LABORATORY CHARACTERISATION OF LEAD-ACID "SOLAR" AND VEHICLE BATTERIES AND BATTERY PERFORMANCE ASSESSMENT IN PV PLANTS IN GREECE

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Background:
PhD Mech. Engineering, University of Wales College of Cardiff, 1992
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Activities:
Dr Protogeropoulos has been involved in the field of renewable energy sources since 1989. He has experience in testing of small-scale renewable energy systems and sizing and optimisation of hybrid wind/PV systems for stand-alone applications. He has also been involved in testing, modelling and performance prediction of lead-acid batteries operating under dynamic conditions.

He works at CRES since 1993 and has been involved with:
- the development of a battery laboratory and lead-acid and Ni-Cd battery testing
- simulated field test solar pump testing
- PV powered lighting systems
- integration issues of renewable energies on the community level
- PV plant performance evaluation

He is currently responsible scientist for a project related with the design and implementation of hybrid wind/PV stand-alone lighthouses and a project concerned with the investigation of accelerated testing methods for the lifetime assessment of lead-acid batteries. He is head of the Photovoltaic Department at CRES since February 1998.

ABSTRACT:
This paper refers to the tests undertaken in the battery laboratory at CRES for the characterisation of "solar" and 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 vehicle battery. The long-term cycling tests indicated that "solar" batteries have significantly extended life time compared to vehicle batteries. The use of car batteries in PV systems should be avoided due to the poor performance in continuous cycling operation. The operational experience of deep cycle lead-acid batteries after long-term use in selected stand-alone PV plants in Greece is also presented.

1. GENERAL TESTING CONDITIONS

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. 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 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. The discharge capacity was measured in each cycle in order to assess the long-term performance of the batteries. Frequent 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.

2. SIMULATION OF THE RIPPLE CURRENT EFFECT

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

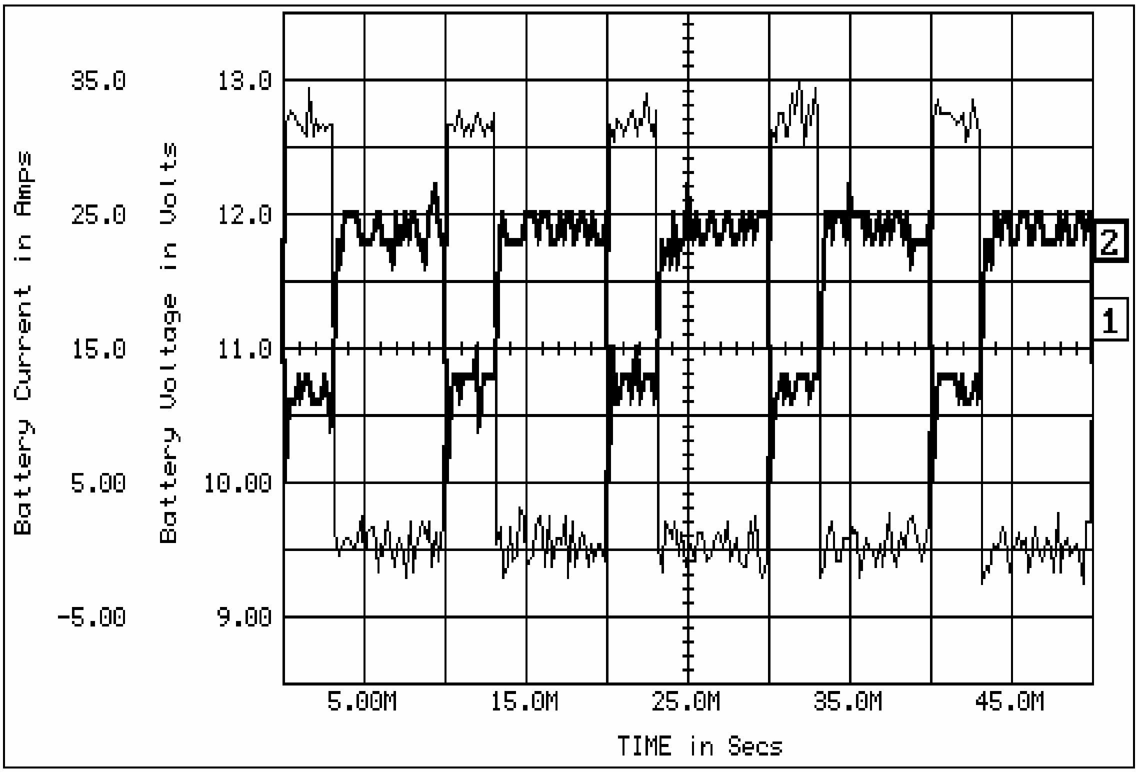

Figure 1. Typical ripple current (fine line) and battery voltage (thick line) profile

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.

3. TESTING PROCEDURES & RESULTS WITH "SOLAR" BATTERIES

Two battery banks each consisting of six 2V cells of 100Ah nominal capacity were evaluated. These lead-acid batteries were type 2 PzO/P50 and were designed for use in PV systems. They incorporated tubular positive plates and a low-antimony negative plate grid.

3.1 Battery Testing Conditions

The two "solar" battery banks 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]	Discharge time	Recharge time
(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	3h30min	10h
(4)	–25	+10	14.2	11.0	4h	10h
boost charge, cycle = 80	–25	+30	16.0	11.0	4h	3h
(5)	–25	+10	14.2	11.0	4h	10h
(6)	–25	+10	15.0	11.0	6h	10h
(7)	–40	+40	16.0	10.5	2h30min	2h50min
(8)	–20	+20	14.4	11.2	3h45min	4h35min

The measured capacity at discharge for the "solar" batteries bank during the long-term cycling test is shown in Figure 2.

