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Dynamic charge acceptance of lead–acid batteries: Comparison of methods for conditioning and testing☆

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ABSTRACT

Dynamic charge acceptance (DCA) is a key requirement for batteries in micro-hybrid vehicles. In automotive applications, DCA reaches a stable level during several weeks or months in service. A conditioning method that accelerates stabilizing DCA is presented. Various test methods for evaluation of DCA are compared. This is necessary for comparing new technologies (e.g. negative electrodes with carbon additives) and cell concepts (e.g. bi-polar batteries).

1. Introduction

A micro-hybrid vehicle requires higher performance of its starter battery compared to conventional vehicles. Stop/start and regenerative braking are the hybridization features used for micro-hybrids, while avoiding the need for a high-volt (above 60 V) electric motor and traction battery. In its most widespread, and lowest cost, implementation, the topologies of a micro-hybrid vehicle's power train and electric power supply system are the same as in conventional vehicles with internal combustion engine, i.e. a 14 V generator with modified control algorithms and one lead–acid battery (or sometimes two) perform the brake energy recuperation.

Together with novel vehicle functions like electrically assisted brakes and steering systems, or cabin pre-heating during key-off, micro-hybridization confronts the starter battery with substantially increased energy throughput by micro-cycling with a typical amplitude (depth of discharge, DOD) around a few percent state of charge (SOC) or less. Fast recharge of the battery during these micro-cycles under a broad range of real world usage conditions, like temperature and driving profiles, is a pre-requisite for consistently high availability of stop/start and other essential functions for the customer. It has been proposed to characterize the recharge ability of vehicle starter batteries as dynamic charge acceptance (DCA) [3]. Fuel savings due to regenerative braking critically depend on the DCA of the battery [10]. With an appropriate modification of the alternator control strategy, lead–acid batteries can provide brake energy recuperation functionality, as was shown by Karden et al. [2], Liebl et al. [6] and Schaeck [11]. However, the dynamic charge acceptance of lead–acid batteries in operation is not very consistent and hard to predict. Carmakers have introduced varying test methods for DCA into their specifications for micro-hybrid starter batteries, and a harmonized DCA test method is being developed by the European industry within battery standardization (prEN 50342-6). The aim of the present paper is to propose a quick conditioning and testing method for DCA to produce performance measurements that are representative of real world conditions.

DCA is investigated during regenerative braking events with a duration in the time range from 3 to 20 s. As a definition of DCA usually the average charge current or the charge current after a certain time is analysed (e.g. after 10 s). There are two different DCA conditions to be considered. The first DCA is obtained while the car is regularly driven without longer parking phases (maximum one weekend or so), the second DCA is defined as DCA obtained after a long parking period (e.g. airport) after which significant recovery of SOC is demanded.

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DCA is mainly influenced by key-off periods, short-term history, temperature, SOC and key off current. In this work, charge and discharge history is always short-term history. Kowal et al. [4] found that DCA is affected by local current distribution and acid concentration. Pb^{2+} ion dissolution at the negative electrode is the rate limiting step during micro-cycle charging [5,8]. Yamaguchi et al. [17] showed the negative influence of pauses on DCA with microscopic investigation on the surface of the negative electrode. Schaeck et al. [12] analysed pauses, temperature and SOC. The test consists in single high-rate charge events immediately after stepwise discharge of the battery from 100% to 90%, 80%, 70% and 60% SOC. A longer pause causes a lower DCA. When SOC is lower, the DCA is higher. DCA decreases with temperature decrease. While similar test methods are well established for advanced batteries (NiMH, Li-ion) in HEV applications, for lead–acid batteries this approach yields much higher DCA readings than would be obtained after run-in under real world usage. In particular, this discrepancy appears to be technology-dependent, for example it is more pronounced for flooded than for AGM batteries. In our limited experience, all (conventional) flooded batteries performed superior over most AGM types in this test, whereas all these types showed similar results after run-in, as discussed along Figs. 2 and 3 in the next section. For Schaeck's investigation only discharge history was taken into account. Thele et al. [16] implicated charge and discharge history. DCA is higher after discharge as new Pb^{2+} ions were formed and fresh fine $PbSO_4$ was precipitated.

In their further work, Schaeck et al. [13] proposed a DCA test method for lead–acid batteries in micro-hybrid applications with frequent capacity tests. DCA results are similar to tests with stop/start in real world conditions (see Fig. 4 in the next section); but in between the capacity tests, DCA does not reach a stable level. The test is technology dependent, as the capacity tests cause acid stratification, which leads to failure for flooded batteries.

A Dynamic Charge Acceptance Test (DCAT) was proposed by Störmer et al. [15] within the German battery standardization committee DKE 371.04. This test was derived from SBA S0101:2006 by adding SOC control, i.e. avoiding early battery failure by undercharge. It consists of continuous micro-cycles with 1–1.5 % DOD with high currents (discharge 48 A 60 s and 300 A 1 s, charge up to 100 A). The test might be useful to compare DCA of batteries and will therefore be included in this study.

