Journal of Power Sources 196 (2011) 3981–3987

Contents lists available at ScienceDirect

Journal of Power Sources

journal homepage: www.elsevier.com/locate/jpowsour

# New accelerated charge methods using early destratification applied on flooded lead acid batteries

K. Mamadou[a,c], T.M.P. Nguyen[b,*], E. Lemaire-Potteau[c], C. Glaize[a], J. Alzieu[b]

[a] Institut d'Électronique du Sud IES, GEM/UMR 5214 UM2/CNRS, Université Montpellier II, C.C. 079, 860 rue Saint Priest 34095 Montpellier Cedex 5, France
[b] Électricité de France EDF R&D, Site des Renardières, Route de Sens, Ecuelles, 77818 Moret-sur-Loing Cedex, France
[c] National Institute of Solar Energy INES RDI, 50 av. du Lac Léman, BP 332, 73377 Le Bourget du Lac Cedex, France

ARTICLE INFO

*Article history:*
Received 18 August 2010
Received in revised form 28 October 2010
Accepted 7 November 2010
Available online 12 November 2010

*Keywords:*
Lead acid batteries
Charge acceptance
Stratification
Overcharge
Fast charge

ABSTRACT

A traditional charge process for flooded lead acid batteries (FLABs) lasts generally from 8 to 14 h. Nowadays, many applications of FLABs require reduction of the charge duration, for instance, a 4 h-charge for FLABs in grid energy storage or 1 h-charge for FLABs in electric buses. These are called accelerated charge and fast charge. Such reductions of charge time imply the use of a new charge process. One way to reduce the charge duration is to perform an early destratification step without waiting for the end of charge. The new charge method proposed in this paper (early destratification method – ED) focuses on the reduction of the charge time for FLABs using early destratification, which is performed and controlled using charge acceptance measurement during the charge. Laboratory experiments presented here aim first to develop charge acceptance measurements followed by an ED charge method compared to an IUi traditional charge process.

## 1. Introduction

In practice, a charge process has to answer three principal conditions: reasonable or desired charge durations, a sufficient state of charge and acceptable electrolyte homogeneity.

*Electrolyte stratification* is a common problem of vented lead acid batteries, in which the electrolyte on the bottom tends to be more concentrated than at the top [1–13]. The stratified battery, exposed to accelerated aging process, loses its capacity prematurely. One way to homogenize the electrolyte is to provoke a sufficient gas circulation to mix the electrolyte by a forced convection.

It is known that gas evolutions due to water electrolysis always occur at the same time with charge reactions in lead acid batteries. They increase with the increase of the charge voltage, and become noticeable beyond a gassing point, called gassing voltage. At this gassing voltage, charge current contributes mostly to proper charge reactions, or in other words the battery is charged with its charge acceptance. The definition of the charge acceptance used in this paper is the current response of the battery at a gassing voltage (cf. Section 2.1). Therefore, a noticeable gas flow can be produced by applying a current superior to the charge acceptance, or by applying a voltage that exceeds the gassing value; this is called the destratification phase. The destratification by gassing is necessary for battery longevity, but the current of gas evolution, called here gas current, has to be controlled to prevent the shedding of active materials, the depletion of the electrolyte and the excessive hydrogen evolution, which increases the flammability risk. The work of Alzieu and Robert [14] shows in Fig. 1 that for a flooded battery, beyond about 8% of overcharge (8% of electrical quantity obtained during the previous discharge), the electrolyte is almost homogeneous and independent on the overcharge rate.

A typical charge of lead acid batteries is composed of three phases, usually called IUi charge (cf. Fig. 2). The first phase is a constant current phase (A) in which the major part of the charge is accomplished. During this phase, the battery voltage increases up to gassing voltage. The second phase (B) is performed at constant gassing voltage. During this phase, the current, called battery charge acceptance decreases asymptotically to a low value. The third and last phase is the destratification phase (C). In this phase, in general a constant current, called overcharge current, whose value is higher than the charge acceptance, is applied.

In this classical charge process, which lasts in general from 8 to 14 h, the destratification phase is achieved at the end where the charge acceptance is sufficiently small to be negligible, so that the current of gas evolution (gas current) is roughly assimilated to the applied current. This makes the evaluation of gas current easier, as well as the global management of the charge. In practice, as the electrical quantity (Ah) used during the previous discharge is usually unknown, a 10–20% of the total electrical quantity accepted during the two previous charge phases (cf. Fig. 2) is applied at the

---

* Corresponding author. Tel.: +33 1 60 73 79 63; fax: +33 1 60 73 74 77.
*E-mail address:* phuong.nguyen@edf.fr (T.M.P. Nguyen).

