging of a battery e.g. from. PV modules and discharging with a non-linear AC load by means of a single phase inverter. Microcycles are also caused by loads with reactive power.

3.1 Experimental details

210 Ah tubular plate cells from BAE (type OPzS 210) have been used for the experiment. Prior to testing, all cells were cycled under standard conditions (IUa or IUa conditions described by the manufacturer for a full charge) until their capacity developed to its full value (precycling). The cells were kept at a temperature of 20 °C all the time.

3.1.1 Description of microcycles

The microcycles chosen in these experiments consisted of a discharge pulse with 180 A for 1.6 msec (-0.288As) and a subsequent charging pulse of 36 A for 8 ms (+0.288 As). 0.4 ms were required for safely switching the IGBTs of the test equipment. The overall charge transfer during a microcycle is therefore zero and the overall state-of-charge of the battery does not change. These microcycles reflect simultaneous charging of a battery from a PV module and operating a non-linear AC load, e.g. an energy saving lamp or a power toll, by means of a single phase inverter. It should be noted that this current profile is a realistic current profile for batteries in small PV systems for rural and residential applications, and represents the battery current existing most of the time. The current amplitude however will not occur very frequently although it is representative of maximum load and solar irradiance conditions. This profile was chosen because it was believed to lead to particularly damaging effects on the battery.

Batteries were subjected to microcycles for 120 hours in each test, resulting in an overall charge throughput of 3456 Ah (charging) and -3456 Ah (discharging). 3456 Ah are 16.5 times the nominal capacity @C10 of the batteries used. Figure 2 shows the battery current when an inductive load is

connected to the AC output of a single phase inverter designed for PV systems in remote rural locations.

The microcycles were controlled using the "Zero-Ah" control described above. It has been estimated to have an accuracy of better than 1 Ah per day. The microcycles were interrupted every 24 hours in one experiment to verify whether an overall change of electrolyte density developed. There was no change of voltage during the microcycles and the interruptions of the microcycles, showing that only negligible electrolyte was consumed.

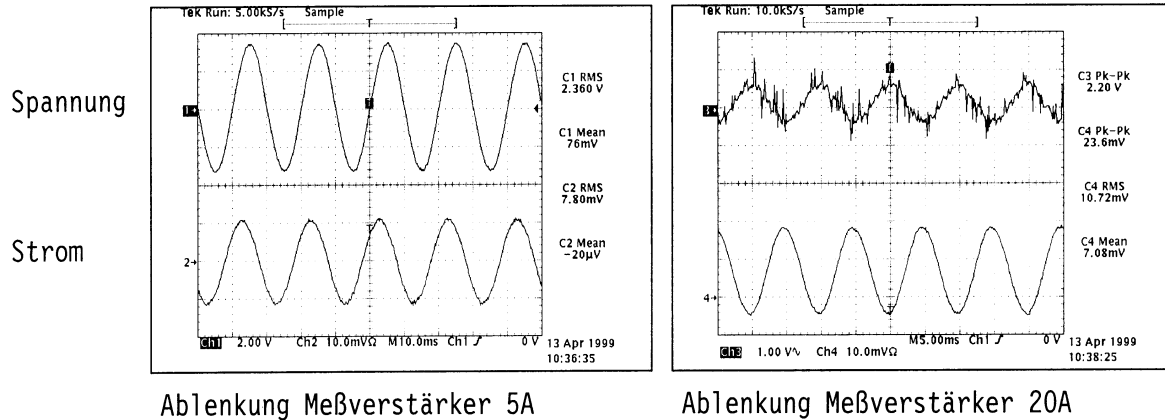


Figure 2: Measurements of battery current when operating an inductive load from a single phase inverter (25% power, $\cos \phi = 0,6$). Left output of inverter, right input (battery-side) of the inverter (measurements by the Fraunhofer Institute for Solar Energy Systems in Freiburg/Germany).

