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Charging of valve-regulated lead/acid batteries under deep cycling applications

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Abstract

Charging methods exert a great influence on the cycle life of batteries used for deep discharges such as electric-vehicle applications. The time for a complete conversion of active materials should be as short as possible, and corrosion effects and gaseous emission must be limited. Changes in the electrical characteristics during ageing cause complications that a good charging system must take into account.

Keywords: Valve-regulated lead/acid batteries; Deep cycling applications

1. Introduction

The constant, although slow, rise in the cycle life of valve-regulated (VRLA) batteries underlines more and more the importance of better management of the battery. Furthermore, the situation tends to become increasingly complicated due to changes in the physical characteristics of VRLA batteries with time. During the past few years, FIAMM has studied various design factors that can benefit the cycleability of VRLA batteries. More recently, however, promising results obtained with batteries designed for cycling applications have opened a new research line. This seeks a solution of two particular problems, namely, the capacity loss during the initial cycles and an optimum recharge method. This paper summarizes the main goals achieved in investigating the latter problem.

The first VRLA batteries used for the cycling tests were built in a similar fashion to FIAMM MONOLITE batteries that are used for standby applications. Their cycle life was short, particularly if 100% depth-of-discharge (DOD) was carried out (note, only IU-type recharge methods were used at that time); no more than 150–200 cycles were achieved. The short life hindered a full evaluation of the unfavourable consequences of their relatively high weight loss (about 1 g per cycle).

The next phase of the test was to investigate the performance of VRLA batteries (6 V, 90 Ah at *C*/5 rate) that were similar to FIAMM MONOLITE 6 SLA 100 batteries, but with certain design parameters modified in a way that, at the time, appeared the most suitable for increasing cycle life [1]. In particular, a higher compression and container formation were adopted. These batteries two-by-two series connected, were cycled with 100% DOD at the *C*/5 rate, followed by a 19 h, IU-type recharge, with $I_{max}=0.2$ *C*/5 and a final voltage $V=2.40$ V/cell. The test was performed in a thermostatic room at 25 ± 1 °C.

The application of this new constructive design has considerably improved the resistance of VRLA batteries to deep-discharge cycling applications (with 100% DOD). The 150–200 cycle threshold was surpassed (Fig. 1(a)). This test had also been able to emphasize that, beyond 200 cycles, the charge factor (Fig. 1(b)) starts to increase faster and faster. The decrease in weight per cycle was the same as that observed with non-optimized batteries, but the increase in battery life enhanced the problem due to the excessive water loss.

Fig. 1(a) and (b) shows the behaviour of the capacity and charge factor during a cyclic test that was performed on three batteries. The trend is quite similar for all batteries, but the effects of weight loss and increase in charge factor are best emphasized for the 'E' battery (i.e., drawn with thicker lines). In this case, when more than 200 cycles were performed, a meaningful capacity increase was observed. This is probably due to the increase in temperature that has resulted from the rapid increase of the charging factor. Afterwards, the battery failed abruptly. This was the result of the battery dryout.

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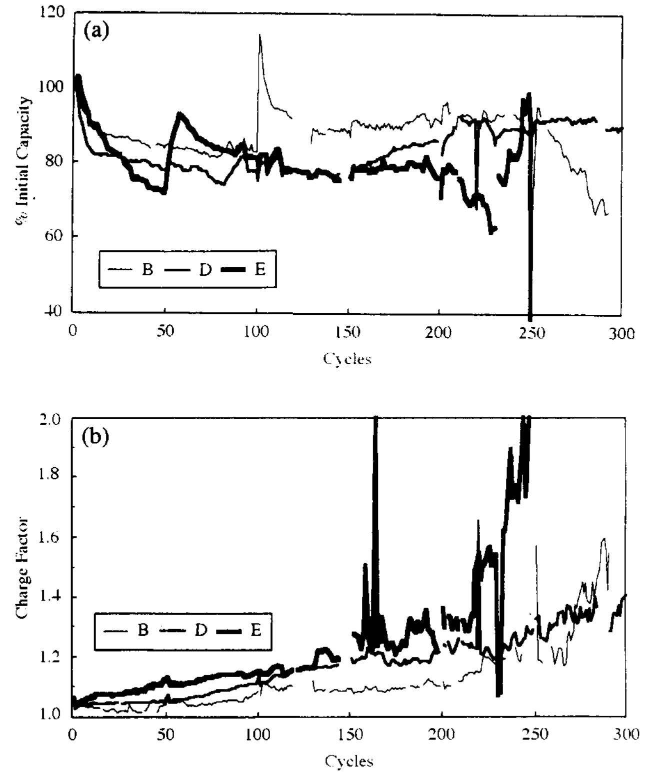