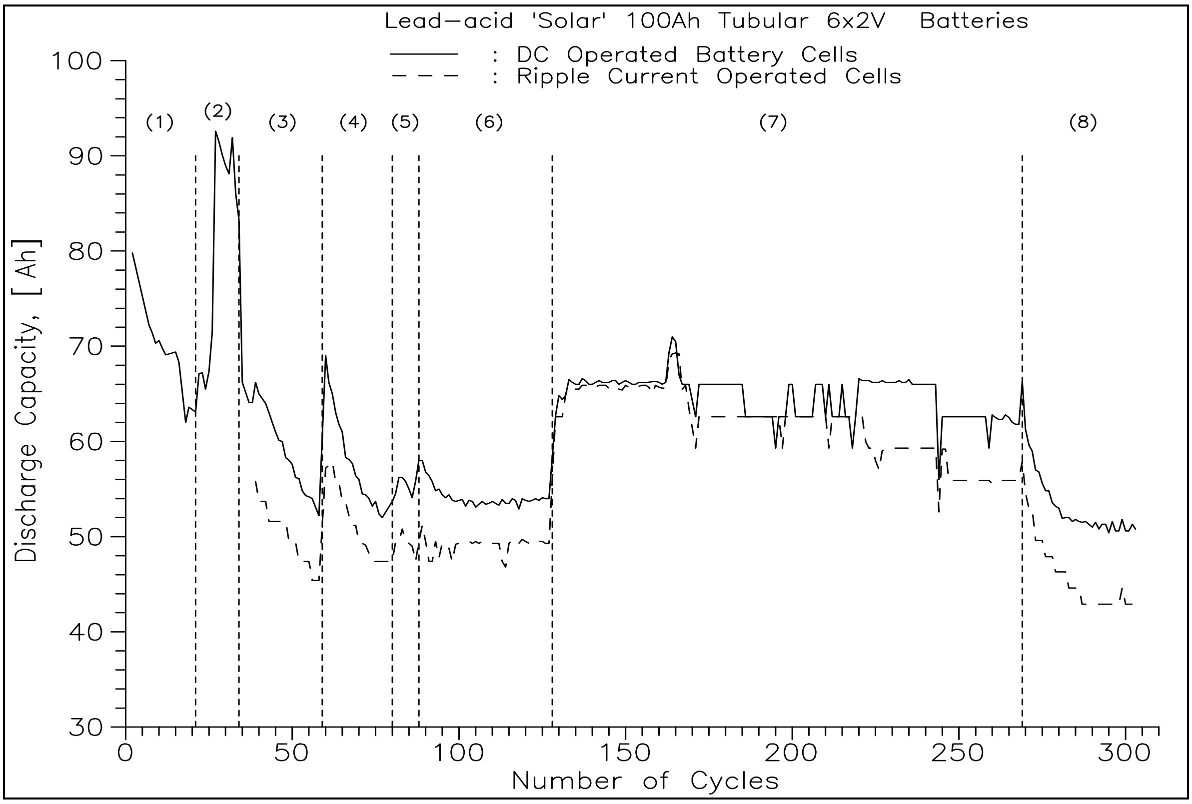

Figure 2. Discharge capacity of the "solar" batteries (refer to Table 1 for conditions)

The results from the capacity tests are summarised in Table 2.

Table 2. Capacity tests of the 100Ah capacity "solar" batteries

Cycle Number	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]	Recharge time	Battery Capacity Test Results, [Ah]	
						Ripple	DC
1	–10.0	+5.0	14.1	11.1	-	98.7	98.7
18	–10.0	+3.0	14.1	11.1	-	76.7	77.6
58	–10.0	+5.0	14.2	11.1	40h	95.9	99.7
128	–10.0	+5.0	14.2	11.1	86h	114.0	115.6

3.2 Discussion of the Results

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 charge rates were maintained at high battery voltage levels up to

16.4V, according to the manufacturer’s recommendations. In region (2), battery capacity reached the nominal value. The conclusions drawn in region (3) are similar to those in region (1). Capacity is now lower due to the higher discharge current of –25A, keeping a moderate 1.85V per cell cut-off voltage level.

Daily comparisons of the capacity of the DC operated battery bank (continuous line), to the capacity of the ripple current operated battery (dotted line), show that, gradually, pulsed currents affect negatively the Ah capacity for the particular batteries under the same voltage, current rate and temperature conditions.

So far, the results indicated an almost constant capacity drop when the “solar” battery operated under moderate to low rates and "narrow" voltage span. Capacity recovery was obtained after increasing the upper voltage limit from 14.0V to 16.4V while recharge current was increased from +5A (C/20) to +40A (C/2.5). In region (4), the relatively low upper voltage limit resulted in poor recharge and therefore, the 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 was in accordance with the manufacturer's recommendations and resulted in a slight capacity recovery, region (5). This was retained in region (6), taking into account that 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.

A long-term high current rate cycling occurred in region (7). The conditions simulate a quick battery ageing mechanism in which, recharge is obtained in approximately 3h, see Table 1, while the assumed load is satisfied in 2.5h. The “solar” batteries operated satisfactorily from the discharge capacity view point. The average discharge capacity was calculated 60.4Ah and 55.7Ah for the DC and the ripple current operated batteries respectively.

