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Development of an on-board charge and discharge management system for electric-vehicle batteries

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Abstract

To improve the service quality of its electric-vehicle (EV) fleet (≈500 vehicles) and master the behaviour of the valve-regulated lead/acid (VRLA) batteries, which power the major part of it, Electricité de France (EDF) has developed an on-board battery-management system. Information on the operating battery behaviour is given to the driver. Overdischarges can then be avoided. Rapid charging of VRLA batteries is monitored. The main available functions of this device are: (i) battery life recording, short- and long-term information storage is available; (ii) charge monitoring, communication with a 23 kW charger is established through an ISO 9141 interface; a fast-charging algorithm for VRLA batteries has been developed and up to 50% of the range can be returned to the EV in 20 min; (iii) battery management during driving, 'orange' and 'red' alarms related to the depth-of-discharge help the driver to manage the driving; cell overdischarges can then be avoided; (iv) maintenance, the faulty groups of cells are identified; (v) gauge (state-of-charge indicator), this function requires mid-term R and D; for the moment, only charged and discharged Ah are indicated but when more accurate state-of-charge prediction algorithms are available, the software will be up-graded.

Keywords: Battery management; Fast charging; Electric vehicles; Lead/acid batteries; Maintenance

1. Introduction

The electric-vehicle (EV) fleet of the Electricité de France (EDF) is composed of about 500 EVs. More than 90% of them are equipped with valve-regulated lead/acid (VRLA) batteries. After three years experience, the main problem encountered by the users has been related to premature failure of the batteries. This situation highlights the battery as still being the weak element of EVs. To improve this situation, the R&D Division (DER) of EDF has developed an on-board battery-management concept. A device has been designed and set up with the French company, Intelligent Electronic Systems (IES), in order to demonstrate the interest and the necessity of such a concept. This paper presents the different functions of this approach and the main achievements obtained on fast-charging of EV VRLA batteries.

2. An on-board battery-management system

2.1. Concept

Laboratory investigations and EV operation problems in the field have resulted in the development of an on-board battery-management system. This type of system must be placed in the vehicle in order to master the battery behaviour during its entire life. The concept is based on:

(i) data acquisition on different parts of the battery, which cannot be considered as a monolith (heterogeneity of the cells must be taken into account);

(ii) data processing to prevent failures, harmful uses, to predict stage of charge, etc.;

(iii) data recording.

The main functions to be covered are: battery life recording, charge monitoring, state-of-charge indication (gauge), maintenance, battery management during driving. These are described in the following sections.

2.2. Hardware

Prototypes of the on-board management device have been developed with IES. The industrial product has

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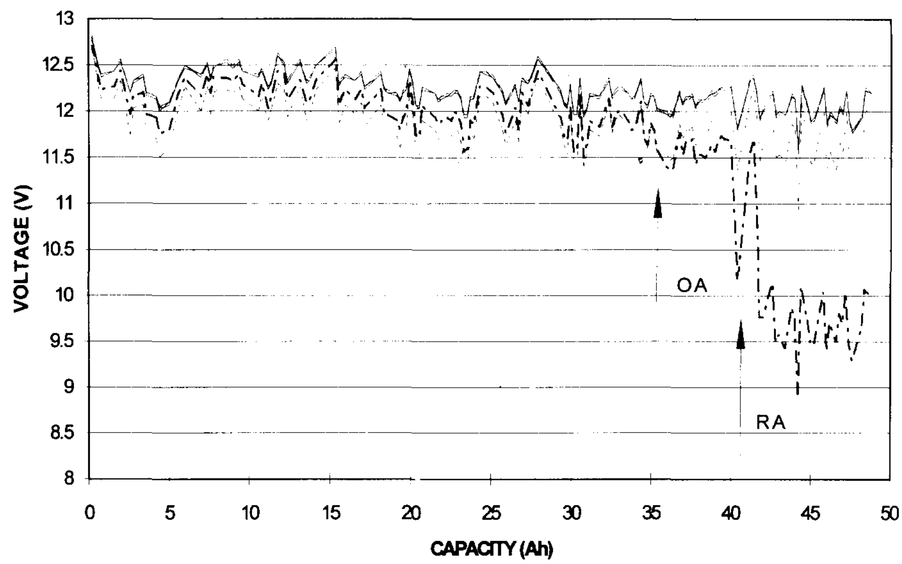

Fig. 1. In-vehicle discharge of a VRLA battery. Voltage profiles of 4 monoblocs among 16, vs. discharged capacity. A weak monobloc is first detected by an orange alarm (OA), while a red alarm (RA) indicates that a critical level has been reached.

to be 'cheap' (price-compatible with automotive production), easy to mass produce, simple to install and reliable. It must also be designed to support future updated functions easily.