Fig. 1. (a) Capacity and (b) charge factor trends during cycling on three couples of series-connected (6 V, 90 Ah) VRLA batteries. DOD = 100%; temperature = 25 °C; charge IU with I_{max} = 0.2 C/5, V_{max} = 2.40 V/cell; 1 cycle/day.

2. Gas generation during deep cycles

To understand better the details of this phenomenon, a series of fundamental experiments was performed. Interest was particularly directed towards the analysis of those conditions that could lead to an excessive water loss. A group of VRLA batteries (12 V, 45 Ah at C/5 rate) was assembled, with a constructive design similar to the batteries described above, but modified to extract and analyze the evolved gas, to measure the internal pressure of cells, and the instantaneous and accumulated gas outflow. The experiments included tests with different discharge depth, recharge current, and final voltage.

Fig. 2 [2] shows the typical trend of internal pressure during a discharge–charge cycle with 100% DOD discharge (C/5 rate) and IU-type charge. It is possible to see a sudden pressure increase up to a maximum value (the opening valve-pressure). This maximum is achieved at nearly the same time as the battery voltage reaches the pre-set maximum value (in this case 2.40 V/cell). Afterwards, the pressure tends to decrease. It is probable that the oxygen generated during the charge, and still trapped in the cells, reacts on the negative plates following the recombination reaction.

The IU recharge profile shows, therefore, a critical situation. Consequently, an attempt was made to find

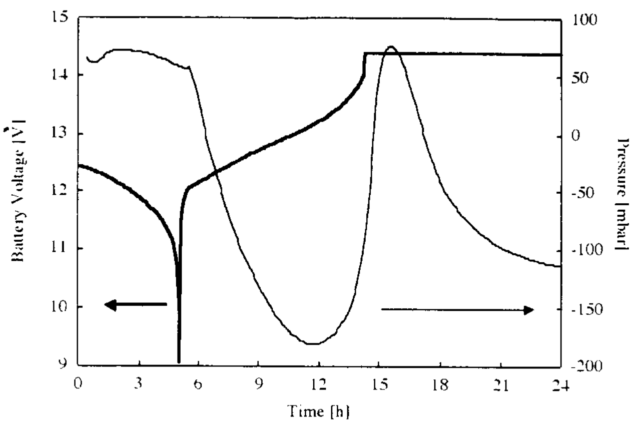

Fig. 2. Cell internal pressure and battery voltage during a cycle on a 12 V, 45 Ah VRLA battery. DOD = 100%; temperature = 25 °C; charge IU with I_{max} = 0.2 C/5, V_{max} = 2.40 V/cell; 1 cycle/day.

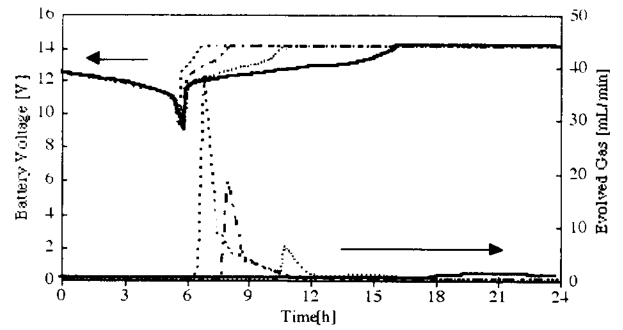

Fig. 3. Instantaneous gas flow during charging. DOD = 100%; temperature = 25 °C; 1 cycle/day; charge IU: V_{max} = 2.40 V/cell; I_{max} during charge = 0.1 (——), 0.2 (···), 0.4 (–·–) and 0.8 (···) C/5.

