RESULTS OF PV AND WIND SIMULATED CYCLING TESTS ON BATTERIES

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ABSTRACT: In the framework of the 'Benchmarking' project, a series of tests were conducted on two types of flooded lead acid batteries. The tests refer to a simulated cycling of batteries under conditions resembling to operation of battery in a RES system. Two profiles were designed in project, one simulating battery operation of a wind system and one of a PV system. Periodically, capacity tests were performed to evaluate battery state of health. Analysis of the measurements has shown that during cycling of the batteries the voltage profile of the battery becomes steeper, mainly at the end of the discharge or charge process, indicating the development of stratification. Stratification was being removed during the periodic capacity tests, but this required an extended overcharge. Operation of the batteries under these conditions of cycling affects their lifetime. For one type of batteries tested, this of flat plate technology, it resulted to values shorter than these expected by manufacturer's data.
Keywords: PV system, Batteries, Lifetime.

1 INTRODUCTION

In the framework of the E.U. 'Benchmarking' project (ENK6-CT2001-80576: "Development of test procedures for benchmarking components in RES applications, in particular energy storage systems" [1]), a series of tests were conducted on two types of flooded lead acid batteries. The tests were conducted by 3 partners of the project, providing their battery testing laboratories. CRES was one of the partners to conduct battery testing. The batteries tested were of the same type for all partners (also from the same product line batch) and were tested under the same procedure.

The tests refer to a simulated cycling of batteries under conditions resembling the operation of a battery in a RES system. Two profiles were designed in project, one simulating battery operation in a wind system and one in a PV system. Periodically, capacity tests were performed to evaluate battery state of health.

The results and measurements of the tests are intended to be used for the evaluation of battery performance under conditions in RES systems, and for the verification of models, which are being developed in the project, regarding battery operation and ageing.

The tests at CRES started on April 2003. The results of tests and analysis of operation of a battery under such conditions are presented in the followings.

2 TEST PROCEDURE

The tests carried out at CRES refer to cycling of batteries under two cycling procedures, one simulating operation of a PV system, and one simulating operation of a wind system. They were performed on two types of stationary flooded batteries (of the same manufacturer):

a. a flat plate (OGi type) 12V, 54Ah battery

b. a tubular plate (OPzS type) 12V, 50Ah battery

Two batteries from each type were used. One of each type was cycled under PV cycling procedure and one under wind cycling procedure. Batteries named OGi1 and OPzS1 were cycled under PV procedure, and batteries named OGi2 and OPzS2 under wind procedure.

Each cycling consists of a number of repetitions of a typical cycle. After each cycling, a capacity test was performed on the battery. The cycling series were continued until the measured capacity was less than 0.6 of initial measured capacity.

The procedures of cycling and capacity tests are described in the following paragraphs.

All the tests are performed at 25^0 C.

2.1 PV cycling

The following profile of a cycle was used as typical for the operation of a battery in a PV system.

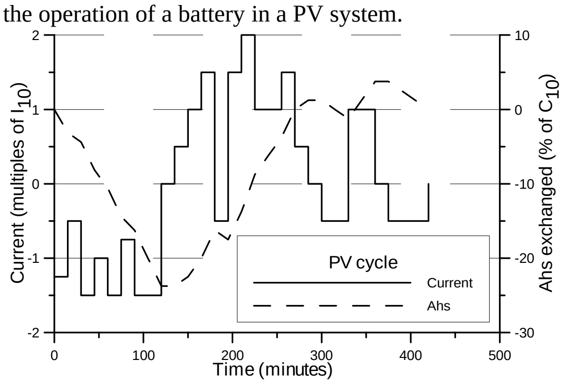

Figure 1: Current (in multiples of I_{10}) and Ahs exchanged (in % of C_{10}) during PV cycle.

The duration of such a cycle is 7h. The cycle is balanced regarding Ahs (total sum of Ahs at end of cycle is zero).

One PV cycling, starting from fully charged condition, consists of the following:

1. One discharge with I_{10} for two hours (to reach 80% SOC)

2. One series of 35 PV cycles

3. One discharge with I_{10} for three hours (to further reduce SOC by 30%)

4. One series of 35 PV cycles

5. One charge with I_{10} for three hours (to increase SOC level by 30%)

6. One series of 35 PV cycles.

Voltage limits: 14.7V (high) and 10.8V (low).