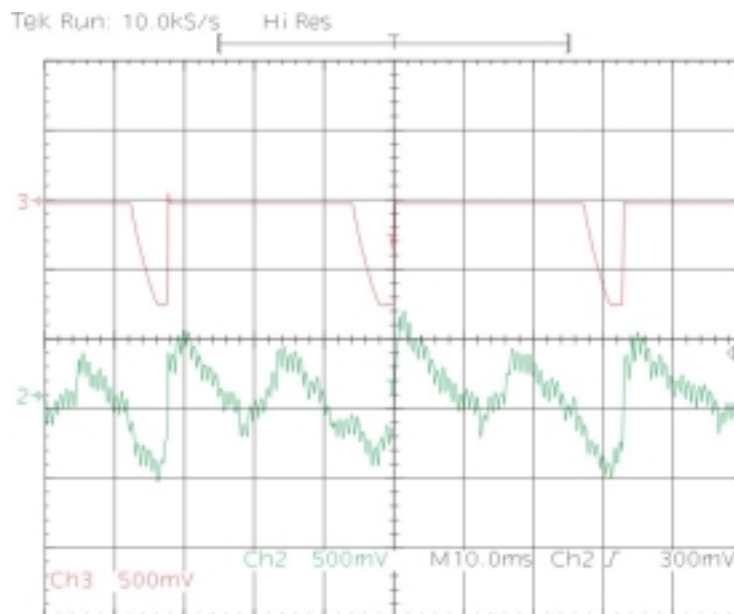


Figure 3: Measurements of battery current of a flooded starter battery system (12V, 55Ah) in a VW Golf. Current measurements with hall sensor (100mV = 1A); 2) battery current showing microcycles with main frequency of approx. 30Hz and an amplitude of ca. 6A; 3) current if ignition coil.

3.1.2 Electrolyte circulation system (ECS)

For some experiments cells were fitted with a commercial electrolyte circulation system consisting of a small air pump and a tube which is passed down one of the corners of the cell container. Air was pumped through the tube to the bottom of the cell and bubbled up freely in the electrolyte. The air flow was throttled so that the electrolyte level above the electrodes moved only slightly when the pump was on. The pump was connected to a time switch and switched on 5 minutes every three hours.

3.1.3 First test series

During the first test series, a 12 V battery was used. The battery was not fitted with an electrolyte circulation system. A capacity test consisted of a constant current discharge with 25 A to 100 % depth of discharge (DOD) at 1.8 V/cell and a IUa charging characteristics. The charging current during the first charging phase was 50 A. The constant voltage charging phase started once the battery voltage reached 2.4 V/cell and stopped when the battery current reached 12.5 A. A constant current phase with 12.5 A was then carried out for three hours. During pre-cycling, the voltage reached approx. 2.65 V/cell at the end of charging and reached a plateau demonstrating that the battery was fully charged. The capacity reached a stable value of approx. 225 Ah (at 25 A discharge current) after 10 cycles.

A microcycle test consisted of a constant current discharge with 25 A for a set time, so that the Ah drawn from the battery was constant but the state-of-charge was slightly different between the experiments. Usually 125 Ah were removed and the state-of-charge reached 45 %. The battery was then subjected to microcycles for 120 hours. After 120 hours of microcycles, the battery was discharged with 25 A to 1.8 V/cell and then recharged with an IUa charging characteristic identical to that used for capacity testing. During some of the initial microcycle tests the zero-Ah control unit was not available and a change in the voltage occurred during the microcycles indicating a change in the state-of-charge. The overall test procedure consisted of a microcycle test followed by two or three capacity tests and lasted approx. 180 hours/8 days. This test procedure was carried out six times.

3.1.4 Second test series

During the second test series, a 2 volt cell was used which was fitted with an electrolyte circulation system. The electrolyte circulation system was operated throughout all of the experiments to ensure uniform electrolyte density.

A capacity test consisted of a constant current discharge with 21 A (I10) to 100 % DOD at 1.8 V/cell and an IUa charging characteristics. The charging current during the first charging phase was 42 A. The constant voltage charging phase started once the battery voltage reached 2.4 V/cell and stopped when the battery current reached 2 A. The charging characteristics led to a complete full charge and a stable capacity value throughout the 12 capacity tests of this series. The charge factor during cycling was between 0.02 to 1.07.

A microcycle test consisted of a constant current discharge with 21 A to reach 20 % states-of-charge. The cells were then subjected to microcycles for 120 hours as above. After 120 hours of microcycles, the battery was discharged with 21 A to 1.8 V/cell and then recharged with an IUa charging characteristic identical to that used for capacity testing. This test procedure was carried out four times.

