EXAMINATION OF RIPPLE CURRENT EFFECTS ON LEAD-ACID BATTERY AGEING AND TECHNICAL AND ECONOMICAL COMPARISON BETWEEN "SOLAR" AND SLI BATTERIES

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ABSTRACT: This paper refers to the effects of ripple currents on battery ageing and the characterisation of standard vehicle batteries. The ripple current effect in battery ageing was investigated by testing identical batteries under pure DC and pulse charge/discharge current. The experimental activities included the identification of polarisation curves at several SOC levels for a SLI battery. The long-term cycling tests indicated that "solar" batteries have significantly extended life time compared to SLI batteries. The use of the vehicle batteries in PV systems should be avoided due to the poor performance in continuous cycling operation.
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1. INTRODUCTION

This paper refers to the R&D work undertaken in [1]. The experimental procedures with lead-acid batteries were carried out in the battery laboratory at CRES which is equipped with two programmable battery cycling units and a water bath for temperature control. Three different lead-acid battery types were tested. The ripple current effect in battery ageing was investigated by evaluating identical batteries under pure DC and pulse cycling currents.

2. GENERAL TESTING CONDITIONS

In the testing procedures, all batteries were at 12V nominal voltage. For each battery type, the tests included one battery operating under pure DC and a second under pulsed current in both charge and discharge modes. A third battery of the same type and production line was used as reference. The batteries under evaluation were placed in a 20^0C water bath in order to obtain comparable results.

The performance of the batteries was examined under several cycling profiles. The conditions were achieved by varying the values of current, upper and lower voltage limits and cycling time periods. The long-term tests included periods of fast discharge and recharge which simulate quick ageing mechanisms rather than a typical PV operation. The discharge capacity was measured in each cycle in order to assess the long-term performance of the batteries. Frequent typical capacity tests were also carried out. Battery recharge was obtained by a constant current until a pre-set upper voltage limit, followed by a period of decreasing charge current at constant voltage.

3. RIPPLE CURRENT EFFECT SIMULATION

A typical profile of a ripple discharge current and the battery voltage fluctuation is presented in Figure 1.

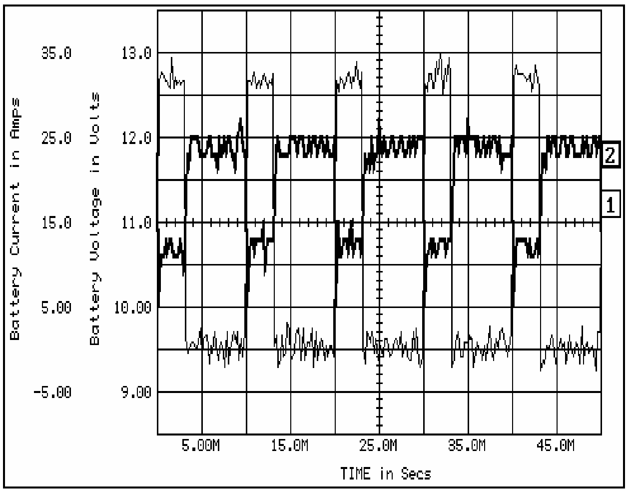

Figure 1. Typical ripple current (fine line) and battery voltage (thick line) profile

This ripple current profile simulates the performance of an inverter in terms of the duty cycle of the current pulses and the average current value. The latter was set equal to the DC operated batteries.

4. "SOLAR" BATTERIES TEST PROCEDURES & RESULTS

Two battery banks designed for PV applications were evaluated in order to examine the ripple current effect in battery ageing. A third 12V bank was used as reference. Each bank consisted of six 2V cells of 100Ah nominal capacity each. These lead-acid batteries were tubular, low-antimony, type 2 PzO/P50.

The two "solar" batteries were tested for more than 300 cycles each. The cycling conditions are shown in Table 1.

Table 1. Cycling conditions of the "solar" batteries

Region in Figure 2	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]
(1)	-15	+5	14.0	11.1
boost charge		+40	16.4	
(2)	-15	+20	15.8	11.1
(3)	-25	+10	14.2	11.0
(4)	-25	+10	14.2	11.0
boost charge	-25	+30	16.0	11.0
(5)	-25	+10	14.2	11.0
(6)	-25	+10	15.0	11.0
(7)	-40	+40	16.0	10.5
(8)	-20	+20	14.4	11.2

The measured capacity at discharge for the DC cycled "solar" battery bank and the ripple current cycled battery during the long-term cycling test is shown in Figure 2.