The total discharged Ahs during one PV cycling correspond to $33.3125C_{10}$.

2.2 Wind cycling

The following profile of a cycle was used as typical for the operation of a battery in a wind system.

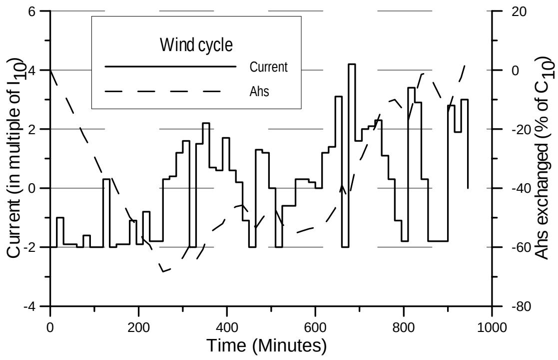

Figure 2: Current and Ahs exchanged during wind cycle.

The duration of such a cycle is 15h and 45min. The total sum of Ahs at end of cycle is $+0.05C_{10}$.

One wind cycling, starting from a fully charged condition, consists of the following:

1. One discharge with I_{10} for one hour (to reach 90% SOC)

2. One series of 50 wind cycles.

Voltage limits: 14.7V (high) and 10.5V (low).

The total discharged Ahs during one such cycling correspond to $57.85C_{10}$.

2.3 Capacity tests

After each cycling (PV or wind) the capacity C_{10} is measured, by a capacity test.

A common procedure has been followed for all the C_{10} capacity tests. The voltage limits were 14.7V (high) and 10.8V (low), the discharge current was I_{10}.

The procedure involves the measurement of residual, 'solar', and actual full C_{10} capacity. Initially the residual capacity is measured, to define the state of battery after a cycling. Following, the battery is charged at constant current up to the upper voltage limit, followed by a constant voltage charge for 5 hours at that voltage, to represent a conventional full charge condition in a solar application. A discharge follows down to low voltage limit, to define the so-called 'solar' capacity. Then the full C_{10} capacity is measured, after the battery has been fully charged. Full charge is accomplished through a IUIa charge with a charge factor of 1.2. Finally the battery is fully charged again.

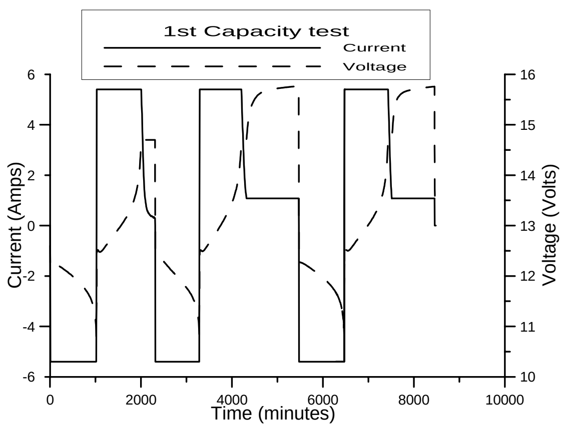

Figure 3: Example of the procedure of C_{10} capacity test, initial (1st) capacity test of Battery OGi1.

3 ACTUAL TEST DESCRIPTION

3.1 Experimental Set-up

Each battery was connected to a programmable charge-discharge unit in order to perform the tests. The same unit was used for the performance of all tests on the same battery, throughout the experiment.

The four charge-discharge units were controlled by a PC, which was used for the download of the various programs for each capacity or cycling test, and for the data acquisition during the execution of tests. Data acquisition included sampling (instant values) of current, voltage, temperature, usually at a rate of 5 minutes.

The first capacity test was conducted before the first cycling period, the second capacity test before the second cycling period, and so on.

For each cycling procedure a program was created and downloaded to the power unit. The cycles which were used were defined in terms of the current. A cycle in the program consists of 15-minutes steps of constant charge or discharge current (or rest period), according to the values described previously. Additionally, voltage limits were used, 14.7V as high limit, and 10.8V as low voltage limit for the PV procedure and 10.5V for the wind procedure.