3.1.5 Third test series

A third test series was carried out with test conditions which were in principle identical to the second test series. During precycling the electrolyte circulation system of these cells was switched on to ensure uniform electrolyte density. In contrast to the second test series, the electrolyte circulation system of the batteries was not switched on during microcycling tests and the subsequent capacity tests.

Microcycle tests were carried out at three different states of charge (20 %, 50% and 80%). Five capacity tests were carried out after each microcycle test using an IUa charging characteristic (without electrolyte circulation) as described above. The same settings and the same end-of-charge criterion were used. The charging time, energy requirement for charging and charge factor increased compared to charging with electrolyte circulation, however, a full charge was not achieved.

3.2 Discussion and results

The current profile of the microcycle consists of a short discharge pulse of high current density and a 5 times longer charging pulse of identical amount of charge. Other profiles, e.g. one consisting of equal

current amplitude and duration during charging and discharging would also reflect the real operating conditions of a battery. However, based on the agglomerate-of-sphere model it was assumed that a high discharge current and a low charging current would be more damaging to the microstructure of the electrodes than equal discharge and charge currents. In addition, Sauer [5] has shown that, if acid stratification exists, low charging currents lead to more inhomogeneous current distribution in the electrode than high charging currents. The current profile that was chosen would therefore be likely to increase any effect of acid stratification in the cells.

3.2.1 Tests with electrolyte circulation (second test series)

Cells which are subjected to microcycles do not show any change in capacity if the electrolyte is stirred and there is uniform electrolyte density between the plates. The charge factor for charging the battery fully is approx. 1.02 during a capacity test but approx. 3 – 4 % higher during the first charge after a microcycle test. This difference was observed consistently. The capacity of the battery remained constant over a total of cycles despite this very low charging factor. It can therefore be assumed that such a low charging factor is adequate to charge the battery fully if the acid density is constant during the whole discharging and charging process. Fig. 2 shows the capacity value for a number of capacity tests. Shown are the 1st and 2nd charging after microcycling with corresponding charge factors.