Pavlov [9] discusses various carbon types that can be added to the negative mass. Carbon forms a skeleton with the lead mass. Pores of the carbon are small, so only H^+ ions can pass them and no SO_4^{2-} ions, as they are too big. Besides these kinetic effects, high-surface carbons added to the negative lead electrode may also increase charge acceptance by their large double-layer capacitance, like in super-capacitors. Further theories on the influence of carbon added to the negative active mass can be found at Moseley [7].

From an OEM perspective, practical DCA should remain robustly above 0.5–1.5 A Ah^{-1} throughout battery service life. Depending on application requirements, targets up to 3 A Ah^{-1} may be justified, e.g. for maximum utilization of regenerative braking with a 180 A alternator and a 60 Ah battery. Obviously, alternative storage devices (super-capacitors [14], advanced batteries [1]), at significant on-cost, can meet such targets with much better consistency than conventional lead–acid batteries. Aim of this work is to meet a similar performance with advanced lead–acid batteries.

2. Dynamic charge acceptance in real world tests

In this work, the DCA is always calculated as average charge current during one period of time (e.g. one driving cycle) and normalized with nominal capacity C_n (to make various battery sizes comparable).

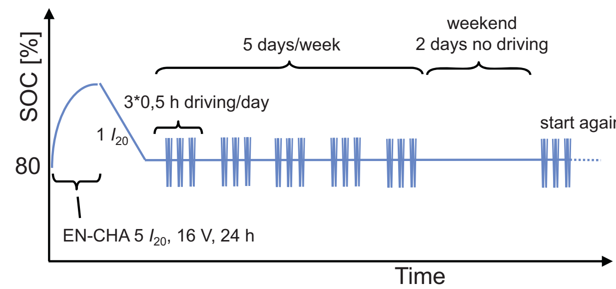

Fig. 1. Schematic course of DCARW test (simulates driving conditions in the field).

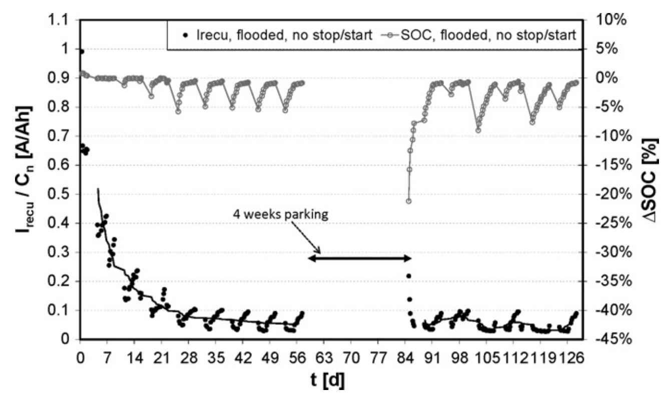

Fig. 2. DCARW test simulates driving conditions in the field without stop/start, measured on new flooded OEM battery, SOC and DCA (calculated as average charge current during one driving cycle, normalized with nominal capacity C_n).

Fig. 2 shows a measurement of the first of the above DCA types, simulating real-world driving conditions (DCARW = Dynamic Charge Acceptance Real World) with regenerative braking (alternator control to partial state of charge, PSOC, but no stop/start) on a new flooded OEM battery. The target SOC is always 80 % (Figs. 2–4). The DCARW test simulates three trips per day of 0.5 h duration each, for 5 days per week followed by a 2-day parking period (Fig. 1). Key-off loads are simulated by a resistor that is connected across the battery terminals throughout the test. The resistor is dimensioned to discharge the battery by 25% SOC within 31 days[1]. The test is conducted in 25 °C water bath. For the result plots, the normalized DCA is shown with one point per simulated trip, as well as a trend line that is constructed from a moving average over 15 trips (one week). As can be seen from Fig. 2, the DCA is between 0.2 and 0.8 A Ah^{-1} for new, traditional flooded lead–acid batteries. After as few as 6–7 weeks in this worst-case usage profile, however, the DCA of the flooded battery without stop/start has decreased to ~0.1 A Ah^{-1}. Qualitatively the same behaviour has been observed for AGM[2] batteries (Fig. 3), too.

During a 4 week parking period (so called airport scenario), only key off loads are discharging the battery. It takes approximately one week for the SOC to recover from the parking period and reach again the target SOC[3] of approximately 80% (Figs. 2 and 3). After the 4 week parking period, the DCA relaxes quickly to a level that is even worse than before the parking period.