The developed device collects data from all the monoblocs of a battery. No complex sensors are used. It measures individual voltages, current (shunt measurement) and two temperatures. The different software functions are processed from these 'classical' parameters. It has been tested in the EDF laboratory at Les Renardières as well as in vehicle trials. A field experiment on 20 EVs of the EDF fleet is also being carried out to validate this management system.

3. Battery-life recording

Data on each monobloc are collected, during both the charge and discharge phases. A long-term permanent file, containing a summary of the service life, is updated after each cycle. Short-term information is also available on the behaviour of each monobloc (the last three charge–discharge cycles are stored). This service-life recording is compulsory to guarantee expert management. The derived information is expected to help users, as well as battery and EV manufacturers, to improve guarantee conditions and cell-replacement criteria. Fig. 1 depicts examples of smoothed discharge curves, drawn from raw recorded data.

4. Gauge (state-of-charge indicator)

This predictive function is one of the key factors of EV development. Unfortunately, no satisfying system is available on the market for VRLA batteries. This function requires mid-term R&D. It must give accurate information about the state-of-charge (SOC) of the battery and must protect it against harmful uses (over-discharges, etc.). EDF is working on the development of such an algorithm for VRLA batteries and aims to produce a prototype by next year.

5. Battery management during driving

Experience on EV service in the EDF fleet shows that no reliable information is given to drivers about battery behaviour during driving. When a drop in EV performance becomes sensitive to the driver, some weak monoblocs may have already been deeply discharged, or even reversed. The cut-off voltage of the whole battery is an inadequate parameter to check the end of discharge. The heterogeneity of the battery has to be taken into account.

Repeated deep discharges can be a cause of premature failure of the EV battery. To warn the driver that a critical discharge limit is reached, an 'alarm' function has been developed for VRLA batteries. Orange and red alarms are provided, according to the state of the battery, to the driver to help manage the driving. The orange alarms indicate that the heterogeneity of the monoblocs has increased, and a critical limit for the battery has been reached when the red alarms come on (see Fig. 1). Moreover, the reference numbers of the monoblocs activating the red alarms are stored in the long-term memory.

6. Maintenance

One of the major problems encountered in EV service is battery maintenance. The criteria, and methods to identify and select faulty monoblocs, are not always relevant. A replacement of the whole battery is often carried out. Data acquisition allow a better definition of the limiting monoblocs. Their reference numbers are displayed during driving and stored in memory.

When EV performance losses reach a critical level, the faulty monoblocs need not always be changed. It has been noticed that some weak cells can recover the major part of their performance after special electrical treatment. Work is being undertaken on this subject. One of the goals is to set up a complete maintenance procedure within the next few months that will allow reliable identification of the monoblocs that must be changed.

The ability of the management system to point out the weak cells of the battery has already been confirmed by the first results from in-vehicle field trials.

7. Charge monitoring

Charge monitoring has been developed first for fast charging. A study of normal charging is now being performed and it is intended to control the on-board or external charger by the above management device.

Fast charging of vented lead/acid batteries requires more than 0.5 V/cell overvoltage [1], in order to generate sufficient volumes of gas. This gas evolution prevents the development of electrolyte stratification. In the case of VRLA batteries, and particularly gelled types, gas evolution has no beneficial effect. In any case, electrolyte stratification does not reach a significant level [2] and gas evolution must be minimized to avoid water losses during fast charging. Several investigations on fast charging of VRLA batteries have been undertaken in the past few years [3–5], often based on the use of pulsed-charging current [6].