The high rate cycling was interrupted in cycle 269 due to the poor operation of two single cells, one of each battery bank. Therefore, the affect of pulsed currents in battery ageing could not be further investigated as cell deterioration has occurred in both battery packs. 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 significance. Finally, in region (8) in Figure 2, the useful capacity of both batteries has dropped mainly because of the limitation of the operating voltage span.

3.3 Single Cell Voltage Measurements

The 2V cell potential of the two “solar” battery packs was monitored from early operational stages in order to ensure no mismatch between individual cells. A typical daily profile of the two cells having the maximum voltage difference during operation is presented in Figure 3.

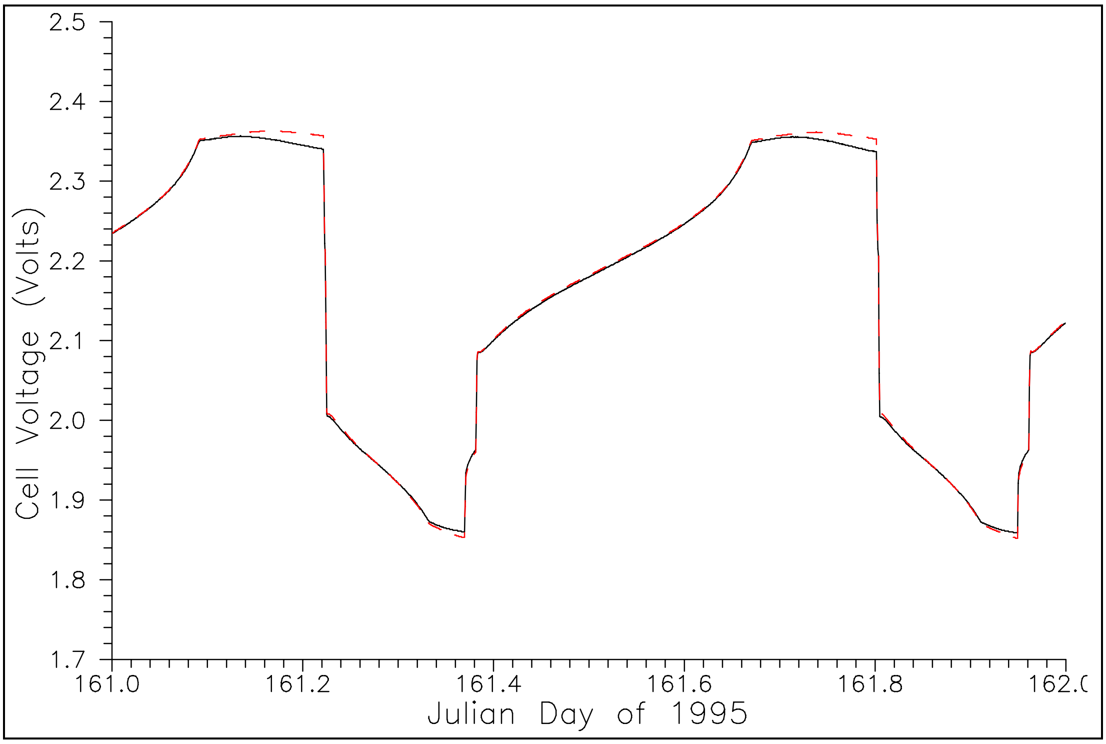

Figure 3. Maximum single cell voltage deviation of the DC operated “solar” batteries

In Figure 4, the results of the single voltage measurements for the both “solar” battery banks are presented, after approximately 6 months of operation.

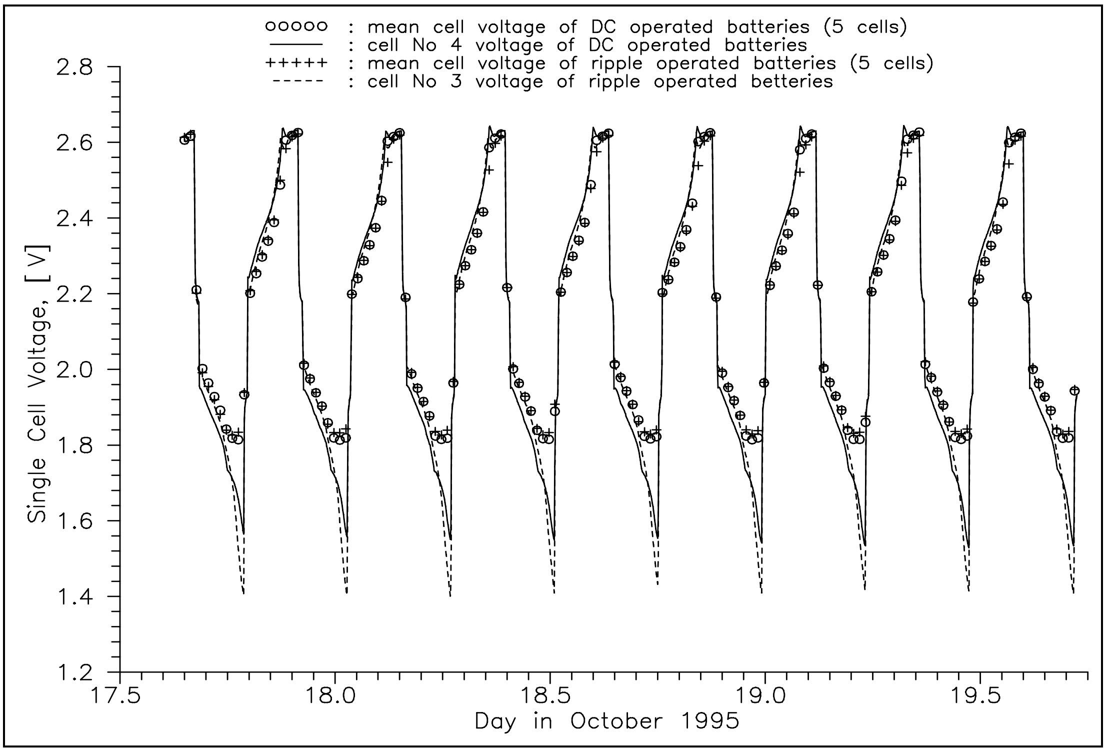

Figure 4. Posterior cell voltage comparison of the “solar” batteries

As it is seen in Figure 4, the cells operate very close to an average value, showing a uniform operation of the DC operated battery pack at the initial cycling stages. The ripple current operated single cells had similar performance.