Fig. 4 shows a variant of the same DCA test on a flooded battery, this time with simulated stop/start during some trips. Fig. 5 compares the DCA trendlines for flooded and AGM battery without stop/start. Further a flooded battery without and with stop/start are

[1] E.g. for a 60 Ah battery the resistor is 620 Ω.
[2] Absorbed glass matt.
[3] The target SOC is equivalent to 0 % ΔSOC in Figures 2–4.

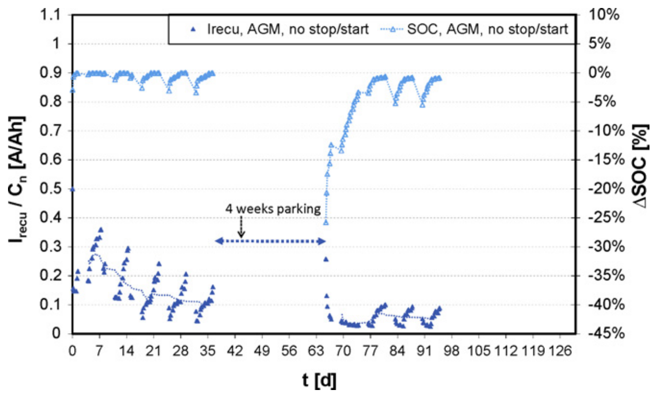

Fig. 3. DCARW test simulates driving conditions in the field without stop/start, measured on new AGM OEM battery, SOC and DCA (calculated as average charge current during one driving cycle, normalized with nominal capacity C_n).

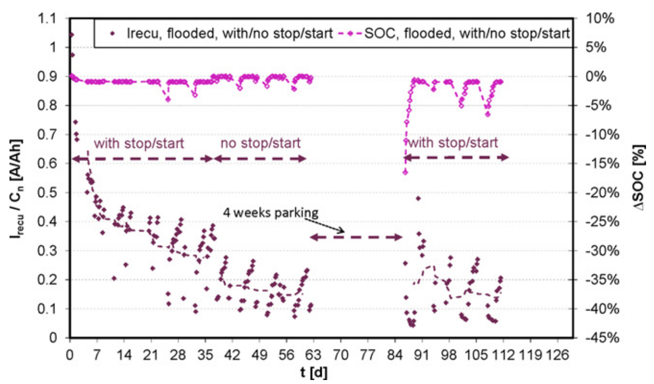

Fig. 4. DCARW test simulates driving conditions in the field with and without stop/start, measured on new flooded OEM battery, SOC and DCA (calculated as average charge current during one driving cycle, normalized with nominal capacity C_n).

shown. The DCA degradation with stop/start function is comparably slow (weeks 0–5) and accelerates when the stop/start function is switched off (from week 6 on).

It can be concluded that in real world application of conventional lead–acid batteries DCA degrades over weeks or months. DCA degradation during this short time period cannot be interpreted as aging of the battery, but is understood as run-in process.

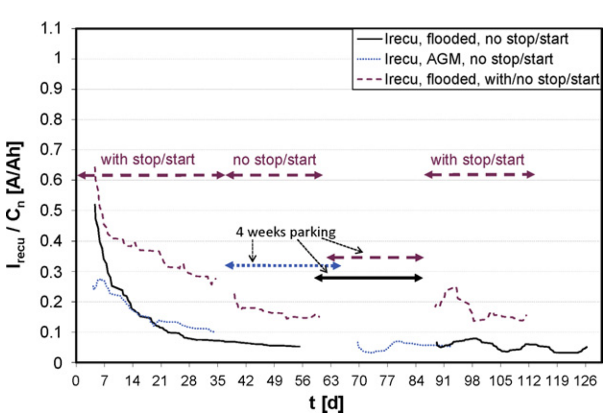

Fig. 5. DCARW test simulates driving conditions in the field with and without stop/start, measured on new flooded and AGM OEM battery, comparison of trendlines of DCA (calculated as average charge current during one driving cycle, normalized with nominal capacity C_n).

3. Conditioning

To compare the DCA of new batteries a test duration of multiple weeks is not feasible. This work aims at defining a conditioning method to achieve a stable DCA within a short time period (e.g. one week). The conditioning method is considered a useful method if resulting DCA values are stable and quantitatively similar or at least well correlated with DCA observed in the field after weeks or months of sustained real-world vehicle usage with PSOC control, comparable to the DCARW results reported above. The degradation of DCA observed early in life is considered a largely reversible run-in effect, by which the battery "forgets" the excess charge acceptance resulting from the discharge history by which the target SOC usually is established – both in real vehicles and in most laboratory tests. Consequently, the stabilized DCARW result is considered the representative beginning of life (BOL) charge acceptance.

Taking results from Thele et al. [16] into account, DCA is always higher but less stable after discharge than after charge history. Discharge and charge history is investigated in this work, but charge history is taken as standard. In several series of experiments and for various types of batteries it was found that DCA obtained with laboratory tests after charging history was at similar levels as typically after sustained real-world vehicle usage with PSOC control. Within this work, always a target SOC of 80% is used as this is a typical value used in vehicles equipped with recuperation control algorithms.