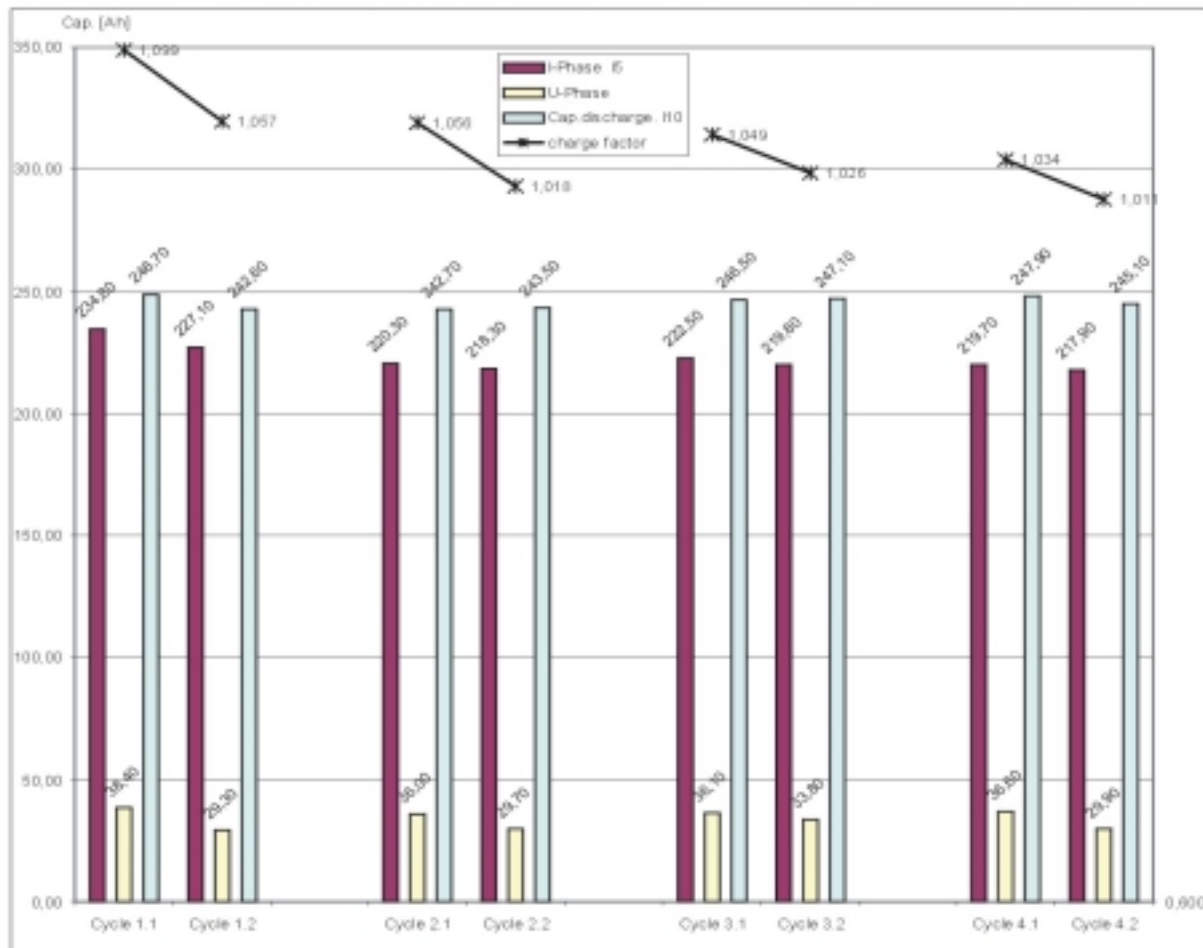


Figure 4: Capacity (total and Ah charged into the battery during the first and second charging phase) and charge factor in subsequent capacity tests. The cell was subjected to microcycles prior to cycle No. 1.1, 2.1, 3.1 and 4.1.

The shape of the current and voltage curve during charging shows a small but consistent difference between charging immediately after microcycling and subsequent recharging after capacity tests. After microcycling, the constant current phase lasts a little longer (approx. 3 – 4 % of the time, i.e. 11

minutes). The constant voltage charging phase lasts approx. 1,5 hours longer and the amount of charge which is charged into the battery during this phase increases by approx. 10 %.

Although there is no loss of capacity, the longer charging time is nevertheless significant because batteries in PV systems are charged under constant power charging conditions with a time limit. Batteries in some PV systems and other applications are charged fully only every few weeks. A daily difference of a few Ah can then easily accumulate to considerably less charge and a subsequent lower state-of-charge which will postpone the likelihood of a full charge even further. It is for this reason, that even small differences in the power requirement for charging can lead to significant differences in PV-systems and all other systems where the battery reaches full state-of-charge only seldom.. Further work needs to be done to quantify this effect and carry out more detailed experiments to analyse the relevance of this effect in different applications.

At this point in time it is presumed that the longer charging time is due to recrystallisation processes as the charging and discharging current are distributed differently across the electrodes. The result would be a distribution of lead sulfate crystals that is shifted to larger and fewer crystals and an unequal amounts of lead sulphate in the top and at the bottom of the electrode. The time difference between the different regions of the electrode reaching a condition where the charging reaction is limited by the amount of lead sulphate that is available will increase. No detailed theoretical studies have been made.

3.2.2 Tests without electrolyte circulation (Third test series)

Fig. 5 shows the current and voltage curve during charging before a microcycle test and during charging after microcycling. The change of the shape of the current and voltage during charging is significant.