However during the progress of the cycling, it was found out, that the voltage limits were reached. The power units, upon reaching the voltage limits, automatically continue operation at that voltage by reducing the current (for both high and low voltage limit), preserving the duration of each step.

3.2 Evolution of tests

3.2.1 Progress in a cycling

During cycling there is a drift of voltage and a trend for the battery to operate progressively in wider voltage range.

This is most obvious in PV cycling, where the voltage range initially is small and after some cycles progressively the voltage operation range expands almost to the high and low voltage limit (Fig. 4). This means that for the same Ahs exchange range (approx. 27%) the battery operates between the whole usable voltage range.

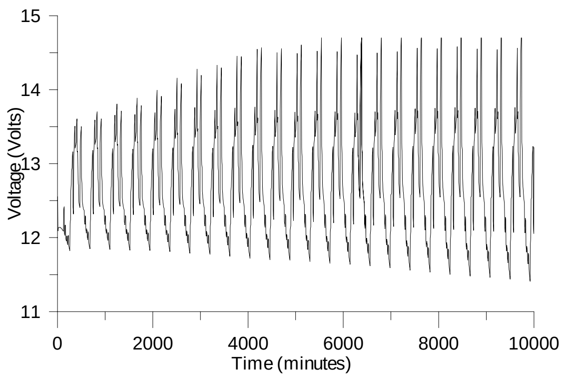

Figure 4: Voltage of battery OGi1 during first cycles of PV Cycling 1.

Analysis of the measurements indicates the following (from [2]).

Initially the voltage profile in a cycle changes from cycle to cycle, mainly due to stratification development. The voltage drift is larger during high and low level of SOC in a cycle (Fig. 5).The voltage drift from cycle to cycle is larger in the beginning of cycling, but as cycling proceeds the voltage profile gets more stable. This is due to the increased amount of gassing in each cycle, as during charge at high SOC level in a cycle the operation voltage is higher. This gassing progressively reduces the voltage drift due to stratification from cycle to cycle. This however is usually achieved when the voltage limits have been reached in a cycle.

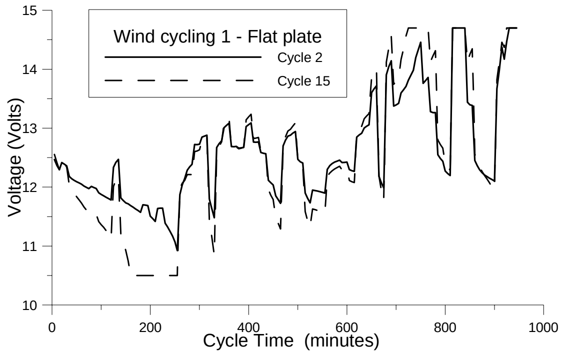

Figure 5: Voltage of battery OGi2 during cycles 2 and 15 of wind cycling period 1.

At the same time there is also a drift of voltage from cycle to cycle due to the shift of the average SOC level, as a result of a non-zero net Ah-balance in a cycle. After some cycles the voltage cycle profile has become more stable due to the increased gassing, but this usually is achieved when the voltage limits have been reached. This affects the Ahs exchanged in a cycle. A shift of the average SOC level, in principal, will affect the time at which the voltage limits will be reached in the next cycle. A negative net Ah-balance in a cycle will cause the next cycle to be performed at a lower average SOC level, and the high voltage limit to be reached later. So the current will start to reduce later and the Ahs charged will be more than the Ahs charged in previous cycle. The low voltage limit on the other hand will be reached earlier so the current will start to reduce earlier and the Ahs discharged will be less. So the net Ah-balance will be less negative in next cycle. Similarly, a positive net Ah-balance will result in a less positive net Ah-balance in next cycle.

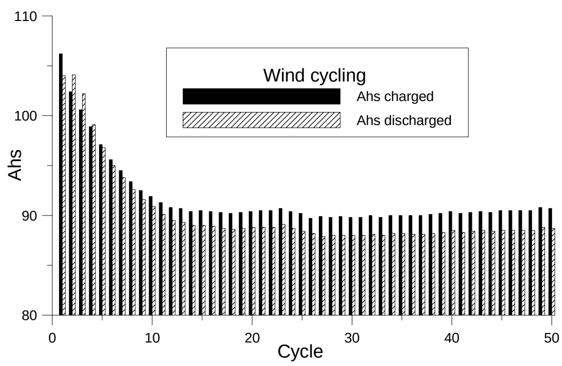

Figure 6: Ahs charged and discharged per cycle, for battery OGi2 during wind cycling period 1.