For the experimental study in this paper various samples of one L2 OEM battery type with a rated capacity C_{20} = 61 Ah were used. All samples were of the same design and manufacturer, same plant, and all were unused when starting conditioning. Only "battery 4" from the list below was intentionally chosen from another, more acid-rich design.

Fig. 6 shows the schematic course of various variations for conditioning. A detailed description of conditioning is given below: first a short name is given, then the complete procedure is described. Two abbreviations are used: DCH means discharge with 1 I_{20} until the voltage reaches 10.5 V, CHA means charge with 5 I_{20} and maximum voltage 16 V (for flooded batteries) for 24 h, followed by 1 h pause (PAU).

Battery 1a: CHA history, PAU 1 h → DCH, CHA, DCH, CHA, DCH, CHA (1 I_{20}) to target SOC, PAU 1 h.
Battery 1b: CHA history, PAU 10 h → DCH, CHA, DCH, CHA, DCH, CHA (1 I_{20}) to target SOC, PAU 10 h.
Battery 1c: CHA history, PAU 100 h → DCH, CHA, DCH, CHA, DCH, CHA (1 I_{20}) to target SOC, PAU 100 h.
Battery 2a: DCH history, PAU 1 h → DCH, CHA, DCH, CHA, DCH (2.2 I_{20}) to target SOC, PAU 1 h.
Battery 2b: DCH history, PAU 10 h → DCH, CHA, DCH, CHA, DCH (2.2 I_{20}) to target SOC, PAU 10 h.
Battery 2c: DCH history, PAU 100 h → DCH, CHA, DCH, CHA, DCH (2.2 I_{20}) to target SOC, PAU 100 h.
Battery 3: CHA history, PAU 10 h (as 1b), less acid stratification → DCH, CHA, DCH, CHA, DCH, CHA (1 I_{20}) to target SOC, PAU 10 h (during the 10 h PAU the battery was tumbled several times to reduce acid stratification).
Battery 4: CHA history, PAU 10 h (as 1b), higher acid/mass ratio → DCH, CHA, DCH, CHA, DCH, CHA (1 I_{20}) to target SOC, PAU 10 h.
Battery 5: Micro-cycles with 10% DOD and 20 I_{20} at 50% SOC, CHA history, PAU 10 h → CHA, DCH (1 I_{20}, 16 h, remain ~20% of SOC), CHA (1 I_{20}, until 45% of SOC), micro-cycles (DOD: 10%; 20 I_{20}; ~12 capacity turnovers), CHA (1 I_{20}) to target SOC, PAU 10 h.
Battery 6: 2 weeks at 50 °C, by self-discharge to target SOC → CHA, DCH (1 I_{20}, 16 h, remain ~20% of SOC), CHA(1 I_{20}, until target