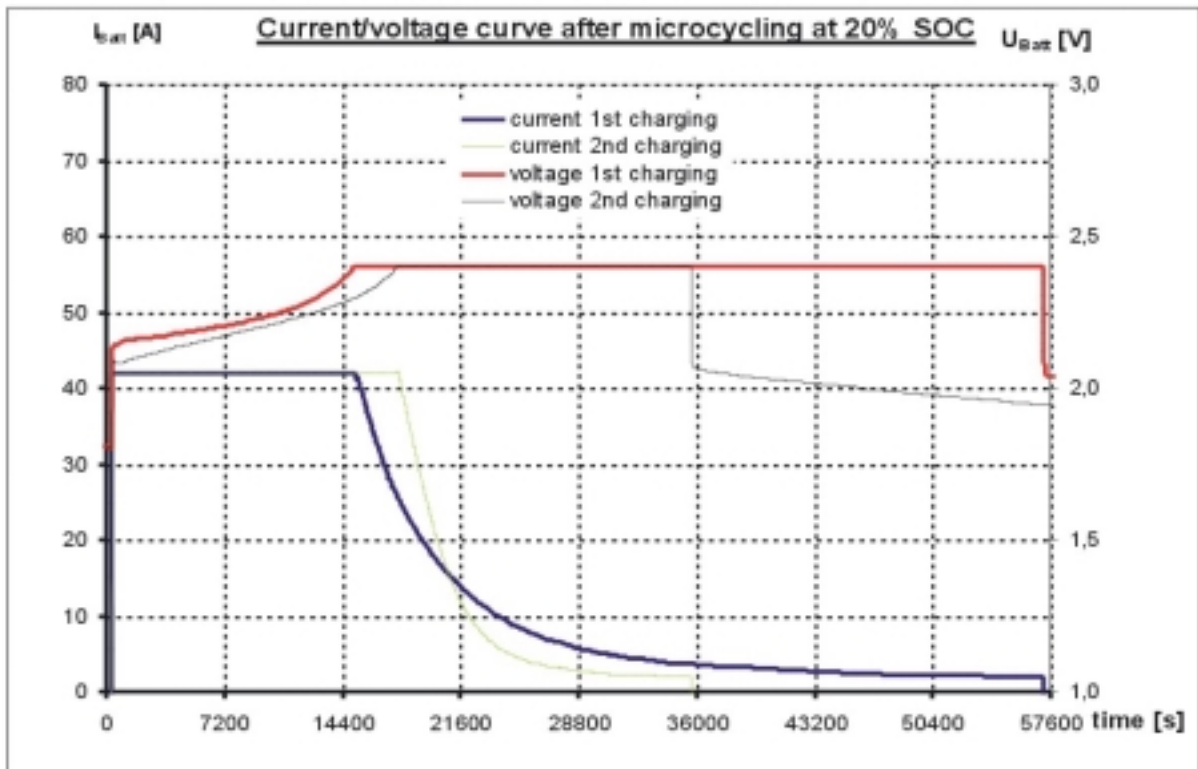


Figure 5: Voltage and current during charging. Blue and red lines refers to 1st charging after a microcycle test (at 20% SOC), and the smaller black and green line refers to the 2nd charging after microcycling. The voltage limit of 2.4 volt is reached approx. 45 minutes later during the 2nd charging. As a result more Ah are charged into the battery within the same time (4% of the nominal capacity).

During the charging immediately after microcycling, the voltage in the constant current phase rises more quickly and the voltage reaches the threshold value of 2.4 V/cell for switching over to the

constant voltage charging phase approx. 45 minutes earlier. The subsequent constant voltage charging phase is considerably longer. The overall charging time is also longer. At the end of charging the current drops very slowly (gradient: 0.01 A/minute) so that the state-of-charge achieved has reached equilibrium or near equilibrium. In DIN 60898-2 Annex2 the end of charge criterion is defined as "no change of current for at least 2 hours at constant voltage charging". This criterion is nearly fulfilled despite the low charge factor of 1.02 to 1.07 (see table 2)

The fact that the constant current charging phase is shorter when the electrolyte circulation system is off leads to a lower amount of charge returned to the battery in a given time. The curves in Figure 5 show that approx. 8.5 Ah (= approx. 5 % of the total charge returned in the first constant current charging phase) can be charged back into the battery during the same charging time. Considering the fact that PV systems are charged fully only seldom this can cause a significant cumulative effect.

Table 2 shows the total capacity (discharge @ I10) the separate Ah during charging and the charge factor of subsequent capacity tests. The capacity continues to decrease during the following capacity tests. Obviously, the charge factor is insufficient and explains the drop of capacity. *This is an indication that electrolyte stratification caused by the discharging process and enhanced by microcycling has an immediate and considerable impact on the following charging process.*

Table 2: Both charging phases, capacity (discharge @ I10) and charge factor in subsequent capacity tests after microcycling at 20%, 50 % and 80 % SOC.