The single cell voltage measurements shown in Figure 4 were carried out between cycles 260 and 268. It is noticed that at the low state of charge, i.e. average 1.75V per cell, the voltage of cell No 4 of the DC operated battery pack and cell No 3 of the ripple current operated battery dropped down to 1.55V and 1.41V respectively. As a result, the remaining 5 cells were not fully discharged in order to retain the average voltage of the batteries at 10.5V.

4. EXPERIMENTATION & RESULTS WITH VEHICLE BATTERIES

Two types of vehicle batteries were evaluated in order to examine their performance in cycling conditions. The tests refer to 20^0C water bath temperature.

4.1 "Heavy duty" Closed Type Vehicle Battery

The so claimed "heavy duty" vehicle lead-acid battery is closed type (not valve regulated), and it is designed for operation in harsh environmental or power demanding conditions, e.g. boats, small electric carriers etc. The nominal capacity of each 12V block is 75Ah. Two batteries of this type were evaluated; one was cycled under DC while the other operated under pulsed current. The long-term cycling conditions are summarised in Table 3.

Table 3. Cycling conditions of the "heavy duty" type 75Ah vehicle batteries

Region in Figure 5	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]	Discharge time	Recharge time
(1)	−7.5	+7.5	14.0	11.4	6h	6h35min
(2)	−10.0	+10.0	14.2	11.0	6h30min	6h35min
(3)	−4.0	+4.0	14.2	11.0	13h	15h
(4)	−4.0	+4.0	14.6	11.0	14h	16h
(5)	−7.5	+15.0	15.0	10.8	4h	3h10min
(6)	−7.5	+15.0	15.0	10.8	6h30min	3h40min
(7)	−7.5	+7.5	15.0	10.6	6h	6h15min
(8)	−7.5	+7.5	15.0	10.6	6h	6h15min

The capacity at discharge during long-term operation of the two "heavy duty" batteries is presented in Figure 5.

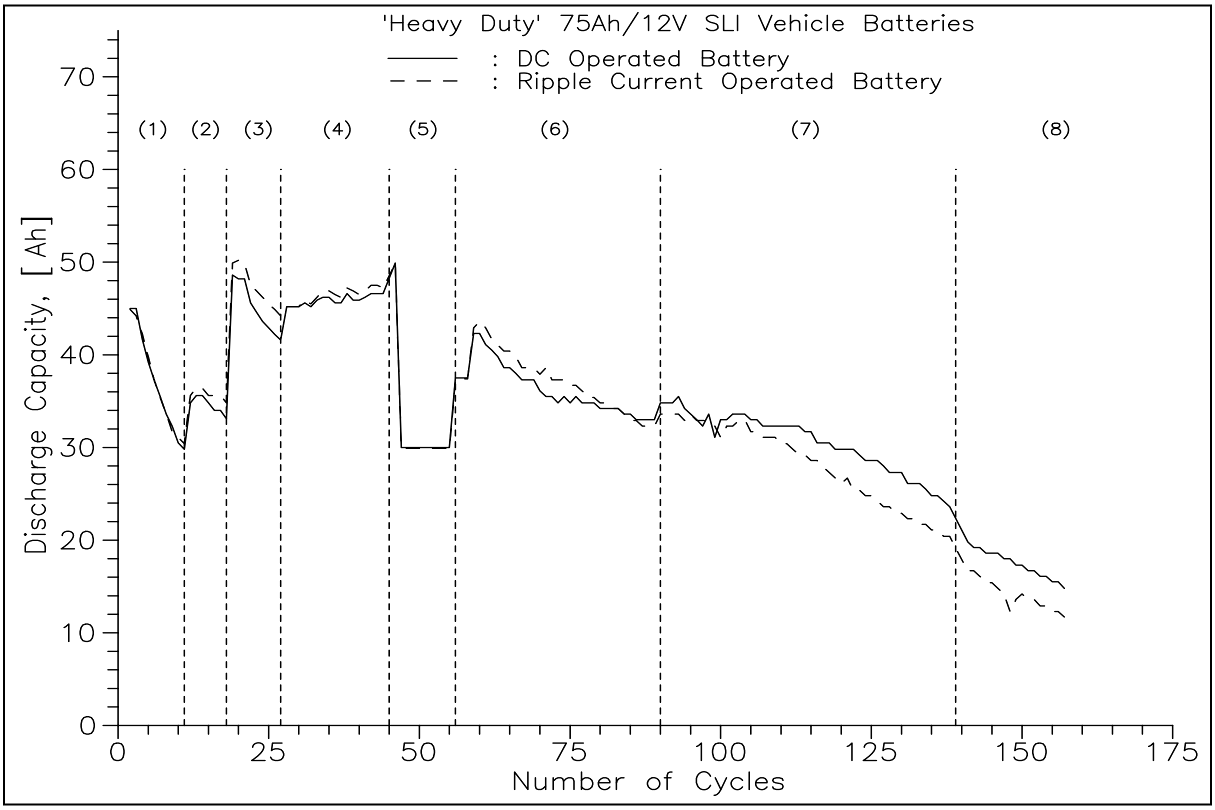

Figure 5. Discharge capacity of the "heavy duty" type vehicle batteries

The results from the capacity tests are presented in Table 4.