0378-7753/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jpowsour.2010.11.040

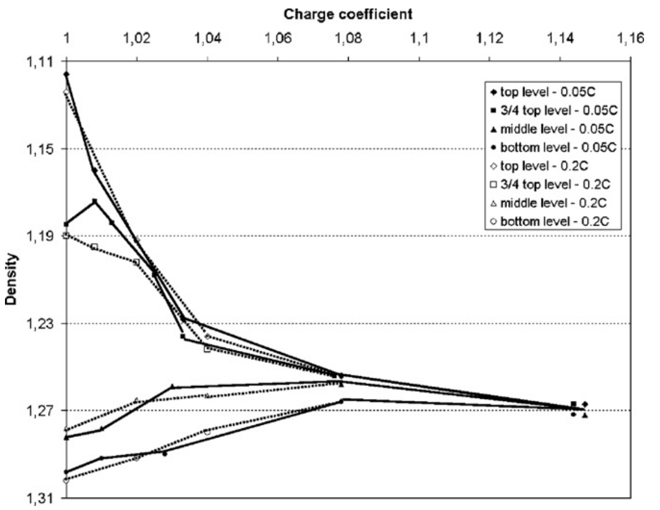

**Fig. 1.** Electrolyte density measured at 4 levels of the cell and as the function of the charge coefficient evolution during overcharge phases at 0.05 C or at 0.2 C. Beyond 8% of overcharge, the electrolyte is almost homogeneous without depending on the overcharge rate [14].

end of the charge process to destratify the electrolyte. In commercial battery chargers, the current generally does not exceed the 0.2C (C/5) rate during the (A) phase and the 0.05C (C/20) rate during the (C) phase. As the gassing current is part of the (C) phase current, its value never exceeds the C/20 rate.

New applications of lead acid batteries require, in general, a reduction of the charge duration, e.g. 4 h or less. Such short charges do not include a final phase just for destratification. All along the charge, charge acceptance remains too high to be neglected. Final destratification by gassing has to be thus carried out in parallel with the proper charge. Here we call this overcharge phase "early destratification".

In this paper, a new charge algorithm is developed applying early destratification. Charge acceptance measurements are achieved in order to evaluate and control gas currents.

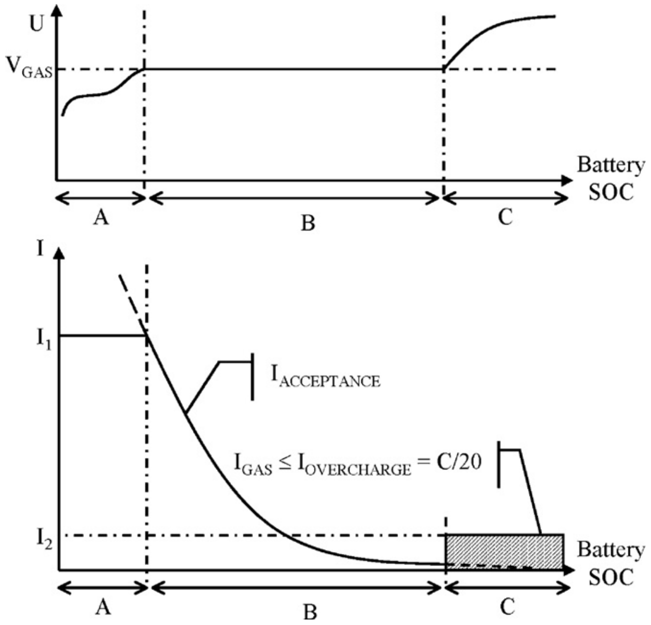

**Fig. 2.** IUi charge of lead acid batteries: (A) constant current phase, (B) constant voltage phase at gassing value $V_{GAS}$ and (C) overcharge or destratification phase at constant overcharge current C/20.

## 2. Charge acceptance measurement method

### 2.1. Charge acceptance definitions

Several definitions of the charge acceptance, in term of a current, of a flooded lead acid battery can be found in the literature [15–20].

Berndt defines the "acceptance" as *the share of the current that actually is "accepted" by the battery and could be retrieved by subsequent discharge* [20]. Indeed, the charge current is partly involved in side reactions, mainly gassing. According also to Berndt [20], charge acceptance is determined by the balance between the kinetic parameters of the main charge current and the gassing current. In other words, it depends on the rate of the main and side charge reactions. This definition is difficult to use in practice because this "acceptance" cannot be directly measured, but only evaluated, by taking into account the losses through side reactions. This definition of the charge acceptance is associated to faradic efficiency ($r_{\mathrm{Faraday}}$) as the following:

$$r_{\mathrm{Faraday}} = \frac{I_{\mathrm{ACCEPTANCE}}}{I_{\mathrm{CHARGE}}} \tag{1}$$

In which: $I_{\mathrm{ACCEPTANCE}}$: charge acceptance, $I_{\mathrm{CHARGE}}$: charge current.

Charge acceptance may also be defined as the maximum current a battery can absorb for its main charge reaction. This corresponds to the maximum value that can be reached in the case of the first definition. Although this concept is easily understandable, measurement of such a charge acceptance is very difficult.

A very different definition is the total charge current (main and side reactions) under a constant charge voltage. The result can widely vary with the chosen voltage value. This includes for instance charge currents under float charges (charge with very low rates to maintain the charge of stationary batteries).