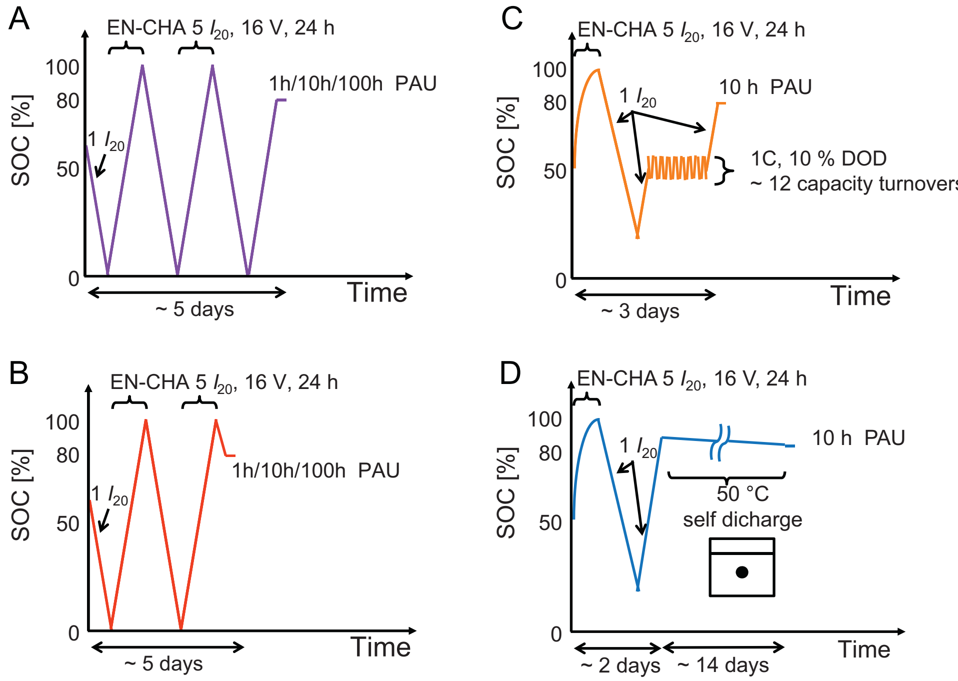

Fig. 6. Schematic course of various conditioning. A: Battery 1a/1b/1c → CHA history, PAU 1h/10h/100h; B: Battery 2a/2b/2c → DCH history, PAU 1h/10h/100h; C: Battery 5 → Micro-cycles with 10% DOD and 20 I20 at 50% SOC, CHA history, PAU 10 h; D: Battery 6 → 2 weeks at 50 °C, by self-discharge to target SOC.

SOC + assumed self-discharge), in oven at 50 °C for 2 weeks, PAU 10 h.

If not otherwise mentioned, all tests were performed at 25 °C.

4. DCA performance tests

After conditioning the DCA itself was measured. Three different DCA tests were performed in identical order to compare the tests. The pause after conditioning before the first DCA test varies among 1 h, 10 h and 100 h; before the second and third tests it is always 10 h.

1. Two Simulated Drive Cycles (SDC 1 and SDC 2) developed from the "New European Drive Cycle" (NEDC) assuming regenerative braking at PSOC, but no stop/start, which results in micro-cycling with low discharge currents ($2.2 \cdot I_{20}$) and high charge currents ($22 \cdot I_{20}$)
   - SDC 1 dynamically adjusts discharge duration (Ah balanced in each trip)
   - SDC 2 includes a pre-scheduled discharge, it is not Ah balanced (results typically in negative charge balance during each trip) and includes an equalization step after each simulated trip (not taken into account for DCA calculation)

   Test sequence: Each test block consists of six units: SDC 1, SDC 2, SDC 1, SDC 2, SDC 1, SDC 2; one unit lasts approximately 1 h and consists of two instances of the simulated NEDC trip (1180 s each) with rest periods in between.
2. DCARW test (Dynamic Charge Acceptance Real World), simulating real-world driving conditions with regenerative braking at PSOC, but no stop/start, details are described in Chapter 2 (Dynamic Charge Acceptance in Real World Tests), one week of Fig. 1 or Fig. 2.

   Test sequence: Test runs for one week, key off resistor is connected before the test and removed afterwards.
3. Repeat simulated drive cycles as in No. 1
4. DCAT test (Dynamic Charge Acceptance Test) [15], test with SOC control, continuous micro-cycles with 1% DOD with high currents ($48\,A = 16 \cdot I_{20}$ on tested batteries) including high current discharge pulses Test sequence: Test runs for one week, no key off resistor

For analysis of DCA in all performance tests, the average charge current during recuperation phases is calculated and normalized with the rated capacity ($A\,Ah^{-1}$).

SDC 1 and 2 (No. 1) represent the actual DCA during one trip at pre-established SOC. In addition, DCARW includes parking times with key off load (No. 2). No. 3 is the repetition of No. 1 to verify stability of DCA during No. 2. DCAT (No. 4) is a micro-cycling test which causes aging, therefore it is performed last. It is presented to compare the correlation of real world DCA with it.

5. Results and discussion

Figs. 7–9 show the chronological order of the tests for DCA after conditioning (no proportion with time on the *x*-axis). Differences between the tests are clearly visible. The DCA is always higher during SDC 2 compared to SDC 1. SDC 2 is not shown in Figs. 7–9, as no further information is gained. The higher DCA during SDC 2 can be explained with the effect that SDC 2 is not Ah-balanced and therefore SOC decreases during SDC 2. SDC 2 will be neglected for further consideration.

Fig. 7 compares DCA of batteries with charge and discharge history. Comparing the first block of SDC 1, DCA after discharge history is significantly higher compared to charge history. With charge history, SDC 1 yields <0.1 $A\,Ah^{-1}$, this is almost in the range of realistic field results. Open circuit voltage (OCV) after charge history is between 13.1 V and 13.55 V, which is an indicator for acid stratification. After discharge history acid stratification is almost absent (OCV around 12.7 V).

Besides the different levels of DCA after charge and discharge history, Fig. 7 shows also that DCA is rather stable after charge history. After discharge history DCA is not stable at all.