Gelled batteries have been instrumented in order to follow cell internal-pressure, gassing, individual voltages, current and cell temperatures. The collected data has enabled the establishment of a fast-charge monitoring algorithm. This is based on measurements of monobloc voltages, current and temperatures. Comparative investigations on standard charging profiles indicate that these could be improved.

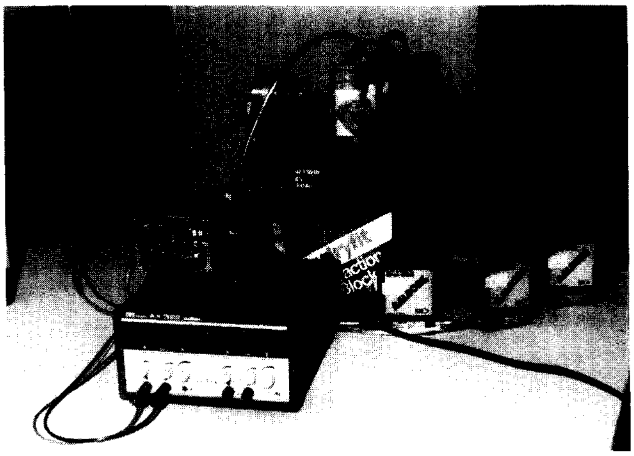

Fig. 2. Instrumented battery for laboratory testing.

7.1. Fast charging at the laboratory

The aim of EDF is to develop a monitoring algorithm for fast charging of VRLA batteries for EVs. Fast charging means less than 30 min. In this condition, charging of gelled VRLA batteries can only be partial. In the first stage, the target was to recover about 50% of the EV range. This requires the battery to recover 30–35% of its nominal capacity. A 160 A fast charger has been developed to meet this requirement in 20 min.

To take into account the influence of battery heterogeneity, testing was performed on 24 V, 160 Ah gelled VRLA batteries, composed of four 6 V monoblocs in series. Each monobloc was instrumented with pressure transducers, gas flow-meters and temperature sensors. Current and individual voltages were also measured. Fig. 2 displays such an instrumented battery.

Before commencing the test for fast charging, the pressure behaviour of the valves was checked. In general, the valves release gas over 30–120 mBar. Internal pressure is practically independent of gas flow. Thus, no dramatic pressure increase can occur in the case of a fast charger default (high current applied).

A wide range of experimental conditions has been explored. Fast charging rates were tested up to the $C/0.5$ rate. Figs. 3–5 show examples of such experiments. The initial battery temperature and its increase have a major influence on the charge-acceptance of the monoblocs. The higher the initial temperature, the sooner gassing occurs and fast charging has to be stopped. Other factors, such as initial depth-of-discharge or rest time, also affect the behaviour of the battery during fast charging.

Analysis of the results of this study has established a correlation between gas evolution and individual voltages, current and temperature rise. A fast-charge monitoring algorithm has been developed and uses only individual voltage, temperature and current measure-