the conditions that limit the problem without adversely influencing the battery performances. Initially, this was considered to be the maximum current in recharge. Fig. 3 displays the instantaneous gas emission (in cm^3 min^{-1}) evolved during a IU-type recharge (carried out after a 100% DOD, C/5 rate). Four cycles were performed, with 2.40 V/cell as final voltage during recharge and changing I_{max} (0.1, 0.2, 0.4 and 0.8 C/5). It can be seen that the highest instantaneous gas emission corresponds to the highest charge current. This result confirms the influence of the recharge method on gas evolution from a 100% DOD discharged battery.

The test was repeated with changes in the depth-of-discharge. Table 1 gives the results obtained at 100, 80 and 60% DOD. The cycles with 100% DOD were carried out under the same conditions described above, i.e., the discharge phase was terminated when the battery voltage was 1.70 V/cell. The cycles with 80 and 60% DOD involve a discharge with I = 0.2 C/5 limited in time to 4 and 3 h, respectively. The recharge time was always 19 h, with variable I_{max} and V_{max} = 2.40 V/cell. Table 1 also lists the times required, during charge, to recover 100 and 107% of the capacity yielded during discharge (note, FIAMM considers as 'optimum recovery charge' a value between 105 and 107% of that

Table 1
Gas evolution from a VRLA battery (12 V, 45 Ah) as function of the DOD and charging current

	Discharge			Charge to 2.4 V/cell			Time (min) to		Charge factor (%)	Cumulative evolved gas (cm^3)
	(h)	(Ah)	(%)	A/C/5	Ah in 30 s	Ah at end of charge	100% discharged Ah	107% discharged Ah		
1	5	52.6	100	0.1	2.25	47.8	762	> 1440	105.4	250
2	5	52.6	100	0.2	4.5	44.5	416	936	108.4	750
3	5	51.6	100	0.4	9	41.5	216	570	110.7	1060
4	5	50.95	100	0.8	18	35.4	122	377	112	2190
5	4	36	80	0.1	2.25	32.4	515	846	108.5	200
6	4	36	80	0.2	4.5	29.68	283	498	109.9	380
7	4	36	80	0.4	9	26.02	167	331	110.1	580
8	4	36	80	0.8	18	20.7	110	261	111.4	780
9	3	26.99	60	0.1	2.25	24.35	378	507	113.7	180
10	3	26.99	60	0.2	4.5	22.21	208	313	114.7	340
11	3	26.99	60	0.4	9	18.07	138	236	115.6	310
12	3	26.99	60	0.8	18	14.67	86	184	117.9	600

yielded during discharge). It is found that the amount of evolved gas relates to the maximum current during charge and, in particular, that the maximum cumulative gas evolution (more than 2000 cm^3) is observed with batteries previously discharged to 100% DOD.

Another comparison was performed, in which the maximum voltage value in charge was changed, i.e., from 2.40 to 2.33 V/cell. From a qualitative point of view, the gas evolution characteristics appear to be similar: on one hand, there is a lower quantity of gas but, on the other hand, the time required for a complete recharge is considerably longer (more than 24 h).

3. Use of an IUIa charging profile

As stated above, a significant amount of gas is evolved from a battery that has been subjected to deep cycles, during recharge with an IU profile, particularly during the transition from a controlled-current to a controlled-voltage charge close to the achievement of the maximum voltage. The higher is the maximum current during charge, the more important is the gas evolution amount; on the other hand, the current must be high enough to keep the charge within reasonable time limits. This also appears to have a good influence on cycle life (tests are running in the A.I.F. laboratory). Another important fact to take into account is the internal pressure reduction during the end of recharge. In this phase, it should be possible to give a higher current to the battery, with negligible gas evolution.

All these considerations prompted an investigation of a different, IUIa-type, recharge system. Compared with the IU method, this procedure involves:

- a reduction of the initial current during the current-controlled period;
- a lower maximum voltage during the voltage-controlled period;
- an additional phase, Ia, with constant current, whose value and duration are both fixed.