Finally the battery reaches a SOC level where the net Ah-balance becomes zero, e.g. the Ah-balance in a cycle is just equal to the losses in a cycle, and the average SOC is kept almost constant (Fig. 6,7).

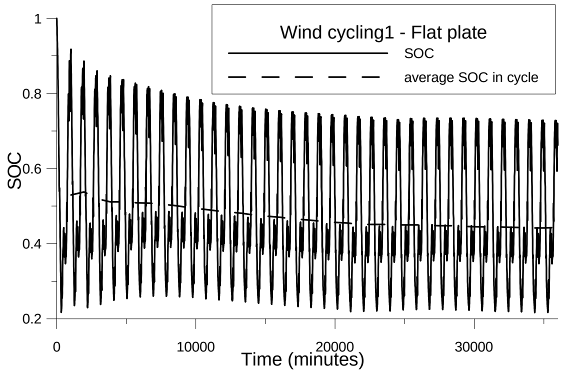

Figure 7: SOC and average SOC per cycle, for battery OGi2 during wind cycling period 1.

After this point the battery continues operation with an almost identical voltage and current profile in a cycle. This indicates that the battery operates in a condition where both SOC level is preserved and stratification has been stabilised. This latter occurs because the amount of gassing in a cycle has been increased enough to stop the progress of stratification from cycle to cycle.

However the battery performs cycles in a condition where some stratification level has been established.

The level of the SOC where a constant Ah-balance has been established and the Ahs exchanged at that level are related to the stratification level.

As can be seen from SOC plot, the usable capacity of the battery, between voltage limits, has been decreased.

3.2.2 Capacity tests

The change in the voltage characteristic due to stratification is noticed also during the capacity tests, and causes reduced values for residual and solar capacities.

At first capacity test, performed according to the described procedure, before any PV or wind cycling, the measured residual, solar and full C_{10} capacity values were very close. The voltage profile also during the three measurement procedures were very similar (Fig.3).

A typical profile of the sequence of capacity tests after a cycling is shown in Fig. 8.

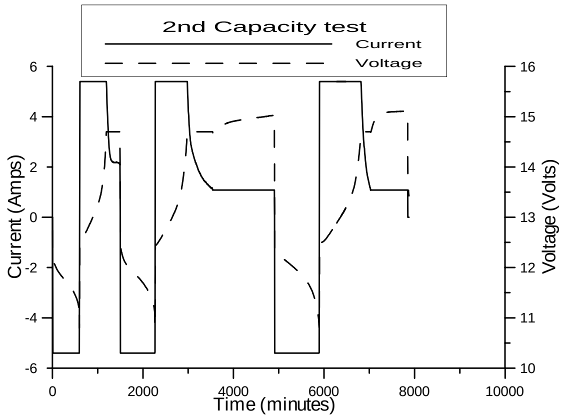

Figure 8: Current and voltage vs. time for second (2^{nd}) capacity test of battery OGi2.

The change of voltage characteristic can been seen in the different voltage profiles of each test, as well as that after each test the voltage profile becomes less steep.

For the residual test, the obtained capacity is lower than expected from SOC calculations.

The residual test consists of a discharge at I_{10} down to 10.8V, where the battery is assumed to have a SOC value of zero. However, due to the developed stratification and non-uniform active material utilization, the low voltage limit is reached sooner and a reduced value is obtained, while there is still active material, e.g. true SOC is above zero. This is confirmed by the following 'solar' test. The solar capacity test consists of a charge (ending with 5h U-charge) and a discharge at I_{10} down to the same low voltage limit, where the battery is assumed again to have a zero value SOC. In many of the tests performed, it has happened that the Ahs discharged during this solar capacity test were more than the Ahs that had been previously charged. This means that after the previous residual test there was still active material, some of which became again available after the 'solar' capacity test and the decrease of stratification.