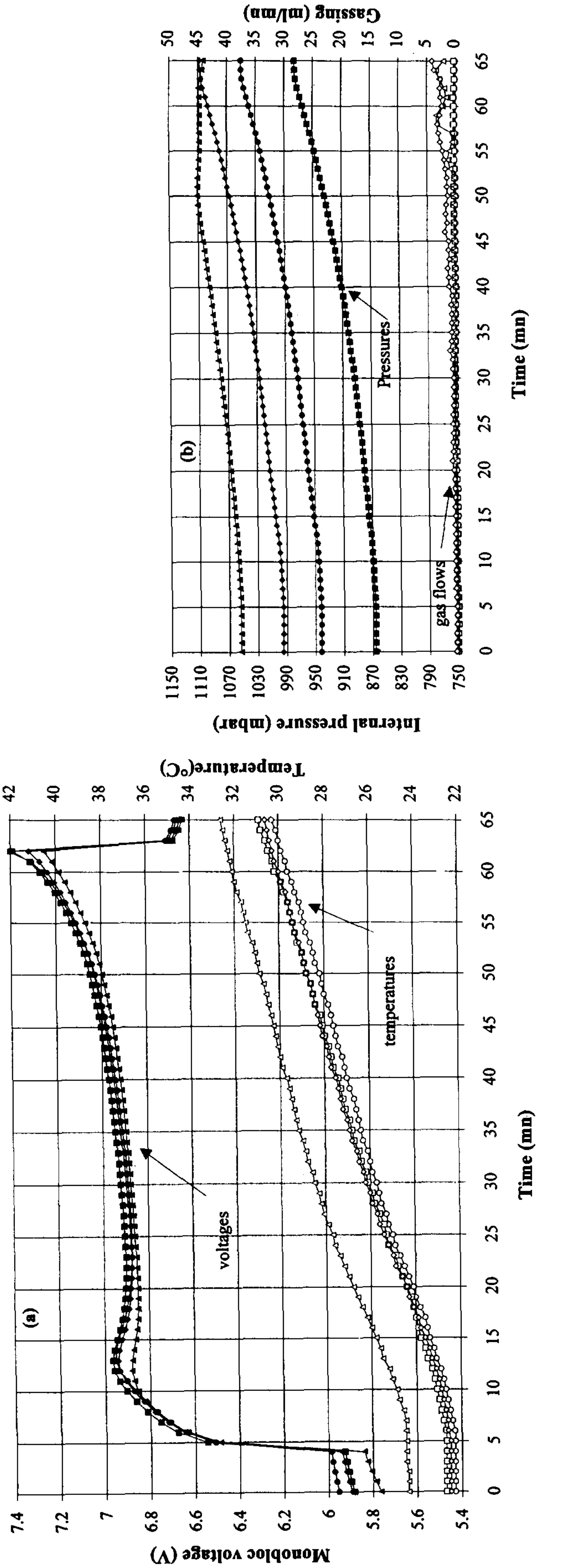

Fig. 3. 100 A charging with a low initial temperature, 23 °C: (a) voltage and temperature of four 6 V monoblocs; (b) internal pressure and gas flow.

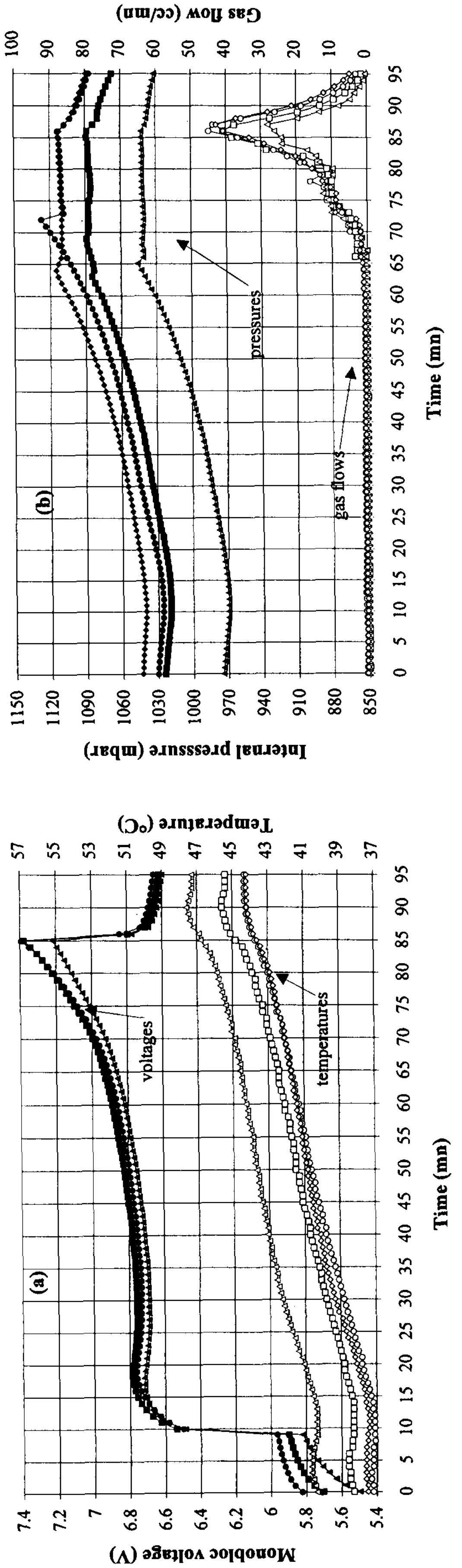

Fig. 4. 100 A charging with a high initial temperature, 38 °C: (a) voltage and temperature of four 6 V monoblocs; (b) internal pressure and gas flow.