The recharge method described here consists of an IU period, with $I_{max}=0.2$ $C/5$, $V_{max}=2.37$ V/cell, and a phase Ia with $I=0.005$ $C/5$, free voltage and a time limit of 3 h. The transition condition between these two periods changed during the test; in the initial phase of the experiment, carried out on 100% DOD discharged VRLA batteries, for example, the IU period was limited to the achievement of a minimum current, whose value could, or could not, be the same as that applied during the next Ia period.

An important laboratory application of this recharge method is the charge of VRLA batteries for EV application during the JRC-ECE 15 test [3]. In short, this test is an attempt to simulate electric-vehicle duty, and consists of a series of consecutive charges, discharges and pauses, making up a microcycle. These microcycles are carried out in succession until the battery reaches the end of discharge (1.70 V/cell), and then recommence after the recharge. A complete cycle is made up of the necessary number of microcyles and of the recharge. In this case, the test has been carried out on four VRLA batteries (12 V, 50 Ah) especially designed for EV applications, and connected in series.

When the IUIa method was initially used to recharge the batteries for the JRC-ECE 15 test, the Ia period started when the current during the IU phase was the same as that imposed for the Ia phase. From a comparison of the behaviour for the first cycle (Fig. 4) with that for the 70th cycle (Fig. 5), it can be seen that the recharge time is longer in the latter case. This is due to changes that occur in the electrical characteristics of the battery during its life [4]. The time increase is, obviously, located in the last period of the IU phase,

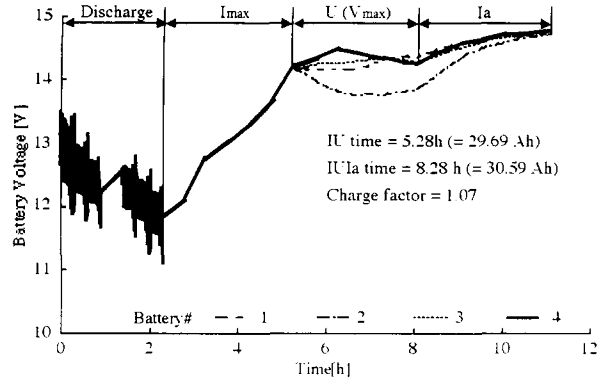

Fig. 4. Battery voltage during the 1st ECE-15 cycle on four series-connected 12 V, 50 Ah VRLA batteries. IUIa charge: $I_{max}=0.2$ $C/5$; V_{max} during IU = 2.37 V/cell; Ia = 0.005 $C/5$.

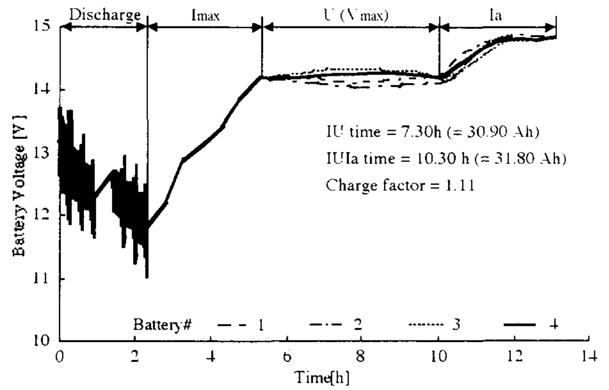

Fig. 5. Battery voltage during the 70th ECE-15 cycle on four series-connected 12 V, 50 Ah VRLA batteries. IUIa charge: $I_{max}=0.2$ $C/5$; V_{max} during IU = 2.37 V/cell; Ia = 0.005 $C/5$.