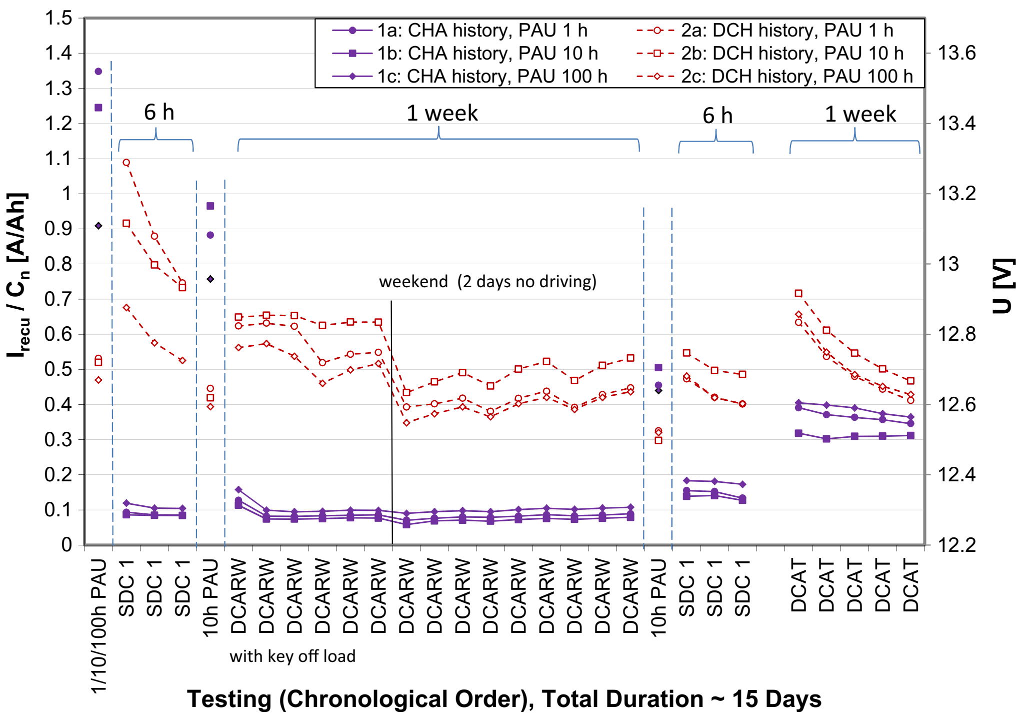

Fig. 7. Various tests for DCA in chronological order, measured on new flooded OEM battery, batteries conditioned with charge and discharge history to target SOC (1a, 1b, 1c, 2a, 2b, 2c), pauses before start of DCA measurement 1 h, 10 h or 100 h, DCA is calculated as average charge current during one driving cycle (nominated with nominal capacity C_n).

In addition to charge and discharge history, the length of pause before the first DCA test was varied among 1 h, 10 h and 100 h. When the battery has charge history, the pause before the DCA test has hardly any influence. When the battery has discharge history, the length of the pause influences the DCA: a short pause allows a higher DCA. The longer the pause, the lower is the DCA. This effect after discharge history was also observed by Schaeck et al. [12] with AGM batteries with a slightly different test procedure.

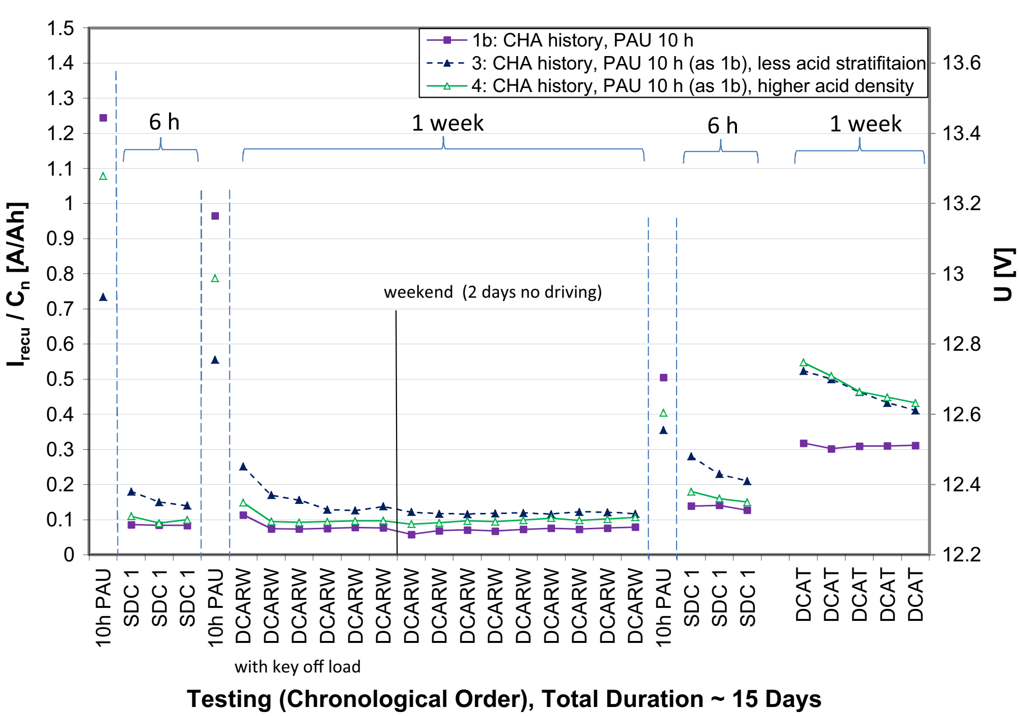

Fig. 8. Various tests for DCA in chronological order, measured on two types of new flooded OEM battery, batteries conditioned with charge history (one with less acid stratification) to target SOC (1b, 3, 4), pauses before start of DCA measurement always 10 h, DCA is calculated as average charge current during one driving cycle (nominated with nominal capacity C_n).

