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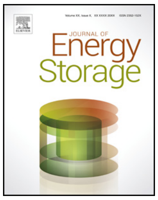

Experimental analysis of Dynamic Charge Acceptance test conditions for lead-acid and lithium iron phosphate cells

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ABSTRACT

This paper presents the results of a series of tests to determine the Dynamic Charge Acceptance (DCA) performance of small form-factor carbon-enhanced VRLA cells designed for use in Hybrid Electric Vehicle (HEV) applications, together with standard lead-acid and lithium iron phosphate (LFP) cells. The results demonstrate how varying the conditions and parameters of the standard DCA test regime can provide a superior evaluation of DCA performance and lead to a better understanding of cell behaviour under real-world conditions. A modified test procedure is proposed, based on the DCA Short Test profile (EN50342-6). Results are presented for a batch of carbon-enhanced cells, tested at various temperatures, rest periods and States of Charge (SoC) for the cell. These conditions having been chosen to mimic a range of real-life scenarios which could potentially be encountered during HEV operation. The resulting analysis demonstrates clear variations and trends in DCA performance which may be used to inform conditions for future testing regimes. The modified test procedure is then applied to standard lead-acid and LFP 26650-type cells and the results compared.

1. Introduction

Recent years have seen battery technology and performance become increasingly important in automotive applications. Driven by a desire to reduce emissions and rises in fuel costs, the function of automotive batteries has shifted from an auxiliary power source to providing significant contributions to the performance of the vehicle; particularly in the case of fully electric vehicles (EV), where it is the only source of energy. This, coupled with increasingly power-hungry driver-aids, entertainment and HVAC systems is making it ever more important that the behaviour of automotive batteries be well understood.

1.1. Battery use in vehicles

In traditional internal-combustion (IC) engined vehicles the battery is used exclusively as an auxiliary energy store for when the engine is switched off, once running the engine provides all power for the vehicle, both mechanical via the drive-train and electrical via the alternator. In this configuration the battery is subject to infrequent, short discharges at high currents (around 16 times the 1-hour rate, C_1) when starting the engine, followed by modest recharging to full state-of-charge (SoC) at around 1 C_1 from the alternator [1]. The use of automotive batteries for starting, lighting and ignition (SLI) and their failure modes under these conditions is well understood.

An increasingly common modification to this method of working is the stop-start system. Here the IC engine is stopped automatically when the vehicle is stationary, and re-started before moving off. This system is designed to reduce the time the engine spends running whilst the vehicle is stationary, thus reducing fuel usage and emissions. Whilst this imposes a more demanding duty on the batteries due to the increased frequency of the discharge-charge cycles experienced by the battery, the fundamental operating mode and recharging mechanism remains the same.

More significant changes to battery operation are imposed by Hybrid Electric Vehicles (HEV). In such vehicles the IC engine is used in conjunction with the batteries such that both provide traction power. There are several configurations possible for the drive arrangement of such vehicles [2], but the principle of operation is similar; the vehicle may be driven by either the engine or batteries alone, or by the two together. This allows such vehicles to drive quietly and with zero emissions at low speeds, such as within cities. It also means they can be fitted with smaller, more efficient IC engines sufficient for most driving, but maintain performance when accelerating by using their batteries to increase available power.

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As the batteries are by necessity much larger in a HEV than in a conventional vehicle, an alternator is not sufficient to recharge them. Therefore recharging is performed by using the electrical machine fitted within the drive-train as a generator [2]. This allows the batteries to be recharged by the IC engine through the drive system, but also allows energy to be stored in the batteries when the vehicle brakes.

This modifies significantly the loads imposed on the battery. Aside from the large discharges associated with starting the IC engine, there are additional discharge spikes caused by acceleration as well as longer periods of lower discharge currents where the vehicle is running in purely electric mode. The charging profile is similarly modified, the batteries are no longer steadily charged back to full SoC, instead operation is often at partial SoC. Charging from the engine is controlled to a modest rate, but is interspersed with large charge spikes due the regenerative braking system; these spikes can reach up to 30 C_1 under heavy braking [1]. The operation of batteries under these conditions of high-rate partial-state-of-charge (HRPSoC) is becoming increasingly common as the number of HEV's increases.

1.2. Charge acceptance

It can be seen from the above that to maximise the effectiveness of the HEV drive-train, as much energy as possible must be recaptured and stored during any and all regenerative braking periods. The main factor limiting the ability to capture this energy is the charge acceptance of the batteries at HRPSoC. As the batteries used in automotive applications are being required to provide more of the electrical power to the vehicle it is crucial that they are able to be recharged sufficiently quickly and that the performance of batteries under these conditions is known. To this end numerous testing methodologies have been developed to characterise the performance of automotive batteries, from stand-alone tests such as Dynamic Charge Acceptance (DCA) and Hybrid Pulse Power Characterisation (HPPC) to full simulated drive-cycle tests like NEDC and WLTP.