Cell No.:1a, (20% SOC)	CapTest 1	CapTest 2	CapTest 3	CapTest 4	CapTest 5
charge (I5)	179,25	197,30	189,25	187,50	184,70
charge U (I_{min} = 2A)	75,39	45,20	43,98	41,30	39,10
discharge (I10)	238,15	230,90	225,45	223,30	218,10
charge factor	1,069	1,050	1,035	1,025	1,026
Cell No.:2, (50% SOC)	CapTest 1	CapTest 2	CapTest 3	CapTest 4	CapTest 5
charge (I5)	203,2	193,9	186,95	181,25	177
charge U (I_{min} = 2A)	48,15	46,5	45,95	44,75	46,05
discharge I (I10)	234,75	228,45	221	218,6	215,25
charge factor	1,071	1,052	1,054	1,034	1,036
Cell No.:3, (80% SOC)	CapTest 1	CapTest 2	CapTest 3	CapTest 4	CapTest 5
charge (I5)	197,13	191,17	185,15	177,525	176,865
charge U (I_{min} = 2A)	52,615	47,29	47,8	45,89	48,135
discharge I (I10)	232,41	227,455	222,1	219,5	217,125
charge factor	1,075	1,048	1,049	1,018	1,036

It was possible to reverse the loss of capacity by switching the electrolyte circulation system on and carrying out two capacity tests (full charge and discharge).

The comparison between the effects of microcycle tests with and without electrolyte circulation led to the assumption that microcycles cause severe acid stratification although the current pulses last only a few milliseconds. As the formation of acid stratification is linked

- to the voltage drop along the electrodes which is caused by the ohmic resistance of the grid, and
 - the amount of free electrolyte above the plates
- this is not surprising.

3.2.3 Experiments without ECS but IUa charging characteristics (first test series)

For this set of experiments 6 cells were used which were connected in series. The cells were not fitted with a system to circulate the electrolyte.

The capacity of the cell measured immediately after the microcycle test was on average 4 - 5% lower than before the microcycle test. This loss of capacity occurred although they same charging characteristics and end of charge criteria were used which led to a stable capacity during pre-cycling. In fact the charging time increased compared to the charging before the battery was subjected to microcycles. A second and third capacity test led to a small increase of capacity by approx. 0.75% per cycle, but not to a return of the full capacity. It is possible that full capacity could have been regained if a sufficient number of cycles would have been carried out. Fig 7 shows the capacity development. After microcycle test no. 4 the capacity had deteriorated particularly and the cell showed the charging behaviour of a deeply sulphated battery, i.e. the voltage of the battery increased above 14.4 volts as soon as charging began and the IUa charging characteristic was in fact a UIa charging characteristics. Obviously deep sulfation and electrolyte stratification that had built up during the previous cycles lead to the same general behaviour during charging.