Gassing becomes noticeable when voltage is above a threshold value, called here gassing voltage. The gassing voltage depends on temperature, charge rate, alloy quality, battery age and history. Moreover, as "noticeable" is subjective, it depends also on the observer appreciation. The gassing voltage is statistically situated between 2.3 and 2.6 V/cell. In this paper, the charge acceptance of the flooded lead acid battery is assumed to be the charge current passing through its electrodes at a gassing voltage. Thele [17] has used a similar definition for modeling the charge acceptance of flooded lead acid batteries.

### 2.2. Experimental

In order to control the gassing current, assuming that during an overcharge phase, the supplied current ($I_{\mathrm{OVERCHARGE}}$) is the sum of charge acceptance ($I_{\mathrm{ACCEPTANCE}}$) and gas current ($I_{\mathrm{GAS}}$), we have to find a way to measure the charge acceptance during the overcharge phase (C) so that the gassing current can be calculated as follows:

$$I_{\mathrm{GAS}} = I_{\mathrm{OVERCHARGE}} - I_{\mathrm{ACCEPTANCE}} \tag{2}$$

As defined above, the charge acceptance ($I_{\mathrm{ACCEPTANCE}}$) that has to be measured is the charge current at a gassing voltage ($V_{\mathrm{GAS}}$).

The charge test to measure charge acceptance called here early destratification charge test (ED charge test), is carried out as follows: at the first phase like in the case of a traditional IUi charge process, battery charge acceptance is high and the charge current is limited by the charger maximum current. During this phase, the battery voltage increases to reach $V_{\mathrm{GAS}}$. Prolonging the charge beyond $V_{\mathrm{GAS}}$ with a constant current ($I_{\mathrm{OVERCHARGE}}$) would increase the share of gassing, $I_{\mathrm{GAS}}$, which is beneficial for destratification, overcharge step. $I_{\mathrm{ACCEPTANCE}}$ can be measured when reducing periodically the battery voltage back to a chosen $V_{\mathrm{GAS}}$ for a very short time, called measurement step; at this $V_{\mathrm{GAS}}$ value, charge accep-

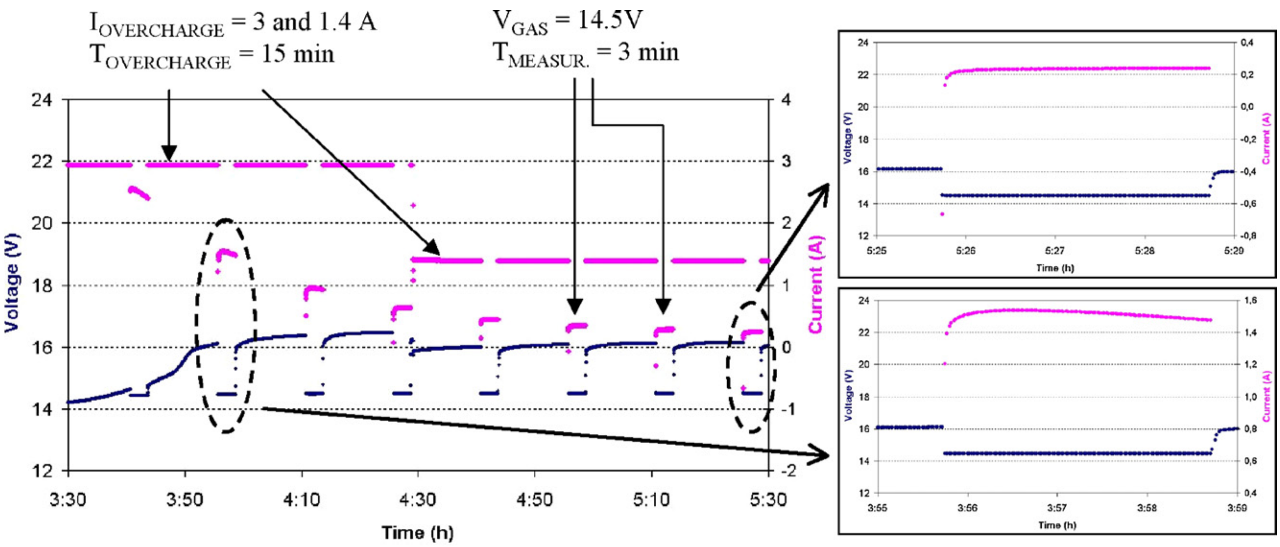

**Fig. 3.** Voltage and current of the battery are presented as functions of time during a charge test with acceptance measurement by voltage square method (ED test): successive steps of overcharge for 15 min at 3 A and 1.4 A and of acceptance measurement for 3 min at 14.5 V gassing voltage were periodically done. Two zooms on the current profile at 14.5 V gassing voltage show transient values, sometimes negative, at the beginning of the acceptance current measurement steps.

tance response of the battery is measured. Every overcharge step and measurement step last 15 and 3 min respectively.

The tests were operated on the flooded lead acid battery 12 V–70 Ah, Monobloc Equipa-Fulmen 070430 A-A, used in photovoltaic applications.