Understanding the DCA performance of automotive batteries has been identified as a key requirement for the development of electric vehicles [3–5], and standard test procedures have been designed to characterise the DCA performance of batteries [6]. This paper presents the results of an investigation into how varying the conditions and parameters of the standard DCA test regime can provide a superior evaluation of DCA performance and lead to a better understanding of the behaviour of the cell under real world conditions.

2. DCA overview

DCA is a measure of the charge efficiency of a battery, the higher the DCA value the better the charge efficiency. The standard test for determining DCA performance involves the application of a defined current waveform to the battery under test, the response of the battery to this waveform is used to calculate DCA performance.

2.1. Microcycling

At the heart of the DCA test is the microcycle, it is this which defines the current applied to the battery, and from which the performance may be determined. The standard microcycle, as defined by the European Standard DCA test A3 specification (EN 50342-6) [6] is given in Fig. 1a, this is summarised in tabular form below.

DCA performance is determined by the response of the battery to the charge phase of the microcycle (step 1). During this phase the test procedure attempts to charge the battery with a current of 1.67 A·Ah^{-1} for 10 s, this will cause the terminal voltage of the battery to rise. If during the charge step the voltage reaches the set limit of 2.47 V per cell (equivalent to 14.8 V for a standard 6 cell battery) the charge current is reduced to maintain the battery at the voltage limit; a reduction in charge current equates to a reduction in the charge accepted by the battery. DCA is thus determined by the difference in the amount of charge accepted by the battery compared to the total available from the charge pulse. All currents used during the microcycle are normalised to the capacity of the battery (C_{exp}), which is obtained experimentally during the test procedure.

Microcycles are applied to the battery in blocks of 20 to form a DCA Pulse Profile (DCAPP). Each microcycle and hence each DCAPP, is inherently energy-balanced. The amount of charge removed during the discharge in step 3 is equal to that accepted by the cell during the charge step, i.e:

$$\int_A^B I(t)dt = -\int_C^D I(t)dt \tag{1}$$

This ensures that the SoC of the battery does not change between microcycles, and therefore does not drift during the course of the DCAPP. Note that this assumes equal efficiencies for both charge

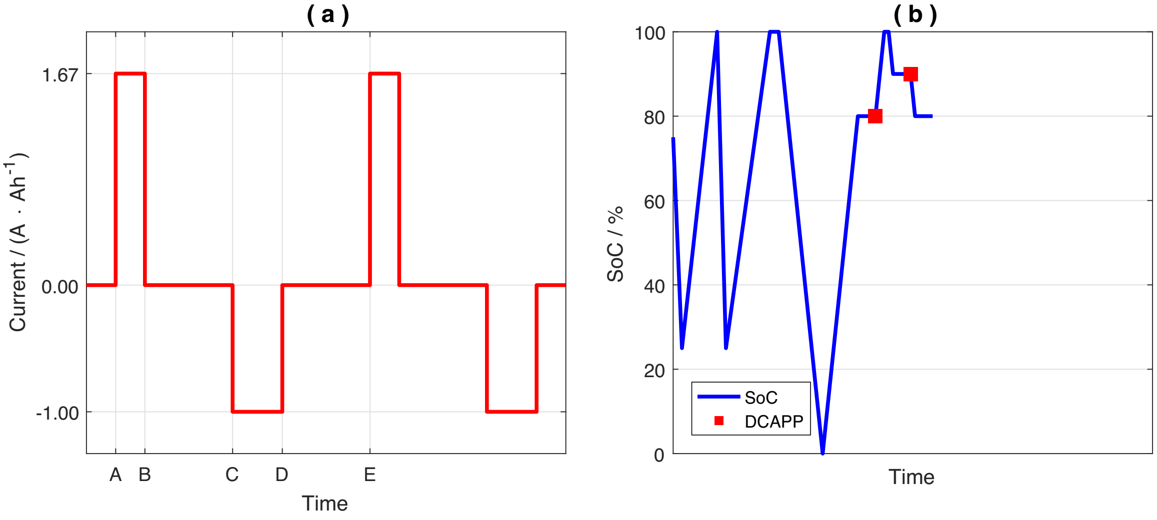

Fig. 1. DCA test A3 profiles. (a) Microcycle current profile (A–E), (b) SoC profile and DCAPP locations.