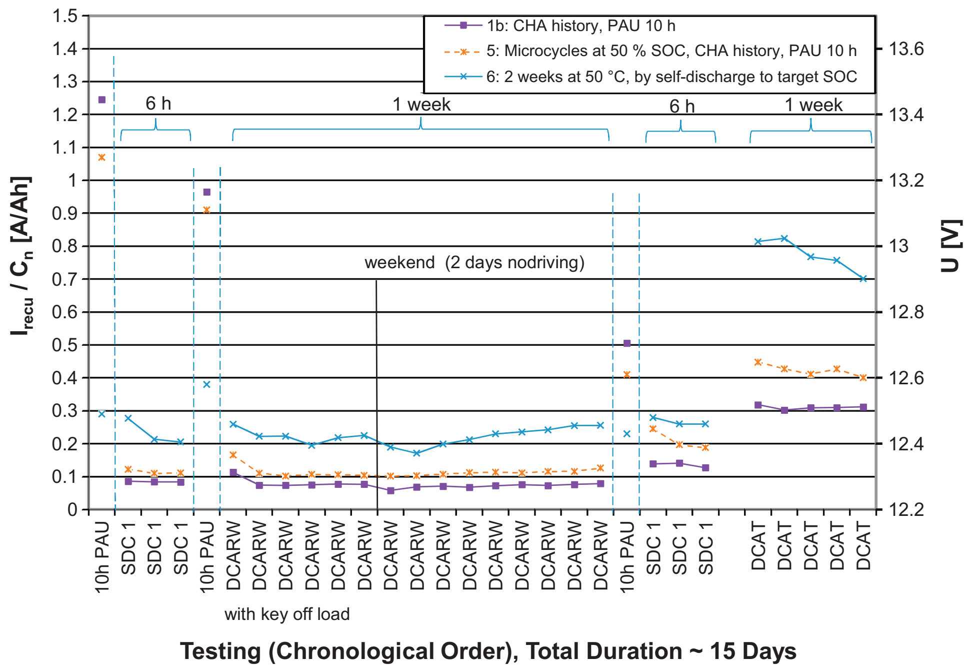

Fig. 9. Various tests for DCA in chronological order, measured on new flooded OEM battery, batteries conditioned with charge history to target SOC or in oven (1b, 5, 6), various pauses before start of DCA measurement, DCA is calculated as average charge current during one driving cycle (nominated with nominal capacity C_n).

The DCARW test shows similar results as SDC1 after charge history (~0.1 A Ah^{-1}). Also in the DCARW test DCA is unstable after discharge history.

The second set of SDC 1 is usually slightly higher compared to the first one. Looking at the open circuit voltage at the end of the pauses in between the test, acid stratification is less after each test, this can be an explanation for a rising DCA towards the second set of SDC 1.

Results of DCAT are significantly higher (factors 3–8) than real world DCA (Figs. 7–9). The reason for the high values is that DCA is measured during continuous cycling with a considerable current (0.8 CA rate for the given design). During discharge fresh sulphate crystals are formed. It is easy to solve the crystals during following charge. Therefore the measured DCA is higher in the DCAT test compared to others that include extended rest periods, with or without simulated low-rate key-off loads. Despite DCA being generally higher in the DCAT, the qualitative correlation with other DCA tests (SDC 1 and DCARW) is good. The reason for the strong relaxation during 1 week DCAT on batteries with discharge history is not completely known.

The DCA of batteries with discharge history shows a relaxation in all the tests, which becomes similar to the DCA level of the batteries with charge history at the end.

The plot for battery 1b (charge history with 10 h rest) will be repeated in all subsequent diagrams as a reference.

In Fig. 8 all tests were performed with charge history and 10 h pause before the first DCA test. Battery 3 has less acid stratification (see open circuit voltage before and between tests), it was tumbled several times during the 10 h pause before the first DCA test. With less acid stratification, battery 3 has twice as high DCA at the beginning of the test and stays continuously higher in all tests compared to the reference charge history (battery 1b).

Battery 4 has a higher acid/mass ratio compared to all other tested batteries. DCA of battery 4 is continuously slightly higher than the reference battery with charge history. Within the present study, this effect could not be finally explained, but again the negative correlation of DCA with acid stratification can be observed (in this case, acid stratification was less pronounced as a consequence of cell design). With the higher acid/mass ratio, the DCA is expected to be less SOC dependent, which was proven in other tests that are not described in detail here.