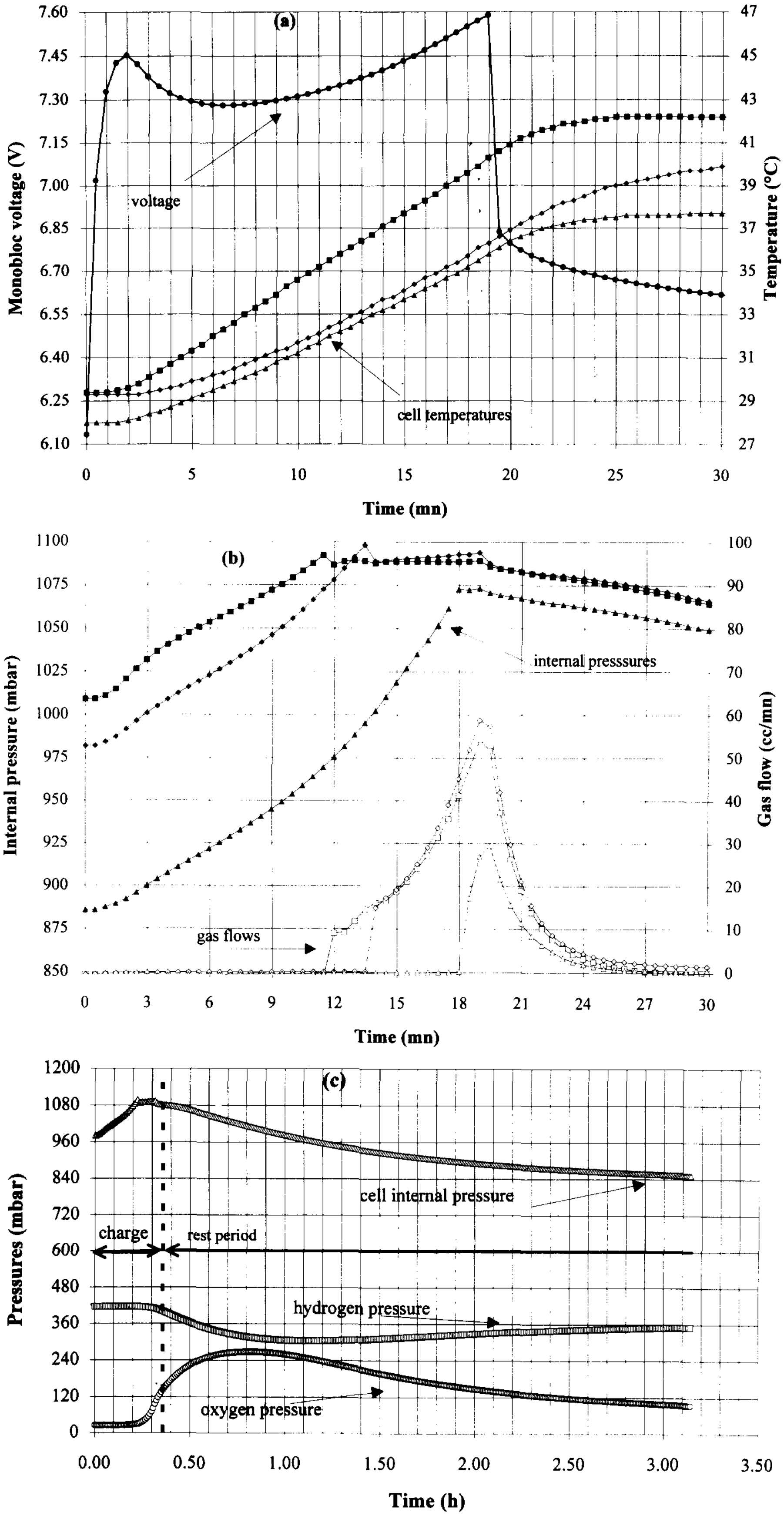

Fig. 5. 250 A charging of a 6 V monobloc: (a) voltage and cell temperatures; (b) cell internal pressures and gas flow; (c) oxygen and hydrogen pressures after charging (response times are in the order of 0.5 h).