Table 4. Capacity tests for the "heavy duty" 75Ah vehicle batteries

Cycle Number	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]	Recharge time	Battery Capacity Test Results, [Ah]	
						Ripple	DC
1	−7.5	+5.0	14.1	11.4	dI/dt<0.06A in 20min	64.0	61.0
45	−7.5	+5.0	14.1	11.4	dI/dt<0.06A in 20min	38.7	34.5
139	−7.5	+5.0	14.1	11.4	dI/dt<0.06A in 20min	16.1	19.5

Eight regions are distinguished in Figure 5. The C/10 cycling rate in region (1) resulted in capacity loss due to poor recharging. Capacity recovery was achieved in region (2), mainly due to the operational voltage widening in both upper and lower levels. Additionally, the ripple current operated vehicle 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 the useful capacity was 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. In regions (7) and (8) the difference in capacity is not significant and therefore, no general conclusions can be drawn on the ripple current effect.

After approximately 150 cycles and the particular cycling conditions, the batteries were in a bad condition as the useful discharge capacity 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 vehicle battery.

4.2 "Maintenance free" Type, Flooded Vehicle Battery

This type of vented battery was designed for use in lightweight vehicles. The nominal capacity of each 12V block is 85Ah and there were approximately 160 cycles carried out. The conditions are summarised in Table 5.

Table 5. Cycling conditions of the "maintenance free" type 85Ah vehicle batteries

Region in Figure 6	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]	Discharge time	Recharge time
(1)	−8.5	+8.5	15.0	10.6	6h	8h
(2)	−8.5	+8.5	15.0	10.6	7h	8h
(3)	−8.5	+8.5	15.0	10.6	7h	8h
(4)	−4.0	+8.5	15.0	10.8	15h	7h
(5)	−4.0	+8.5	15.0	10.8	12h	7h

The long-term measured discharge capacity of the "maintenance free" vented vehicle batteries is shown in Figure 6.

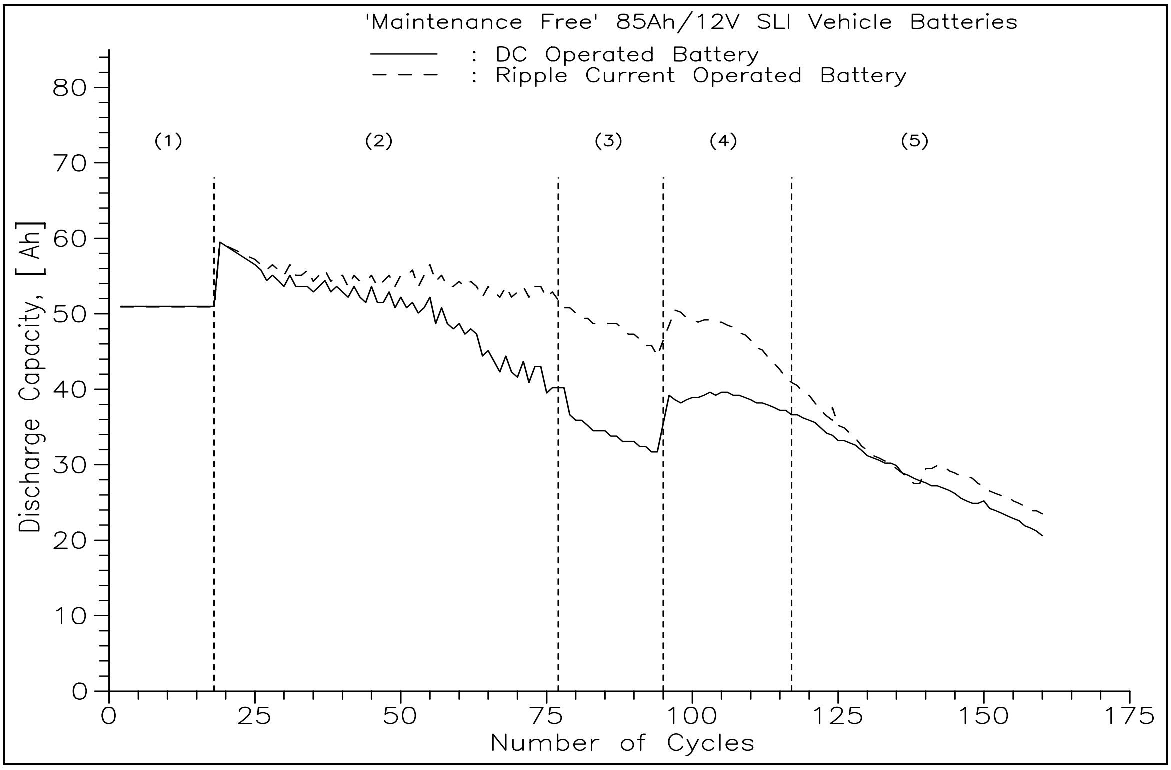

Figure 6. Discharge capacity of the “maintenance free” type vehicle batteries

The results from the capacity tests are shown in Table 6.

