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Charging performance of automotive batteries—An underestimated factor influencing lifetime and reliable battery operation

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Abstract

Dynamic charge acceptance and charge acceptance under constant voltage charging conditions are for two reasons essential for lead-acid battery operation: energy efficiency in applications with limited charging time (e.g. PV systems or regenerative braking in vehicles) and avoidance of accelerated ageing due to sulphation. Laboratory tests often use charge regimes which are beneficial for the battery life, but which differ significantly from the operating conditions in the field.

Lead-acid batteries in applications with limited charging time and partial-state-of-charge operation are rarely fully charged due to their limited charge acceptance. Therefore, they suffer from sulphation and early capacity loss. However, when appropriate charging strategies are applied most of the lost capacity and thus performance for the user may be recovered.

The paper presents several aspects of charging regimes and charge acceptance. Theoretical and experimental investigations show that temperature is the most critical parameter. Full charging within short times can be achieved only at elevated temperatures. A strong dependency of the charge acceptance during charging pulses on the pre-treatment of the battery can be observed, which is not yet fully understood. But these effects have a significant impact on the fuel efficiency of micro-hybrid electric vehicles.

Keywords: Lead-acid; Charging; HEV; Charge acceptance; Flooded; AGM

1. Introduction

In various applications with partial-state-of-charge operation (PSOC) and – at maximum – sporadic full recharge, lead-acid batteries suffer from rapid capacity loss and shorter lifetime compared with the real potential of the lead-acid technology. Sulphation is the dominating ageing mechanism under such conditions [1,2]. Various investigations have shown that batteries in the field are often regarded as at the end of their lifetime, while sufficient charging could recover a significant portion of the capacity (e.g. [3–5]).

Two typical PSOC battery applications are autonomous power supply systems based on volatile renewable energies such as photovoltaics or wind power generators, as well as automotive batteries in modern cars. Both applications have limited time slices for charging and the charging processes are very often interrupted by discharging periods. Charging times for automotive batteries are limited by the driving time during one trip, which is on average well below 30 min and very seldom as long as 3 h or more. However, the European Standard defines the standard charge for flooded starter batteries as 16 V constant voltage over 24 h [6] to achieve full charging, though both voltage and duration are not realistic under real-world vehicle operating conditions. In photovoltaic systems charging times are limited at maximum to the duration of daytime. In both applications, power generation and power consumption show large variability. Hence, charging and discharging periods change frequently.

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In automotive applications, batteries are currently facing a new challenge: Micro-hybrid operation with start/stop of the internal combustion engine and regenerative braking by the alternator or starter-generator cause charging pulses in the range 1–2 C rate and several seconds [7,8]. To minimise fuel consumption the battery's charge acceptance under such dynamic conditions is crucial.

During discharge lead-sulphate crystals are formed and these crystals tend to grow with each partial cycle. Only during a full charge the sulphate is reconverted completely into charged active mass (lead or lead-dioxide for the negative or the positive electrode). However, after prolonged PSOC operation the sulphate crystals grow to a limit where they can be hardly reconverted which then results in permanent sulphation appearing to the battery user as a capacity and power loss.

Dissolution of lead-sulphate crystals is a chemical process and therefore it depends on the temperature, time, crystal surface and the concentration of ions in the electrolyte. These parameters have an impact on the charge acceptance. Adequate charging strategies take these parameters into account and assure that the battery is getting charged as much as possible within the limited available time.

If a battery fails, it is typically stated that the battery has a short lifetime or is insufficient for the application. In many cases, this is only one side of the story. Insufficient charging due to non-adequate charging strategies or due to limited available charging power, energy or time is a core reason for early performance decline of lead-acid batteries. State-of the art automotive power supply system design methods ensure battery service life by appropriate system sizing.

This paper presents several examples for reactivated capacity by appropriate charging strategies. Furthermore different aspects of dynamic charge acceptance will be discussed that demonstrate the strong effect of charging regimes The discussion among battery manufacturers, power supply system designers and component suppliers must be intensified to achieve the full potential of lead-acid battery technology to remain competitive with other battery technologies. Today, as performance tests focus on discharging and partial state of charge operation, charging is done typically with an excessive charging regime resulting in a full recovery of the capacity every time.

2. Results from charge acceptance tests on gel batteries

In the following, two examples for the recovery of capacity by appropriate charging regimes are shown.

The first example is a field test which has been performed with a gel type, flat plate battery in a PV system located in Germany. The system was operated as a PV-battery-load system without an additional power generator and with a conventional charge controller. The charging voltage during normal operation was limited to 2.35 V per cell. More details on this system can be found in [3].

A capacity test was performed every 6 months. For the capacity test first a so-called "solar charging" regime was used, which consists in cccv[1] charging with a maximum current of I_{10} and a constant voltage charging period at 2.35 V for 5 h. The duration of 5 h reflects the best charge conditions which a battery in such a system can achieve under Central European weather conditions. Fig. 1 shows the capacity test for two blocks, which were tested individually after 1 year in service. The available capacity was 80% of the nominal capacity. By definition, this is the end of life criterion for a stationary battery.

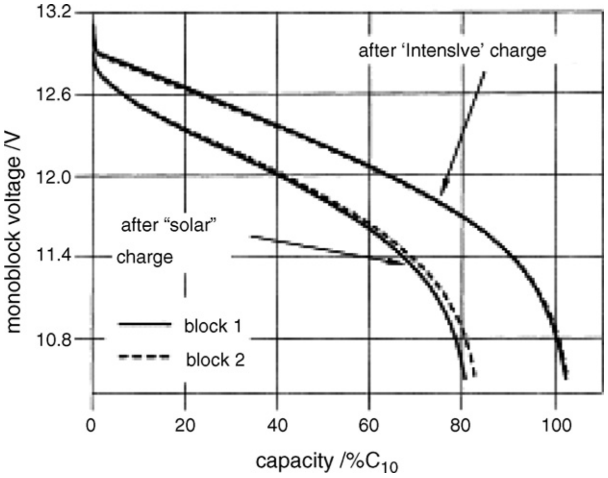

Fig. 1. Comparison of discharge curves after a cccv charging with 5 h cc at I_{10} and cv at 2.35 V per cell and 5 h ("solar charge") and after cccvcc charging with cc at I_{10}, cv at 2.45 V until current $<0.1I_{10}$ and cc at $0.1I_{10}$ until recharge of 112% of C_{10} during the complete cccvcc charging (figure from [3]).

However, after this first test an "intensive" cccvcc[2] charging with constant current at I_{10}, constant voltage at 2.35 V per cell and the additional constant current at $0.1I_{10}$ without voltage limit was performed. The constant current charging at low rate was performed until 112% of the nominal capacity is recharged to the battery within the complete charging cycle.

The capacity after this "112% intensive charging" was back to 100% of the nominal capacity. A similar behaviour was observed every 6 months. An increase of 20% in capacity was very normal. Various authors (e.g. [9,10]) have presented the beneficial effect of constant current charging steps with low rates but without voltage limit for VRLA batteries.

This example shows very clearly that the available capacity for the user taking into account the available charging times and charging conditions can be significantly less than what the battery would be able to deliver under optimum charging conditions. The example also shows where the problems among battery users and battery manufacturers are: The battery user sees a battery at 80% capacity in its application; the battery manufacturer sees a battery at 100% of the nominal capacity when using the appropriate charging regime. But how are battery capacity and battery lifetime defined properly?

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[1] Constant current charging until voltage limit is reached, constant voltage charging at this voltage limit until end-of-charge criterion.

[2] Constant current, constant voltage, constant current; second constant current charging at low current rates with a time or Ah limit.