Our first cycle of tests consists to evaluate the battery charge acceptance response at different gassing voltage values (from 13.8 to 15.3 V). To simplify the ED test program, the overcharge current value (i) is set to be equal to the constant current of the first charge phase (I). They are both fixed at 3 A.

Our second cycle of tests consists to compare ED charge acceptance measurement with the one obtained at a charge IU (a classical charge without the overcharge phase, cf. Fig. 2). The depth of discharge, the charge rate and the gassing voltage value are the same in both cases (15 Ah, 10 A and 14.8 V respectively).

The depths of discharge were chosen in such a manner that a discharge–charge cycle could be done during a working day shift (less then 8 h).

The ED charges were operated using a bipolar alimentation and amplifier (KEPCO BOP 20-20 M), which is controlled by a function generator (HP 33120A).

The battery voltage and current and temperatures of the battery and of the ambient were recorded using JUMO Logoscreen 500.

### *2.3. Results and discussion*

#### *2.3.1. Evaluate charge acceptance responses of the battery at different gassing voltage values*

Results of ED charge test at the gassing voltage of 14.5 V is presented in Fig. 3.

It can be observed that while the voltage is brought back to the fixed gassing value at 14.5 V, the current at first drops abruptly to a very low value (that can be negative) for a short time (around 5 s) then it increases to reach stabilized values. This transient phase of current response can be related to the fact that the double-layer capacitance is discharged when the battery voltage falls from a given potential to a lower one [21,22]. According to this hypothesis, the higher the voltage gap between the overcharge value and the gassing value, the more deeply the double layer capacitance is discharged and therefore the lower the current falls down before stabilizing.

#### *2.3.2. Comparison of charge acceptance measured in ED test with the one in IU test*

It is shown in Fig. 4 that the current values measured at 14.8 V in ED test forms a current profile that matches well with the one obtained from IU charge.

Now let us take a closer look in zooming two measurement steps at the beginning and at the end of the overcharge phase of the ED test. As already observed, there is always a transient phase at the beginning of measurement steps. Transient values are far lower than the charge acceptance values of IU charge. Then the current increases and follows a profile that is almost parallel with the charge acceptance profile of the IU charge, slightly greater (about 0.1–0.2 A). In this case of 14.8 V, it takes about 5 s to get rid of the influence of this transient phase shown in both zooms of Fig. 4. So two situations can happen regarding the data obtained for later use:

- If current data measured at a transient point (e.g. earlier then 5 s) its value can be negative and it is a wrong charge acceptance value.
- If current data is measured beyond 5 s, this value can be a little smaller or higher than the one of charge acceptance, but stays close to it.

The first situation, especially when data measured is negative, should be avoided. The second situation can be used despite of a little gap between the two charge acceptance values because this difference is just some hundreds mA, it is small compared to C/20 (3.3 A for a 70 Ah battery) that is the recommended gassing current for destratification. Moreover, it is possible to take into account this difference when controlling the percent of electrical quantity.

### *2.4. Conclusions of charge acceptance measurement method*

ED with voltage square test gives promising results for the charge acceptance measurement, which match well with the ones obtained from an IU charge at the same gassing voltage value. Nevertheless, set gassing voltage values at which charge acceptance measurement steps are carried out and the duration of these steps as well as the moment to get the current data have to be set in such a manner to avoid inaccurate voltage–current information. Many experimental tests show that gassing values should be between