Table 6. Capacity tests of the “maintenance free” type 85Ah vehicle batteries

Cycle Number	Discharge Rate, [A]	Recharge Rate, [A]	Vmax, [Vdc]	Vmin, [Vdc]	Recharge time	Battery Capacity Test Results, [Ah]	
						Ripple	DC
1	–8.5	+5.0	14.1	10.8	dI/dt<0.06A in 20min	75.0	77.5
77	–8.5	+5.0	14.1	10.8	dI/dt<0.06A in 20min	52.6	39.5
95	–8.5	+5.0	14.1	10.8	dI/dt<0.06A in 20min	45.1	32.5
162	–8.5	+5.0	14.1	10.8	dI/dt<0.06A in 20min	10.2	17.3

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 6. 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.

5. COST DATA AND EVALUATION

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

The long-term cycling indicates that batteries designed for solar PV applications have considerably extended life cycle compared to standard vehicle batteries. As expected, vehicle 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 life-time economics and applicability questionable despite the lower capital cost.

6. 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. For this assessment, the “maintenance free” type flooded 85Ah vehicle battery was selected 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 7 and 8 show the I−V characteristics at discharge of a new and a cycled “maintenance free” type battery respectively.

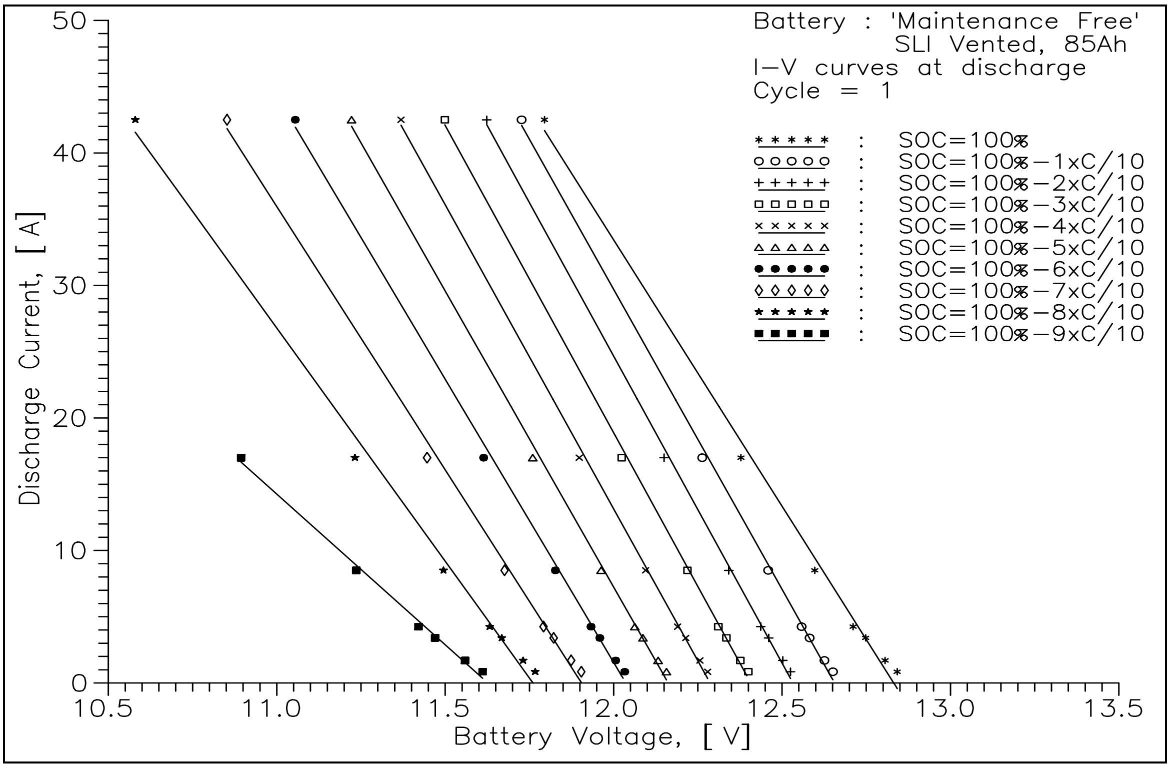

Figure 7. Discharge polarisation curves of a new battery

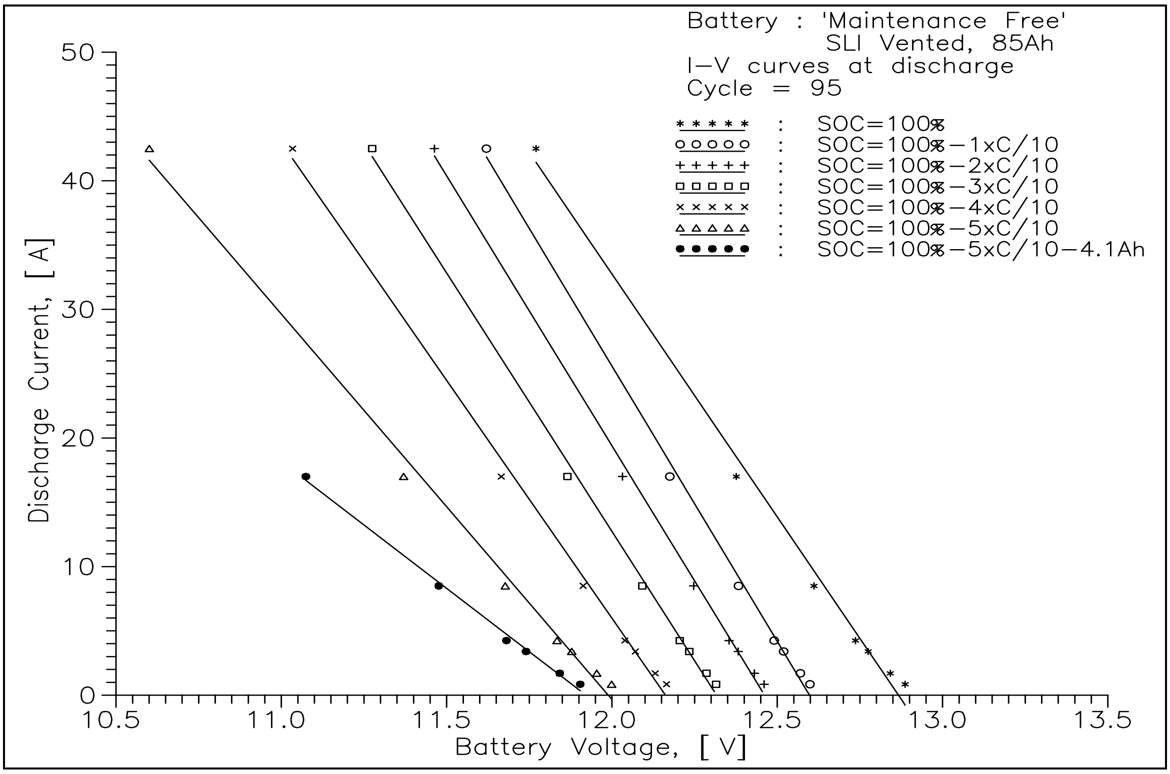

Figure 8. Discharge polarisation curves of a cycled battery

The slope of the curves in Figures 7 and 8 represent battery conductance. A uniformity of the polarisation curves at discharge for the new battery is noticed in Figure 7 as the slope of each curve is almost constant at high charge levels. Moving to lower SOC values, 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, see Figure 8. 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.

7. FIELD EXPERIENCE FROM STAND-ALONE PV SYSTEMS IN GREECE

The operational experience of deep cycle lead-acid batteries after long term use in selected stand-alone PV stations and applications plants in Greece and the lessons learned are presented in the following sections.

7.1 Arki Island PV Plant (installed 1988)

7.1.1 General information

Type:	stand-alone, hybrid PV/diesel
PV Array:	27.5kWp
Battery:	1440Ah capacity at C/100, 302.4kWh total
Diesel:	100kVA, 3-phase
AC/DC:	rectifier for battery recharge, 3-phase
Inverter:	30kVA
Charge Controller:	PWM, shunt type

7.1.2 Battery storage

Type:	Lead-acid
Cell:	2V, vented, water recombination
Configuration:	105 cells in series
DC Bus:	210V
Max. / Min. voltage:	2.35V per cell / 1.90V per cell
Floating voltage:	2.23V per cell