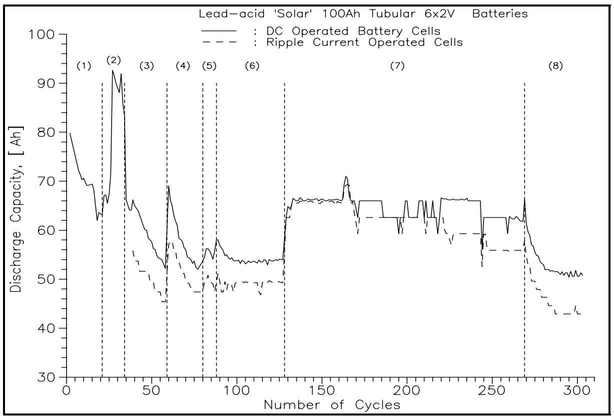

Figure 2. Discharge capacity of the "solar" batteries

Eight regions are distinguished in Figure 2. In (1), a constant Ah loss is noticed with a trend to reach 60% of the nominal capacity. In this area, recharging was done at a fairly low +5A until 14.0V upper limit. A boost recharge period resulted in capacity recovery, region (2). Discharge currents were kept at -15A for comparison purposes to region (1), while a charging current +20A was applied at a higher battery voltage level i.e. 16.4V, according to the manufacturer's recommendations. Battery capacity reached the nominal value in region (2). Region (3) resembles to region (1) and the discharge capacity is lower than the nominal due to the high discharge current of -25A and the moderate 11.1V cut-off voltage level.

In region (4), the relatively low upper voltage limit resulted in poor recharge and therefore, the discharge capacity during cycling dropped gradually. A capacity test was carried out at cycle 58 and Ah recovery was achieved after 40h recharge time with upper voltage limit 14.2V. At cycle 80, a boost charge with +30A reaching 16.0V resulted in a slight capacity recovery, region (5). This was retained in region (6), in which, the recharge rate decreased to +10A and the upper voltage limit was set at 15.0V.

In regions (4), (5) and (6), it is noticed that, gradually, pulsed currents seem to affect the Ah capacity for the particular batteries under the same voltage, current rate and temperature conditions.

Region (7) refers to a long-term high current rate cycling. The conditions simulated an extreme operating profile where recharge is done in approximately 3h and the load is satisfied in 2.5h. Although these conditions do not represent a typical battery operation in a PV plant, the batteries performed satisfactorily. In particular, the average discharge capacity was calculated 60.4Ah and 55.7Ah for the DC and the ripple current operated batteries respectively. In region (8) in Figure 2, the useful capacity of both batteries dropped mainly because of the failure of two 2V battery cells, one of each bank.

General conclusions for battery ageing due to ripple currents could not be drawn as more battery samples of the same type should undertake life cycle laboratory testing in order to acquire statistical data.

5. EXPERIMENTAL PROCEDURES AND RESULTS WITH VEHICLE SLI BATTERIES

Two SLI battery types were evaluated in order to examine the long term performance in a hypothetical PV station. As with the previous tests, the performance of the vehicle batteries refers to 20^0C temperature.

5.1 "Heavy duty" Type SLI Battery Cycling

The so claimed "heavy duty" SLI lead-acid batteries were closed type and were designed for operation in harsh environmental or power demanding conditions, e.g. boats, small electric carriers etc. The nominal capacity of each 12V block was 75Ah. Two batteries of this type were evaluated; one was cycled under pure DC while the other operated under pulsed current. The long-term cycling conditions are summarised in Table 2.

Table 2. Cycling conditions of the "heavy duty" type SLI batteries

Region in Figure 3	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]
(1)	-7.5	+7.5	14.0	11.4
(2)	-10.0	+10.0	14.2	11.0
(3)	-4.0	+4.0	14.2	11.0
(4)	-4.0	+4.0	14.6	11.0
(5)	-7.5	+15.0	15.0	10.8
(6)	-7.5	+15.0	15.0	10.8
(7)	-7.5	+7.5	15.0	10.6
(8)	-7.5	+7.5	15.0	10.6

The capacity at discharge during long-term operation for the two "heavy duty" batteries is presented in Figure 3.