Fig. 9 compares battery 5 (micro-cycles with 10% DOD and 20 I_{20} at 50% SOC, CHA history) and battery 6 (2 weeks at 50 °C, by self-discharge to target SOC) with the reference charge history battery 1b.

Battery 6 (conditioning in oven) has a higher DCA consistent in all DCA tests. Conditioning by rest time at high temperature is not useful to reproduce DCA run-in as it occurs over weeks in the field. During conditioning with high temperature mainly self-discharge and sulphation primarily of the positive electrodes occur.

For the conditioning, charge history is a key factor for measuring realistic DCA values. Compared to charge history, micro-cycles during conditioning of the battery are less important (battery 5).

For future work, it will be interesting to compare various battery types (e.g. conventional AGM or flooded battery with carbon additives) with the proposed test method.

Fig. 10 shows current, voltage and DCA at the beginning of the first SDC 1 (first 10 min). Batteries shown here are the same as in Fig. 7. DCA in the first few pulses is higher than the following. Already after approximately 5 pulses a stable value for the DCA is reached. Therefore it is realistic to measure realistic DCA already with few single pulses.

6. Summary

DCA of lead–acid batteries in PSOC operation degrades within weeks or months of simulated real-world operation to a stable level, which can be as low as ~0.1 A Ah^{-1} in applications that lack regular micro-cycling with higher rates (e.g. stop/start). With a duty cycle that contains frequent stop/start utilization, the DCA stabilizes on a slightly higher level after a run-in period that is typically longer than without stop/start. AGM batteries show similar results to flooded batteries.

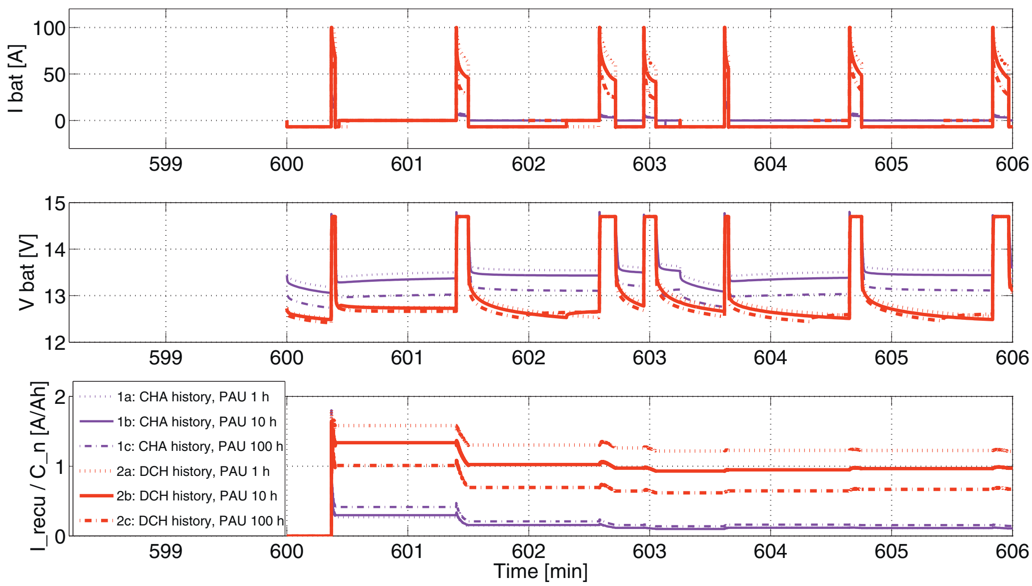

Fig. 10. Current, voltage and DCA of first SDC1 for batteries 1a, 1b, 1c, 2a, 2b, 2c.

Conditioning methods that create the stabilized DCA level in a short time period are presented. This is necessary for evaluating new technologies (e.g. negative electrodes with carbon additives) and cell concepts (e.g. bi-polar batteries). Various conditioning and test methods for evaluation of DCA are compared.

Preceding charge history is a promising method for measuring DCA that is not only stable but also quantitatively comparable to the run-in DCA level under worst case (no stop/start, etc.) field operation. The test results show that acid stratification has a major impact on DCA, too. Therefore initial cycling of battery samples prior to a DCA test should be performed in a way that it creates minimum acid stratification or at least a well-defined initial condition. After appropriate conditioning, charge pulses during few micro-cycles can already yield stable and realistic values for DCA.

With two test methods (SDC1 and DCARW) the range of DCA after few weeks in the field can be achieved. When higher discharge pulses are applied (e.g. DCAT test), the DCA is higher because fresh sulphate crystals are formed during discharge that are easy to dissolve.

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