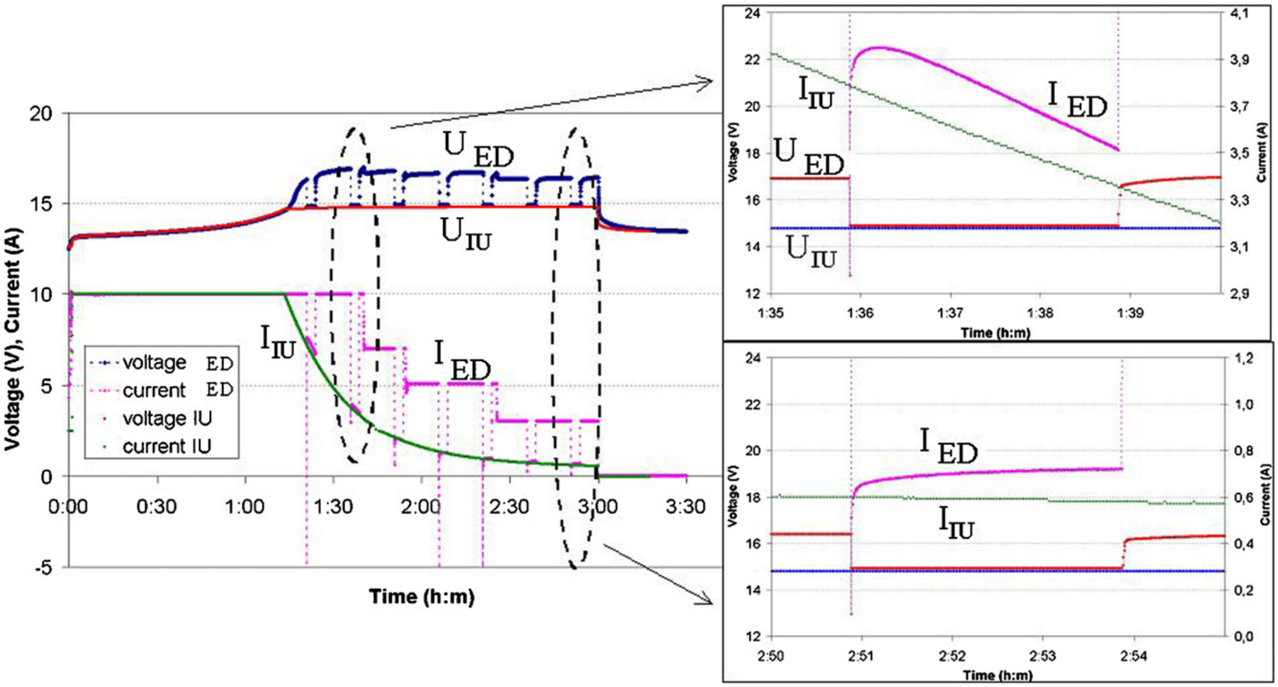

**Fig. 4.** Comparison of the charge acceptance measured by ED test and the charge acceptance obtained from IU charge. Gassing voltage was set at 14.8 V for both tests. Regardless of the transient values, charge acceptance measures of ED test matches well with charge acceptance at a fixed gassing voltage of IU charge.

14.3 and 14.8 V for a 12 V battery and duration of about 5 s is convenient to measure and collect the data.

This method can be used in accelerated charges as well as fast charges.

## 3. New charge method with early destratification for reducing charge time (ED charge method)

Nowadays, many applications of lead acid batteries require reduction of the charge duration, for instance, a 4 h-charge for lead acid batteries in grid energy storage or 1 h-charge for lead acid batteries in electric buses. Such reductions of charge time imply the use of a new charge process.

One way to reduce the charge duration is to perform an early destratification step without waiting for the end of charge. Early electrolyte destratification by gassing is possible. It can start as soon as spare power of the charger is available, i.e. as soon as the charge acceptance becomes lower than the maximal current of the charger. However, limitation of this gassing is not possible using traditional charge methods when charge acceptance is higher than C/20. Indeed, not only the current value share for destratification (gassing current) can become too high and damage the battery, but also it becomes very difficult to estimate and thus to control the electrical quantity supplied for the destratification.

The new charge method proposed here (early destratification charge method – ED charge method) focuses on the reduction of the charge time for vented lead acid batteries using early destratification, which is performed and controlled using charge acceptance measurements during the charge.

### 3.1. Objectives

This new charge method aims to reduce the charge time for flooded lead acid batteries in controlling the destratification phase as follows:

- Starting early the destratification phase, when the charge acceptance is not yet negligible. Practically, destratification can start as soon as the charge acceptance becomes lower than the charger maximal current.
- Controlling the total electrical quantity for gassing (or for destratification); for instance 7% of the total charged electrical quantity.
- Maintaining the gassing current at a value not too high (to avoid the risk of material degradation).

### 3.2. Principle

Fig. 5 represents the principle of the ED charge method in order to reduce charge time, consisting in the following steps:

- I step at constant current or constant power during which the voltage increases continuously up to the gassing voltage ($V_{GAS}$). This step is similar to the *A* phase of the IUi charge (Fig. 2).
- IIa step, dedicated to charge acceptance measurement. These steps consist in fixing the voltage at $V_{GAS}$. To get rid of transient effects, a certain latency time is included between the voltage fixation and the current measurement. This latency time is a few seconds, for instance 3–10 s.
- IIb step of overcharge during which an overcharge current ($I_{OVERCHARGE}$) is supplied to the battery. $I_{OVERCHARGE}$ is determined from the measured charge acceptance ($I_{ACCEPTANCE}$) and a convenient gassing current ($I_{GAS}$).

$$I_{OVERCHARGE} = I_{ACCEPTANCE} + I_{GAS} \tag{3}$$

Two ways to determine a convenient gassing current value are considered:

- For the shortest duration of charge, $I_{GAS}$ is set at the maximum value the battery can afford (e.g. C/20).
- For applications where the charge duration is set in advance (e.g. 4 h), $I_{GAS}$ is calculated taking into account the electrical quantity