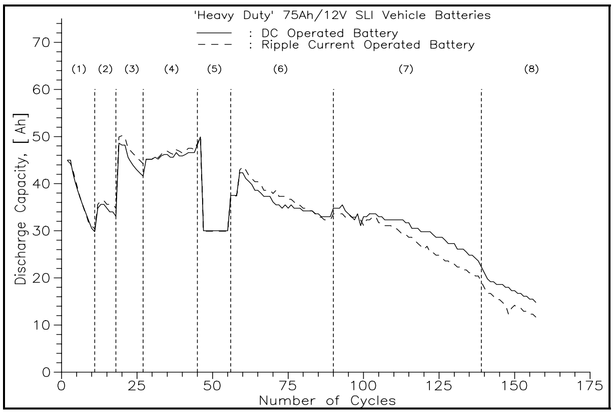

Figure 3. Discharge capacity of the "heavy duty" type SLI batteries

Eight regions are distinguished in Figure 3. The C/10 current cycling rate in region (1) resulted in capacity loss due to the "narrow" voltage span, i.e. the upper voltage limit was set 14.0V while the cut-off voltage was 11.4V. These conditions did not allow the battery to fully charge and this phenomenal capacity decrease was expected. Capacity recovery noticed in region (2) was mainly due to the operational voltage widening in both upper and lower levels. Additionally, the ripple current operated SLI battery showed a trend to have slightly higher useful cycling capacity at discharge in comparison to the DC operated battery, see region (3).

The current rates in (4) were set at approximately C/20, which is a moderate cycling operation. Cycling in region (5) is closer to the PV operation and a rapid useful capacity loss was measured, reaching only 30Ah for both batteries, i.e. less than half the nominal. The change of the cycling charge and discharge timing resulted in capacity recovery at the beginning of region (6), followed by a declination of the capacity curve. In region (7), recharge was done by a C/10 rate, while the upper and lower voltage limits were kept at 15.0V and 10.6V respectively. A slight ripple current negative effect is noticed in regions (7) and (8), although the difference in capacity is not significant and therefore, no general conclusions can be drawn.

After approximately 150 cycles and the particular cycling conditions, the useful discharge capacity for both batteries was around 15Ah, that is some 5 times less the nominal capacity claimed by the manufacturer. In comparison to the "solar" batteries, ageing came at earlier stages with this type of SLI battery.

5.2 "Maintenance free" Type SLI Battery Cycling
The so called "maintenance free" vented lead-acid battery for use in lightweight vehicles was also evaluated. The nominal capacity of a 12V block was 85Ah. There were approximately 160 cycles carried out and the conditions are summarised in Table 3.

Table 3. Cycling conditions of the "maintenance free" type SLI batteries

Region in Figure 4	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]
(1)	-8.5	+8.5	15.0	10.6
(2)	-8.5	+8.5	15.0	10.6
(3)	-8.5	+8.5	15.0	10.6
(4)	-4.0	+8.5	15.0	10.8
(5)	-4.0	+8.5	15.0	10.8

The long-term measured discharge capacity of the "maintenance free" vented batteries is shown in Figure 4.

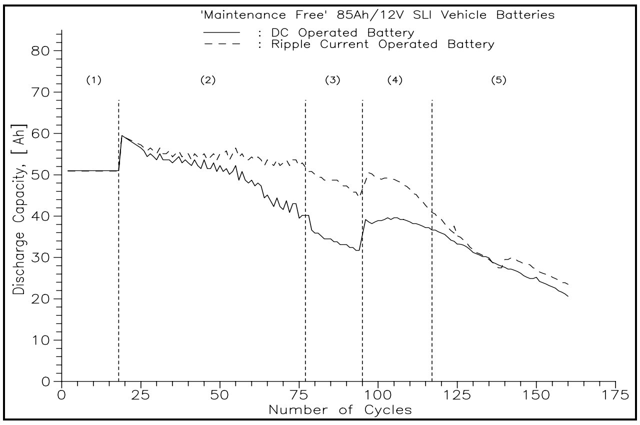

Figure 4. Discharge capacity of the "maintenance free" type SLI batteries

The measured cycling capacity of the ripple current operated battery was considerably higher compared to the DC operated unit, see regions (2), (3) and (4) in Figure 4. The capacity difference reached almost 15Ah in region (3). This is in contrast to the results drawn in the previous tests, especially with the "solar" battery type.

6. COST DATA AND EVALUATION

The kWh cost in 1995 prices of the "solar", the SLI "heavy duty" and the SLI "maintenance free" batteries tested herein was 144ECU, 102ECU and 80ECU respectively. After almost 310 cycles, the "solar" battery retained around 50% of its nominal capacity while, the "heavy duty" had only 20% of the nominal capacity after 160 cycles and the "maintenance free" only 29% after 160 cycles.

The long-term cycling have shown that solar batteries have extended life cycle compared to standard vehicle batteries. SLI batteries showed accelerated capacity loss, especially under high charge and discharge rates and widespread upper and lower voltage limits. In a PV system, vehicle batteries would have to be replaced at earlier stages compared to "solar" batteries and this makes their applicability questionable despite the lower capital cost.

7. POLARISATION CHARACTERISTICS

Polarisation or I-V characteristics represent the internal resistance of a battery. A series of I-V battery tests were undertaken in order to investigate the differences between a cycled and a new battery. The “maintenance free” type 85Ah SLI battery was used and a new battery was tested against the DC cycled battery.