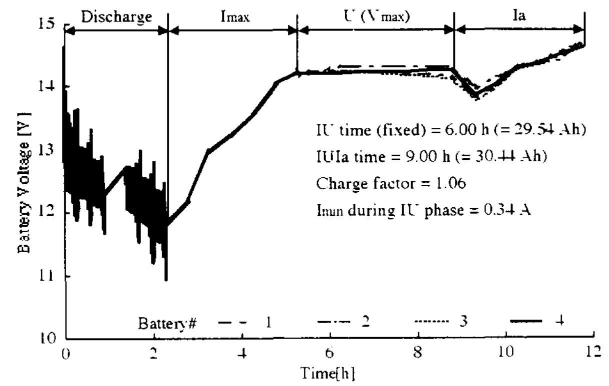

Fig. 6. Battery voltage during the 100th ECE-15 cycle on four series-connected 12 V, 50 Ah VRLA batteries. IUIa charge: $I_{max}=0.2$ $C/5$; V_{max} during IU = 2.37 V/cell; Ia = 0.005 $C/5$.

because the time (indicated in Figs. 4 and 5) to reduce the current to its lower limit is longer. The consequence is an increase of the total charged Ah and, therefore, of the charge factor, cf., Figs. 4 and 5. Afterwards, a time limit of 6 h was placed on the IU phase. As an example, the situation during the 100th cycle is shown in Fig. 6. The following is observed: (i) a reduction in the charge factor; (ii) a voltage step corresponding to the transition from the IU phase to the Ia phase. This sudden decrease in potential indicates that the current at the end of the period was higher than 0.25 A (= 0.005 $C/5$).

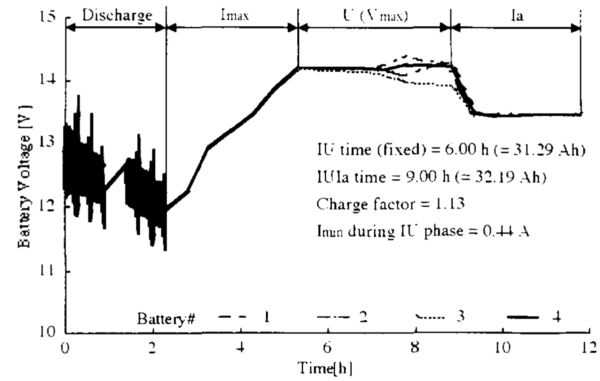

Fig. 7. Battery voltage during the 101st ECE-15 cycle on four series-connected 12 V, 50 Ah VRLA batteries. IUIa charge: $I_{max}=0.2$ $C/5$; V_{max} during IU = 2.37 V/cell; Ia = 0.005 $C/5$.

Between the 100th and the 101st cycle, the test was interrupted for two months, because of a change in the organization of the laboratory. When the test restarted, a rather high current was observed at the end of the IU phase (Fig. 7, 101st cycle). The charge factor was under control, however, by virtue of the time limitation: compared with the previous plots, it is possible to notice that the voltage in the Ia phase is relatively low and does not increase, although there is no voltage limitation. The test was continued until the 200th cycle. At the end, the weight loss was about 0.3 g cycle^{-1}.

4. Conclusions

Various factors are responsible for the changes in the electrical characteristics that occur during VRLA battery life. Among them, in particular, are: depth-of-discharge, recharge method, frequency of use, working temperature, water loss, changes in internal resistance and corrosion phenomena. Because of the change in the battery behaviour, a recharge method that is considered as optimum for a new battery can become less and less suitable for a battery undergoing a progressive ageing process. Control of the final current (Ia) during recharge, taking into account the effective recombination capability of the battery, can avoid incidental overcharge, without, however, having a negative influence on battery performances. But, on the other hand, such a controlled recharge method could be slightly inadequate during the initial stages of the battery life since, in this case, the current that the battery can accept could be higher than the fixed value.

At present, several recharge methods are being considered in order to determine their adaptability to various conditions. To date, tests in both the FIAMM laboratory and in the field show encouraging results, with the following observations.

- For better recharge, in terms of time length and battery protection, higher maximum currents and lower maximum voltage should be used during the IU period.
- The recharge method described above appears to be correct only for batteries that are discharged to 80% DOD, or more. For lower depths-of-discharge, a further reduction in the IU phase length is required.
- The length of the IU phase should not be measured from the start, but from when the prefixed maximum voltage value is reached.

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