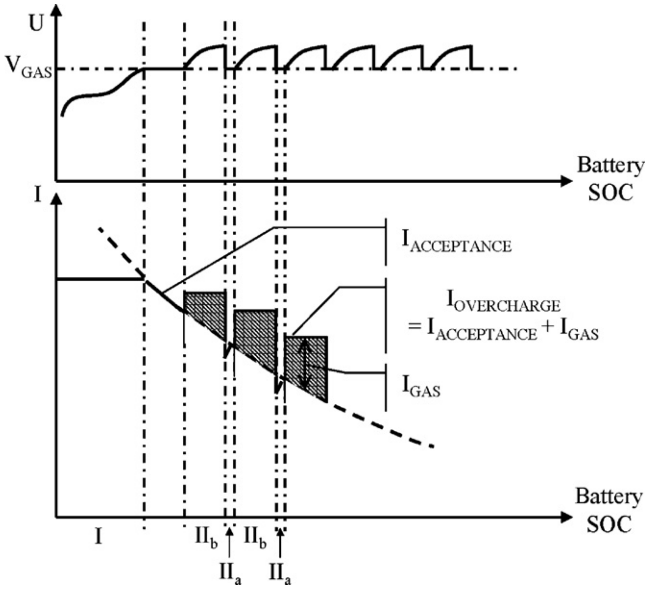

**Fig. 5.** ED charge principle to reduce charge time for flooded lead acid batteries: (I) constant current step, (IIa) charge acceptance measurement steps at gassing voltage, (IIb) overcharge steps at overcharge current ($I_{OVERCHARGE}$) which equals to the total sum of charge acceptance ($I_{ACCEPTANCE}$) and gassing current ($I_{GAS}$): $I_{OVERCHARGE} = I_{ACCEPTANCE} + I_{GAS}$.

for destratification $Q_{DES}$ and the remaining charge time $T_{remain}$.

$$I_{GAS} = \frac{Q_{DES}}{T_{remain}} \tag{4}$$

The $Q_{DES}$ is calculated as a function of the depth of the preceding discharge. As mentioned above, during the first charge step at constant current, i.e. from the beginning of the charge to the moment when the battery voltage reaches the gassing value, 60–90% charge is accomplished. In practice, $Q_{DES}$ can be set as a percentage, e.g. 11%, of this electrical quantity that has been provided to the battery during the first step of the charge (I step).

In order to update regularly the charge acceptance value, the IIa and IIb steps are repeated $n$ times until $Q_{DES}$ is reached.

### 3.3. *Experimental*

In the context of MICROSCOPE project – grid connected inverter combined with energy storage for production optimization – a 4-h charge algorism of ED type has been developed at EDF R&D in cooperation with Montpellier II University. This algorism is integrated to 12 and 48 V commercial chargers of IES-Synergy without any modification of the charger maximum power.

In this application, batteries are charged by the grid during the night at lack period, i.e. from 1 to 5 am, and by the photovoltaic panels during the day except during the time when they supply energy to the grid. They are usually discharged in average of about 50% DOD.

The ED charge and the traditional IUi charge are achieved by IES-Synergy charger using a prototype of compressed battery 140 Ah/12 V developed at EDF R&D (cf. Table 1 and Fig. 6). The battery was charged with an IUi profile followed with an 8-h charge at 14.6 V then discharged at 50% DOD before being tested with the IES-Synergy charger. These cycles were operated with BITRODE Battery Charge and Test System, Module Type LCN 200 A–12 V.

During charging with IES-Synergy charger, the charged electrical quantity, the voltage and the current at the output of the charger were recorded by Provista software via a computer. Battery voltage and current were measured by HOBO software (via a shunt to measure the current). The electrolyte density is manually measured at the top of the battery using Atago Refractometer BC-2E – Battery Coolant Checker.

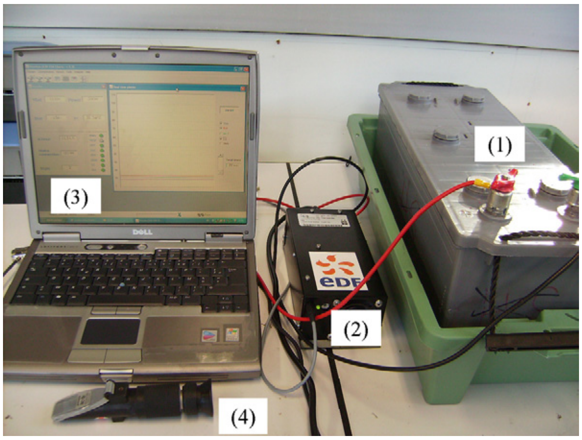

**Fig. 6.** Montage of the charge of the compressed battery (1) with either IUi or ED profiles using the 12 V commercial charger IES-Synergy (2); voltage and current are at the output of the charger recorded by Provista logical via computer (3); electrolyte density is measured by the Battery Coolant Checker (4).

### 3.4. *Results and discussion*

Fig. 7 shows the battery voltage, battery current and measured density profiles during the ED charge. In I step of constant current, the measured charge acceptance and the gassing current are clearly observed. This means that the duration of the charge acceptance measurement at 5 s can ensure accurate information of the battery current response. On the voltage profile, a slight increase of $V_{GAS}$ is observed which can be explained by the contribution of drop voltages on the cables. These drop voltages depending on the resistance of the cable and the current flow, decrease with the decrease of the charge current.