Prior to testing, the batteries were charged to 100% SOC. Each characteristic was obtained by applying a number of discharge currents, in the range -1A to -40A and by measuring the voltage difference after 3sec. Between measurements, the battery was left at rest for 3min. All data in the same curve correspond to the same SOC as the battery is assumed not discharged in 3sec time period. Before the measurements of a new I-V curve, the battery was discharged by -8.5Ah, i.e. the new SOC level was C/10 lower in capacity. Figures 5 and 6 show the I-V characteristics at discharge of a new and a cycled “maintenance free” type battery.

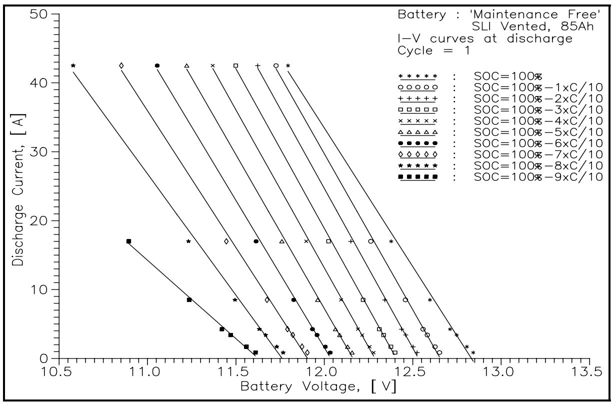

Figure 5. Discharge polarisation curves of a new battery

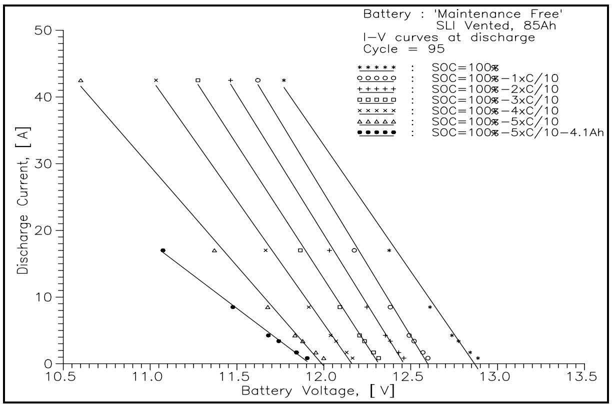

Figure 6. Discharge polarisation curves of a cycled battery

The slope of the curves in Figures 5 and 6 represent the battery conductance. A resemblance of the polarisation curves at discharge for the new SLI battery is noticed in Figure 5. In all SOC levels, the slope of each polarisation curve is almost constant. Moving to lower SOC levels, the slope of the polarisation curves decreases, i.e. higher resistance at the end of discharge. The new 85Ah battery was discharged down to -9×8.5Ah=-76.5Ah and 10 in total polarisation characteristics at discharge were obtained.

The cycled battery had similar performance although not more than 46.6Ah were extracted, giving 7 in total I-V characteristics, Figure 6. Comparing the experimental data, the cycled battery has higher resistance values at the same SOC levels compared to a new battery. A procedure could therefore be established for quick battery ageing examination in real PV stations, provided that at least one polarisation characteristic at a particular SOC is known on delivery of the batteries.

8. CONCLUSIONS

This paper reported on the ripple current effect on lead-acid batteries during long-term cycling operation. A “solar” type tubular battery was tested and evaluated against two SLI battery types at constant temperature. One battery of each type undertook pulsed current operation while a second battery was cycled under DC. In the testing procedures, the current rate, the high and low voltage limits and the discharge/recharge time were the varying parameters. The cycling tests included fast recharge and deep discharge periods.

After 310 cycles for the “solar” type battery and 160 cycles for each of the two SLI batteries, the experimental results indicated that general conclusions concerning the negative effect of ripple currents on battery ageing cannot be drawn. In fact, the difference in useful cycling capacity was very little and in one case, the ripple current operated SLI battery had greater discharge capacity in the end of the cycling period.

A techno-economical analysis showed that the use of vehicle batteries should be avoided in PV applications. Daily cycling of two SLI batteries resulted in more than 70% capacity loss after 160 cycles. On the other hand, “solar” batteries showed in practice their good performance in deep cycling, the fast capacity recovery during recharge etc. These features justify the additional capital cost of “solar” type batteries.

The polarisation tests with a SLI battery indicate that there is a correlation between the slope of the curve, i.e. conductance, and battery ageing. A procedure for identifying the state of health of a battery in PV plants could be investigated in future R&D projects.

REFERENCES

[1]. “Characterisation of Battery Types for Renewable Energy Applications and Development of Battery Life Extension Electronics and Strategies”, EU JOULE II Programme, DGXII, contract No JOU2-CT94-0410