Number of cycles :	at 30% of DOD cycles=4500, at 85% of DOD cycles=1500
Ah Efficiency:	at 30% of DOD η =95%, at 70% of DOD, η =80%

7.1.3 Control features

- the modular construction of the controller groups 7 PV module strings to an independent sub-array; there are 6 sub-arrays
- 4A fuses restrict the maximum permissible consumption

7.1.4 Battery performance data and operational experience

- due to oxidation, the connectors on the battery poles were worn out
- active material has been gathered on the bottom of many battery cells
- the diesel generator guarantees that the batteries are most of the time well charged
- battery cells No 27 and 28 are weaker compared to the rest 103 cells of the battery bank
- the actual autonomy of the PV station never reached its design level (3 to 4 days)

7.2 Marathi Island PV System (installed 1990)

7.2.1 General information

Type:	stand-alone
PV Array:	3.1kWp
Battery:	300Ah capacity, 28.8kWh total
Inverter:	2.5kVA
Charge Controller:	shunt-switch, Pulse Width Modulated
Auxiliary Sources:	petrol engine (no battery recharge feature)

7.2.2 Battery storage

Type:	Lead-acid, 2V cells
Configuration:	12 cells in series per battery bank, 4 banks in parallel
DC Bus:	24V
Maximum voltage:	2.4V per cell

7.2.3 Control features

- temperature compensation: $-5mV/^{0}C$ per cell
- adjustable voltage limit: (2.25 to 2.50)V per cell
- load disconnection at 1.8V per cell

7.2.4 Battery performance data and operational experience

Single cell voltage measurements were carried out at the Marathi stand-alone system. The results are summarised in Table 7.

Table 7. Battery cell voltage measurements at the Marathi stand-alone PV system

	Battery Pack			
Battery Cell	**A [Volts]**	**B [Volts]**	**C [Volts]**	**D [Volts]**
1	2.200	2.205	2.081	2.216
2	2.190	2.195	2.077	2.211
3	2.200	2.195	2.080	2.203
4	2.190	2.195	2.084	2.215
5	2.190	2.195	2.076	2.206
6	2.185	2.193	2.079	2.213
7	2.210	2.195	2.414	2.196
8	2.190	2.187	2.399	2.198
9	2.205	2.202	2.011	2.200
10	2.206	2.200	2.403	2.206
11	2.196	2.204	2.403	2.205
12	2.190	2.200	2.405	2.204
Total Voltage	26.352	26.366	26.512	26.473

From Table 7 it is noticed that battery cells 1 to 6 of pack C (shaded region), retain a voltage level well below the average cell value of 2.202V. It was concluded that, at some stage, the user has connected directly on these batteries an external 12Vdc appliance. Other remarks concerning the battery operation at Marathi refer to,

- partial shading of the PV array during afternoon hours due to bad sitting
- an AC/DC rectifier should be installed for battery recharging when the petrol engine is operating
- parallel battery operation should be avoided