I step at 15 A lasts about 3 h, meaning that 45 Ah is charged. According to the ED algorithm, the $Q_{DES}$ has to be 11% of this value, so 4.95 Ah. As soon as the battery voltage reaches 14.6 V, the overcharge step is done to destratify the electrolyte. At the beginning of this step, the $I_{OVERCHARGE}$ is limited at 15 A (the maximum output current of the charger) then it is equal to $I_{ACCEPTANCE} + I_{GAS}$ which is about 3 A. It means that during 1 h of early destratification, the overcharged Ah is less than 3 Ah, so 6.7%, which is less than 11% expected. In this case, the setting of $I_{GAS}$ at 3 A instead of 4.95 A programmed, was due to a calculation error of the program integrated in the charger.

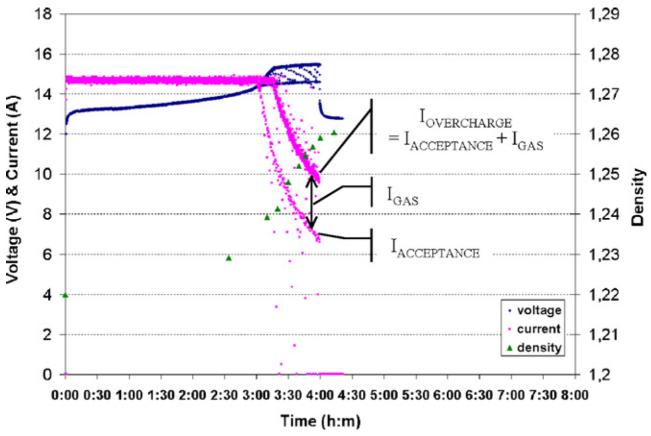

**Fig. 7.** Voltage, current and electrolyte density profiles measured during ED charge. The battery had been discharged with 50% DOD. The total charge time was 4 h.

**Table 1**
12 V IES-Synergy charger: electrical characteristics, integrated ED and IUi charge profiles.

| | |
|---|---|
| Electrical characteristic of the IES-Synergy charger | Max output power: 222 W ± 3%<br>Max output current: 15 A ± 2%<br>Nominal battery voltage: 12 V |
| ED charge profile (cf. Fig. 5) | $V_{GAS}$: 14.6 V<br>$Q_{DS}$: 11% of total charged Ah during I step<br>$I_{GASmax}$: C/20<br>$I_{GAS}$: $Q_{DES}/T_{remain}$<br>Total charge duration: 4 h<br>Duration of IIa step: 5 s<br>Duration of IIb step: 60 s |
| Traditional charge IUi profile (cf. Fig. 2) | $V_{GAS}$: 14.6 V<br>$I_1$: 15 A<br>$I_2$: 3 A<br>Duration of phase (B): until the charge current reaches $I_2$<br>Duration of phase (C): until 17% of charged electrical quantity during phase (A) and phase (B) phases is obtained |

Nevertheless, an obvious improvement of the electrolyte density stratification can be observed when using the early destratification. This result fits with the electrolyte density evolution illustrated in Fig. 1 showing that most of the stratification is removed with a 5% overcharge. During I step at constant current, the density increases slightly with the battery voltage. As soon as the $I_{OVERCHARGE}$, which is the sum of the measured charge acceptance and the calculated gassing current, is applied the density increases with an obvious higher rate. This reveals that the early destratification process has effectively started. After 4 h charge, the electrolyte density at the top is around 1.26. It should be noted here that, at the end of this ED charge, the acceptance is still high, 6.5 A. This shows that ED charge is, of course, not a complete charge, but a partial charge. This is the second reason why the electrolyte density is not higher.

A traditional IUi charge was also operated on the same battery (cf. Table 1). Results of this charge, battery voltage, current and electrolyte evolutions, are illustrated in Fig. 8. Similar to the ED charge, during I step at constant current, the density increases slightly. When the battery voltage reaches the gassing value, 14.6 V, the density increases faster phase after phase. Electric quantity during the third phase (C) is 17% of charged Ah during the first and second phases (A + B). The electrolyte density reaches 1.275 at the end of charge lasting 7 h 15 min.

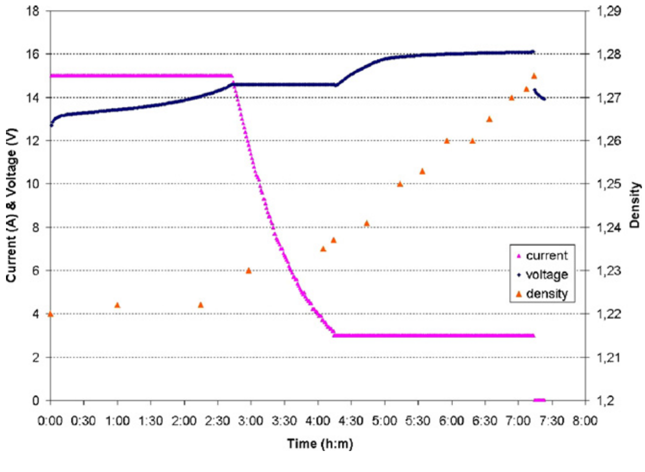

**Fig. 8.** Voltage, current and electrolyte density profiles measured during IUi charge. The battery had been discharged with 50% DOD. The total charge time was 7 h 10 min.