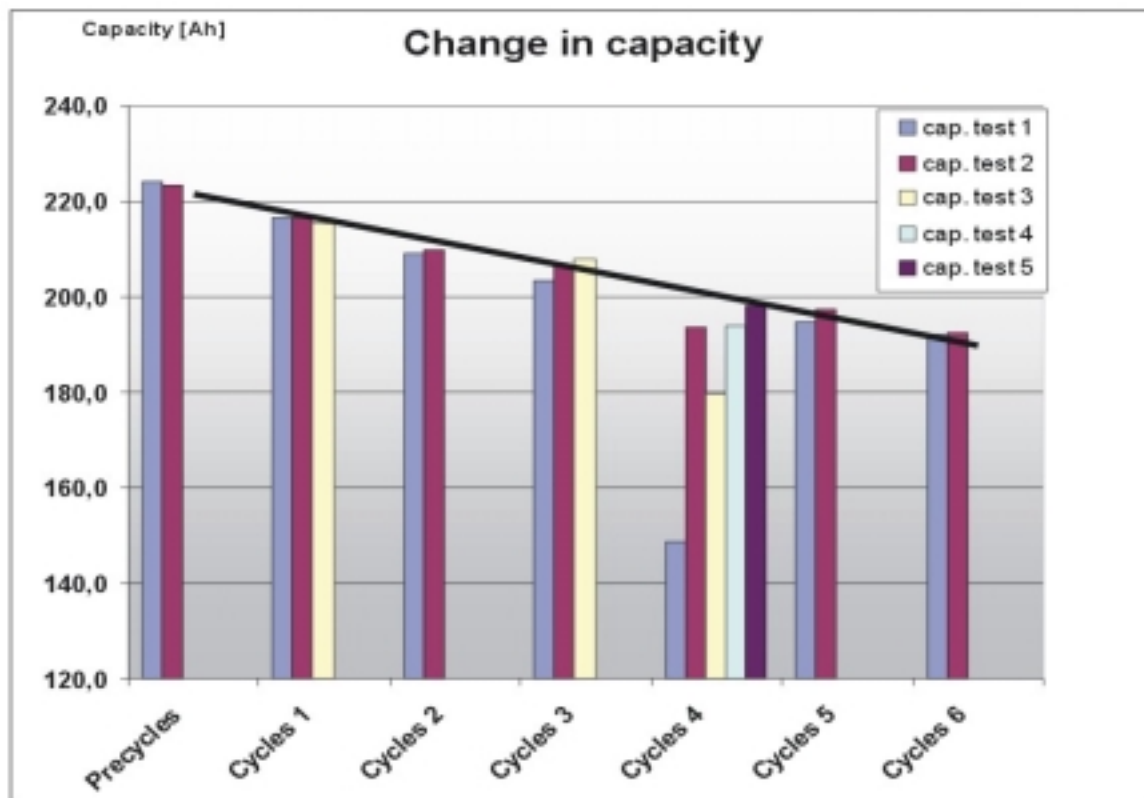


Figure 7: Development of capacity. Microcycling was carried out at 45% SOC except for microcycle number 4 to 6 which was carried out at 25% SOC.

The voltage and current curve during charging showed the same general characteristics as discussed above. The voltage during the first constant current charging phase increased more quickly than either before or after the microcycle test and the constant voltage phase lasted longer. The end of charging voltage in the final constant current charging phase (fixed duration of three hours) was considerably lower and the voltage was still rising at the end of charging. This clearly showed that the battery had not yet reached equilibrium although the charging time was longer.

Two cells were microcycled and tested in the discharged state by the manufacturer BAE and the Zentrum für Solare Energie und Wasserstofftechnik (ZSW), in Ulm They showed a very distinct sulfation at the bottom of the electrodes. The active material of the negative plate had 75% lead

sulphate at the bottom of the electrodes but only 41 % in the middle and 37% at the bottom (see table 3). The active material of the positive electrode was also investigated at the top, the middle and the bottom but in addition also on the side facing the grid and facing the electrolyte.