This can be seen also on SOC plots, where the minimum value of SOC is above zero, though the low voltage limit has been reached.

The measured 'solar' capacity is also reduced, due to the fact that during the 'solar' charge only limited amount of Ahs has been restored. The voltage profile during the I step of charge is very steep and the high voltage limit is reached very early. The following 5h of U charge are not sufficient to charge adequately the battery.

After the 'solar' test, a full charge is following. During the first stage of this charge (I step of the charge), the voltage profile is less steep, but not yet as the profile of the initial charge, of a battery with no stratification. However after the full capacity test the next full charge is very close to the initial charge profile. This means that a good charge at an extended period is required to remove stratification.

The consequences of the fact that the voltage profile gets steeper, to the time required for a full charge of battery are shown in Fig 9.

The Ahs charged during the 1st full charge of a cycled battery (immediately after the 'solar' test) and the Ahs charged during the initial full charge of a battery with no preceded cycling, are plotted vs. time. Though the solar test has preceded, the time for a sufficient charge of the battery is still increased by several hours.

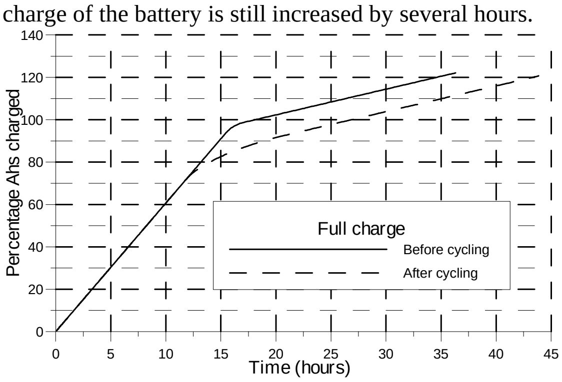

Figure 9: Percentage of Ahs charged versus time.

4 RESULTS

The results of the capacity tests are summarised into the following Fig.10 (tests on OPzS batteries are going on).

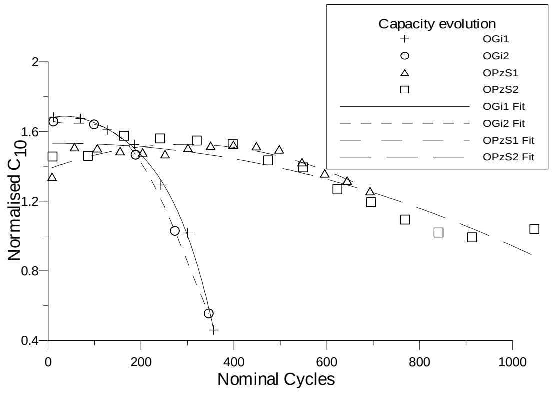

Figure 10: Results of full C_{10} capacity tests.

5 CONCLUSION

A series of simulated cycling tests have been performed on two types of flooded batteries (flat and tubular), that result to operation at partial state of charge. This mode of operation has been found to lead the battery into a condition where some level of stratification is established. This stratification results in the battery voltage profile becoming steeper, mainly at the end of the discharge or charge process. This in turn limits its useful capacity and hinders the charge process. Removal of stratification that is developed requires several hours of gassing. So it is important for a charge controller not only to feature a high enough upper voltage limit, but also to allow operation at that voltage for sufficient time.

In the tests performed, the periodic capacity tests resulted in the restoration of homogeneity of the electrolyte. The profiles which have been used, representing typical operation with low recharge factor, indicate hard conditions for batteries in RES systems.

Operation of the battery in this mode greatly affects the cyclelife. For one type of battery tested, the flat plate technology, cyclelife was significantly shorter than the cyclelife expected by manufacturer data, which refer to cycles with full recharge after each discharge. This is confirmed by the tests performed at other partners' laboratories also [3]. Tubular plate technology achieved a much better performance.

Another interesting conclusion is that, despite the fact that two different profiles were used, for each type of battery the total Ah throughput, expressed as nominal cycles in Fig.10, was the determinant factor for cyclelife.

Acknowledgement
This work was funded in part by the European Union under the 5th framework program (contract: ENK6-CT2001-80576: "Benchmarking").

6 REFERENCES

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