Compared to ED charge, at IUi charge without early destratification, after 4 h charge, the electrolyte density is about 1.235, which is lower than in the case with early destratification, i.e. 1.26. This confirms again efficiency of the early destratification. It is clear that, within 4 h of ED charge, the battery is not charged as well as in the case of 8 h of traditional IUi charge regarding the state of charge. But, within half reduced charge duration compared to a traditional IUi charge, it can be acceptable in condition that longer charge is periodically achieved to establish a good state of charge, e.g. once a week.

## 4. Conclusions

A new charge method is proposed for fast charges and accelerated charges of flooded lead acid batteries using early destratification with charge acceptance measurements. The following conclusions can be drawn:

- The overcharge phase, which begins as soon as the charge acceptance becomes lower than the maximum output current of the charger – early destratification, can efficiently homogenize the electrolyte.
- Thanks to the charge acceptance measurement, the overcharge current as well as the electrical quantity for destratification can be calculated and controlled.
- The modification of a '12 h' charger with an algorithm of the early destratification, enables the battery to be available for a discharge in duration of the order of 4–6 h. This division of the charge duration of a factor two is obtained without increasing the charger power.

Evolution towards a rapider charge requires increasing the initial charge rate, so using more powerful chargers. For a fast charge whose duration is less than 1 h, the estimation of charge acceptance is no longer sufficient; one has to take into account its derivative. After several accelerated charges, charges with longer duration should be periodically achieved to re-establish a good state of charge of the battery.

A patent of EDF and University Montpellier II has been submitted in 2008 about this subject. Since 2009, about thirty IES-Synergy chargers with integrated ED charge profile have been experimented at Paca France in the occasion of PREMIO project.

## Acknowledgment

The authors gratefully acknowledge financial support from the Agence Nationale de la Recherche (ANR, France).

## References

[1] Y. Guo, W. Yan, J. Hu, Journal of Electrochemical Society 154 (2007) A1–A6.
[2] T.G. Chang, D.M. Jochim, Journal of Power Sources 64 (1997) 103–110.
[3] F. Mattera, D. Desmettre, J.L. Martin, P. Malbranche, Journal of Power Sources 113 (2003) 400–407.
[4] J.F. Cole, Journal of Power Sources 116 (2003) 243–247.
[5] R.H. Newnham, W.G.A. Baldsing, Journal of Power Sources 66 (1997) 27–39.
[6] R.H. Newnham, W.G.A. Baldsing, Journal of Power Sources 133 (2004) 141–146.
[7] D.J. Spiers, A.D. Rasinkoski, Journal of Power Sources 53 (1995) 245–253.
[8] M. Kim, E. Hwang, Journal of Power Sources 64 (1997) 193–196.
[9] D.U. Sauer, Journal of Power Sources 64 (1997) 181–187.
[10] D.U. Sauer, J. Garche, Journal of Power Sources 95 (2001) 130–134.
[11] P.R. Stevenson, Journal of Power Sources 116 (2003) 160–168.
[12] D. Pavlov, V. Naidenov, S. Ruevski, V. Mircheva, M. Cherneva, Journal of Power Sources 113 (2003) 209–227.
[13] K.R. Bullock, M.C. Weeks, C.S.C. Bose, K.A. Murugesamoorthi, Journal of Power Sources 64 (1997) 139–145.
[14] J. Alzieu, J. Robert, Développement d'accumulateurs au plomb à hautes performances, ANVAR project, EDF R&D, 1987.
[15] H. Bode, Lead Acid Batteries, John Wiley & Sons, New York/London/Sysney/Toronro, 1977.

[16] Y. Yamaguchi, M. Shiota, M. Hosokawa, Y. Nakayama, N. Hirai, S. Hara, Journal of Power Sources 102 (2001) 155–161.

[17] M. Thele, J. Schiffer, E. Karden, E. Surewaard, D.U. Sauer, Journal of Power Sources 168 (2007) 31–39.

[18] Klang, K. James, Apparatus and Method for Step-Charging Batteries to Optimize Charge Acceptance, GNB Battery Technologies, Inc., Mendota Heights, MN, United States, 1996.

[19] D.U. Sauer, E. Karden, B. Fricke, H. Blanke, M. Thele, O. Bohlen, J. Schiffer, J.B. Gerschler, R. Kaiser, Journal of Power Sources 168 (2007) 22–30.

[20] D. Berndt, Maintenance-Free Batteries, Second ed., Research Studies Press Ltd./John Wiley & Sons Inc., Taunton/Somerset/New York/Chichester/Toronto/Brisbane/Singapore, 1997.

[21] Lead-Acid Battery Test Method, Ford Motor Company, Dearborn, MI, United States, 1974.

[22] V. Srinivasan, G.Q. Wang, C.Y. Wang, Journal of Electrochemical Society 150 (2003) A316–A325.