Fig. 6. Volta EV and fast charger used for in-vehicle testing.

ments. These data are processed to follow the battery behaviour during fast charging, and stop the charge before any critical temperature or gas flow level is reached. When fast charging is properly monitored, the volume of gas evolved is much lower than the one observed during a conventional charge.

7.2. Fast charging on EV

An in-vehicle, fast-charge test has been carried out on a VOLTA, equipped with a 160 Ah 96 V gelled VRLA battery (Fig. 6). The battery-management device controls an SGTE Westinghouse 23 kW fast charger. This type of charger is used at La Rochelle, within the framework of the PSA 106 and AX experiment for fast charging of Ni/Cd batteries. Its available power limits the fast-charging current of VRLA batteries on the EV to ≈160 A (*C*/1 rate). Communication between the charger and the management device is established through an ISO 9141 interface.

Fig. 7 presents monobloc voltage variations of a 16×6 V, 160 Ah gelled VRLA battery during a 160 A fast charge on a VOLTA. The vehicle was previously discharged until the red alarm appeared on the battery. The initial temperature was 22 °C. The charge was stopped after 29 min. About 50% of the nominal capacity was recovered, which in fact represents 60–70% of the effective available capacity during an EV discharge. Comparison with laboratory results shows that individual voltages at the end of this fast charge would cause only a low degree of gassing. Four monoblocs of this battery were controlled to release less than 0.1 litre of gas per cell for the total fast-charging procedure. In-vehicle tests have now commenced to investigate the influence of fast charging on battery cycle life and performance.

8. Conclusions

For EDF, an on-board battery management is necessary to make EVs operate correctly. This is because batteries remain the weak element in the total system. The device limits battery problems and prevents harmful use. The collected information can help in defining improved guarantee conditions and appropriate cell-replacement criteria. For VRLA batteries, optimized operating instructions and procedures can be set up. In-vehicle performance is likely to increase and to be more in accordance with claimed values. EDF's investigations show that it is possible to fast charge VRLA batteries on EVs with a 23-kW charger. The influence of fast charging on cycle life is now under investigation during in-vehicle testing.

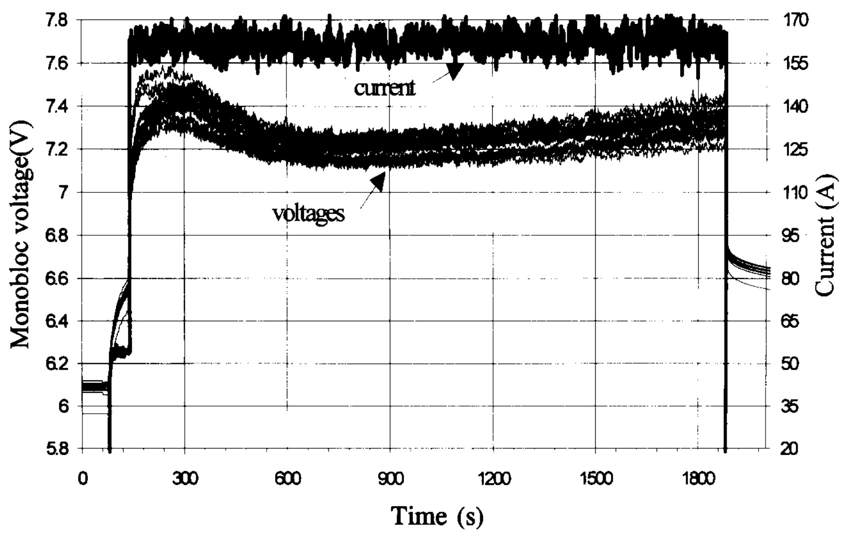

Fig. 7. Current and monobloc voltages of a 96 V, 160 Ah gelled VRLA battery vs. time during a 29 min fast charging at 160 A; initial temperature, 22 °C.

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