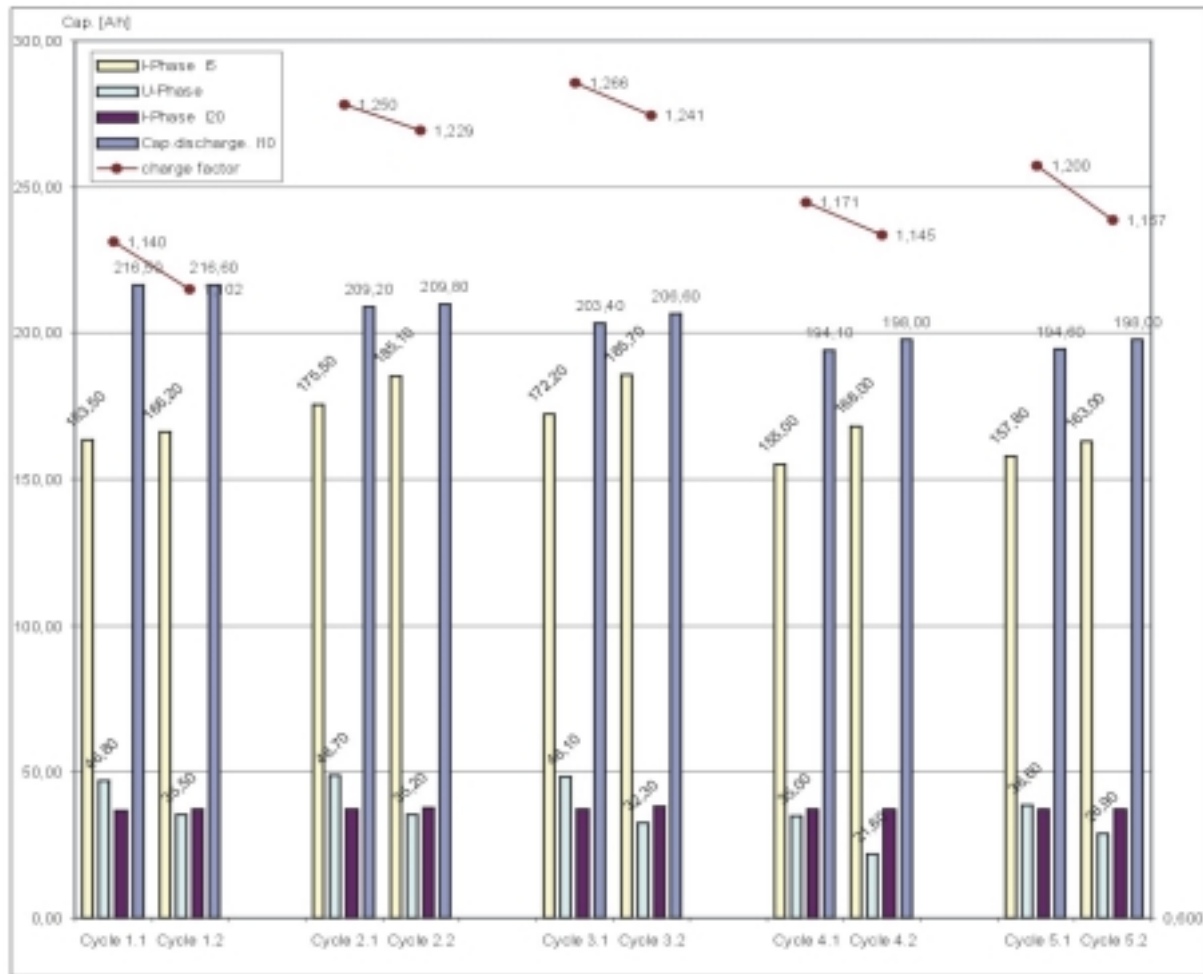


Fig. 8: Development of charge factor and Ah (total and for each charging phase separately). The cell was subjected to microcycles prior to cycle No. 1.1, 2.1, 3.1, 4.1 and 5.1.

Table 3: Distribution of PbO₂ and PbSO₄ of two cells after microcycling experiments.

	Cell 2				Cell 3			
	Near grid		Near electrolyte		Near grid		Near electrolyte	
	PbO ₂	PbSO ₄	PbO ₂	PbSO ₄	PbO ₂	PbSO ₄	PbO ₂	PbSO ₄
Top	84.5	14.4	50.2	49.5	84.6	13.3	43.1	55.2
Middle	85.0	14.3	46.6	53.0	85.5	12.6	42.9	56.0
Bottom	47.5	52.0	35.5	64.0	60.8	37.3	33.7	65.6

The results show the behaviour of a very distinct sulfation particularly on the negative electrode, but also on the positive electrode and a clear difference between the active material near the electrolyte compared to the grid.

These results confirm that the changes initiated by microcycles led to severe acid stratification an inhomogenous state of charge (SOC) of the electrode which could not be removed by the standard charging characteristics that were used. The second microcycle test was started with a stratified cell of lower capacity and the sequences of events led to this very severe sulfation.

4 Conclusion

The effects of microcycles on lead acid batteries can be described as follows.

1. Microcycles cause and/or increase existing acid stratification.
2. Charging characteristics capable of achieving a full charge under normal conditions are no longer capable of restoring full charge and removing acid stratification fully. Cells with significant acid stratification require more time for recharging. A different end-of-discharge criterion has to be chosen when a battery is microcycled. This leads to significantly longer charging times.
3. If the charging characteristics are not changed, cells which are microcycled loose capacity and have acid stratification even after the end of charging.
4. The loss of capacity can be removed by electrolyte circulation.

It seems possible to explain the effects of microcycles on batteries by inhomogeneous current distribution during the charging and discharging phase. This is to be expected as a result of the ohmic resistance and the current dependent overvoltages of the electrochemical reaction. A state-of-charge dependent rest-potential as is the case with lead acid batteries is an important aspect which increases this effect but may not be a necessary condition for the effects observed. For these reasons, it can be expected that microcycles will have effects on the performance of other battery systems as well.

Acknowledgement:

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