7.3 Gavdos Island PV Plant (installed 1987)

7.3.1 General information

Type:	stand-alone
PV Array:	20.8kWp
Battery:	468Ah cell capacity, 234kWh total
DC/DC:	25KW converter, step-up with MPPT 160Vdc (PV) to 250Vdc (battery)
Inverter:	30kVA

7.3.2 Battery storage

Type:	Prototype lead-acid
Cell:	2V, vented, water recombination
Configuration:	125 cells in series, 2 banks in parallel
DC Bus:	250V
Minimum voltage:	1.8V per cell

7.3.3 Control features
- load switch off: V < 130Vdc, load switch on: V > 200Vdc
- the operating load and battery voltage is determined by the energy available, the energy required and the battery SOC

7.3.4 Battery performance data and operational experience
- precipitate has gathered at the bottom of the cells
- the battery bank total nominal capacity of 936Ah cannot be reached
- low electrolyte density is usually measured
- in 1990, the positive plate of some cells was unusually enlarged causing a crack to the cover
- the general condition of the battery bank cells can be characterised as poor
- a DC/DC converter should not be used; instead, more PV panels should be connected in series per string
- oxidation of the converter and the inverter PC boards
- poor PV plant maintenance & frequent shortages

7.4 Antikythira PV Plant (installed 1987)

7.4.1 General information

Type:	stand-alone, central with extended grid
PV Array:	27.6kWp
Battery:	546Ah at C/100 capacity each, 236kWh total
Inverter:	30kVA
Charge Controller:	stepped battery charge regulation

7.4.2 Battery storage

Type:	Lead-acid, flat plate
Cell:	2V, vented, water recombination
Configuration:	108 cells in series, 2 banks in parallel
DC Bus:	216V
Minimum voltage:	1.7V per cell

7.4.3 Control features
- battery overvoltage and cut-off voltage
- temperature compensation
- disconnection of 1 to 8 solar generator groups (depending on the optimum battery charge rate)
- disconnection of 1 to 4 consumer groups (load shedding)

7.4.4 Battery performance data and operational experience
- active material has been deposited on the bottom of almost all battery cells
- the battery bank was at very low SOC in winter 1991
- bad sitting of the PV plant (fog concentration)
- defected PV modules were replaced
- maintenance activities are not scheduled

7.5 Elounda Island Villas PV System, Crete (installed 1996)

7.5.1 General information

Type:	stand-alone, hybrid PV/diesel
PV Array:	6.4kWp
Diesel:	15kVA
Battery:	680Ah each cell, 65.3kWh total
Inverter:	2 DC/AC units rated 5kVA and 6kVA

7.5.2 Battery storage

Type:	Lead-acid, 2V flooded, tubular positive plate
Configuration:	24 cells in series, 2 banks in parallel
DC Bus:	48V

7.5.3 Battery performance data and operational experience

In general, the system is new and no major problems have been reported. However, due to the poor measured efficiency of the inverters, the battery storage is quite often discharged deeper compared to the level expected in the design phase of the system. Replacement of the inverters has already been scheduled.

7.6 PV Powered Lighthouses, Beacons & Buoys (installed between 1983 to date)

The Hellenic Navy has installed more than 350 solar powered lighthouses of total installed PV capacity 27.3kWp.

7.6.1 General information

Type:	stand-alone
PV Arrays:	16.5Wp to 4.7kWp
Battery:	105Ah nominal capacity, (usual case)

7.6.2 Battery storage

Type:	Lead-acid, low antimony, 12V and 6V blocks VRLA, 2V cells flooded (depending on the size of the system)
Configuration:	1 battery, parallel connection if more capacity is needed
DC Bus:	12V (usual), 24V and 48V
Design Autonomy:	10 days

7.6.3 Battery Performance Data and Operational Experience

The operational experience from the early installations is not positive as the batteries had to be replaced after short periods of use. The new VRLA 6V and 12V batteries have satisfactory performance, while the vented 2V cell battery bank installed at the Lithari PV lighthouse is still under operation after 10 years of usage. Other experiences refer to,

- lead-acid battery replacement is scheduled every 3 years on average
- system breakdowns are usually due to failures of the electronic parts, such as electronic flashing timers, charge controllers etc.
- problematic operation can also occur due to the extreme environmental conditions, i.e. humidity, low ambient temperatures, high content of salt in the air, gusts etc.

8. CONCLUSIONS

This paper reported on laboratory testing of "solar" and vehicle lead-acid flooded batteries and particularly, the effects of ripple currents on the long-term battery performance. Reference to the experiences concerning battery behaviour in existing stand-alone PV plants in Greece was also made. A "solar" designed tubular battery was tested, evaluated and compared with two vehicle battery types at constant temperature. One battery of each type was cycled under ripple currents while a second battery was tested under pure 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" battery and 160 cycles for each of the two vehicle 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 battery had greater discharge capacity in the end of the cycling period.

The techno-economical analysis showed that the use of vehicle batteries should be avoided in PV applications. Daily cycling of two standard vehicle batteries resulted in more than 70% capacity loss after only 160 cycles. On the other hand, "solar" batteries showed in practice their good performance in deep cycling, in terms of fast capacity recovery during recharge, long life cycle in accelerated testing 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 conductance and battery ageing. This can be used as a procedure for identifying the state of health of a battery in PV plants although uncertainties such as the SOC before the measurements etc. are implemented.

Finally, from the experiences gathered from existing PV plants in Greece, battery failures are usually due to the unattended operation in small PV systems and the poor battery maintenance activities (e.g. water refill, charge equalisation, malfunction of charge controllers etc.), in large stand-alone solar stations.