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Lead-acid batteries in micro-hybrid vehicles☆

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ABSTRACT

More and more vehicles hit the European automotive market, which comprise some type of micro-hybrid functionality to improve fuel efficiency and reduce emissions. Most carmakers already offer at least one of their vehicles with an optional engine start/stop system, while some other models are sold with micro-hybrid functions implemented by default.

But these car concepts show a wide variety in detail—the term “micro-hybrid” may mean a completely different functionality in one vehicle model compared to another. Accordingly, also the battery technologies are not the same. There is a wide variety of batteries from standard flooded and enhanced flooded to AGM which all are claimed to be “best choice” for micro-hybrid applications.

A technical comparison of micro-hybrid cars available on the European market has been performed. Different classes of cars with different characteristics have been identified. Depending on the scope and characteristics of micro-hybrid functions, as well as on operational strategies implemented by the vehicle makers, the battery operating duties differ significantly between these classes of vehicles.

Additional laboratory investigations have been carried out to develop an understanding of effects observed in batteries operated in micro-hybrid vehicles pursuing different strategies, to identify limitations for applications of different battery technologies.

1. Introduction

For reasons of fuel saving and reduction of carbon dioxide emissions, most car manufacturers developed different types of hybrid cars recently. Within the wide range of possible concepts, currently the most important seem to be full-hybrid and micro-hybrid vehicles. While full-hybrid vehicles are based on a high-voltage electrical system and exhibit the ability to drive a certain distance pure electrically, micro-hybrid vehicles are technically orientated at the common 14 V electric system of today’s cars.

Currently, especially in Europe a strong focus on micro-hybrid vehicles is observed, and around 2.8 million micro-hybrid cars are on the road already. Car manufacturers are committed by law to lower their fleet fuel consumption. In the European Union there is a target of 130 g CO_2 emissions per km to be reached in 2015, for example. For 2015 it is expected that 70% of all new cars will comprise micro-hybrid features. In other regions similar legal requirements have to be met, and the widespread usage of micro-hybrid vehicles is one way to get closer to this goal.

For different micro-hybrid applications, the battery industry offers different types of lead-acid batteries. The range of batteries implemented in current micro-hybrid vehicles varies from standard lead-acid starter batteries to enhanced flooded to AGM batteries. Which battery fits best to which application, is dependent on operating strategies, technical requirements and life time expectations.

1.1. Micro-hybrid functions

Starting in 2006, we have investigated many micro-hybrid vehicles available in Europe. All of these cars offer an engine start/stop function, some of these combined with additional functions like regeneration of braking energy, charge voltage control and passive boost functions. Not all of these functions are combined in one car, but we have found different combinations of these functions.

An overview of the micro-hybrid functions is shown in Fig. 1.

The engine start/stop function switches off the combustion engine while the car stopped (e.g. at traffic lights or in traffic congestions) and restarts the engine afterwards. In some cars the engine is stopped when the speed is below a certain limit, of 6 km h^{-1}, for example. It is most important to ensure full power supply of the vehicle electric system in the stop phases as well as to ensure the engine re-crank. For the lead-acid battery this means higher performance requirements: the battery undergoes more and deeper cycling due to stop phases and has to exhibit a high charge accep-

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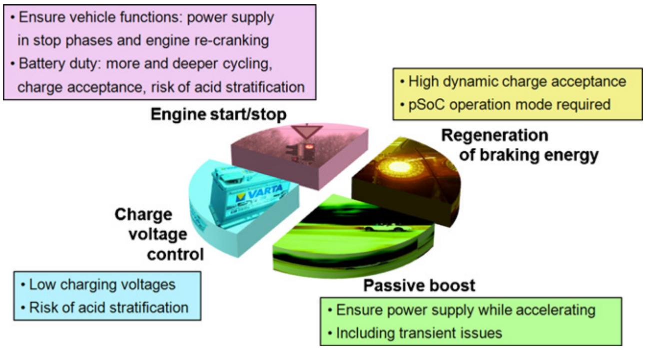

Fig. 1. Overview of micro-hybrid functions found in vehicles.

tance capability for being recharged quickly after the end of each stop phase. For flooded batteries this operation mode may imply a severe risk of acid stratification and subsequent deterioration.

The regeneration of braking energy (recuperation) means to recover a part of the kinetic energy of the car by recharging the lead-acid battery predominantly while braking. To achieve a higher energy balance, the recharge voltage is increased during braking or rolling phases of the car. For the battery this means the necessity of a high charge acceptance capability. As charge acceptance is low for fully charged batteries, they are intentionally operated at a partial state of charge (pSoC), with a target SoC significantly below 100%. This pSoC operation mode implies a risk of sulfation of the battery's active masses. In consequence, this means that it is recommended to fully recharge the battery regularly to avoid sulfation. The effectiveness of battery refresh was investigated by Schaeck et al. [1].

Passive boost means to de-energize the alternator while the car is accelerated. From a car driver's point of view, in this phase a larger portion of the combustion engine's power is available for traction; a reduced portion is needed to generate electrical energy. The lead-acid battery has to supply the electrical system's load requirements in this phase. Due to this additional discharge and subsequent recharge, the cycle load of the battery increases. Again, a higher cycling ability of the battery has to be ensured. This operation mode includes transient issues—a highly dynamic alternation between high-rate charging and discharging, which is not the usual operating mode of SLI batteries up to now.

The charge voltage control function is implemented to minimize the energy needed for recharging the battery. By decreasing the recharge voltage to a minimum value, the battery is sufficiently charged, but not overcharged at any time. The battery is not charged when the efficiency of the combustion engine is low (e.g. during idling phases). For flooded batteries this means an increased risk of acid stratification again—recharge with low voltages may be an issue for flooded batteries, especially when combined with a pSoC operating mode.

1.2. Battery technologies

There are several lead-acid battery technologies on the market with significantly different performance levels.

(a) The standard flooded starter battery is the most common of these products. It is used for engine starting, lighting and ignition (SLI). For many of the conventional vehicle applications it is the best choice in terms of cost–performance-ratio. For micro-hybrid applications the standard flooded battery is not recommended, because micro-hybrid operations require a higher cycling ability and higher robustness against acid stratification.

(b) Recently enhanced flooded batteries (EFBs) were developed, specially designed to fulfill higher cycling requirements and to withstand some impacts from acid stratification significantly better than standard flooded batteries. EFB design includes more robust active masses and a protection against mass shedding. The enhanced flooded battery is most often used for micro-hybrid cars with engine start/stop functions on a high SoC target level.

(c) The AGM battery (adsorbent glass mat technology) exhibits the highest cycling ability of all these lead-acid technologies and does not show any acid stratification [2]. The sulfuric acid is bound in a glass mat separator, and by battery design, the AGM type battery is robust against mass shedding and acid stratification. The limited amount of acid may be regarded as critical for high-heat applications, but simulations as well as real-life tests show, that the performance of AGM batteries under high-heat operating conditions in a taxi fleet test may be even higher than the performance of flooded batteries [3].

2. Batteries in micro-hybrid applications

Standard lead-acid batteries are designed for the use in vehicles with a conventional electrical system. Their main tasks are to crank the engine, to buffer the electrical system while driving, and to ensure power supply during parking.

Batteries installed in micro-hybrid applications have to fulfill many more requirements. Deeper discharges due to stop phases and passive boost, a lower target SoC for regeneration of braking energy or charge voltage control mean some additional stress to the battery which was not a design goal in former days. Nevertheless, the lead-acid batteries used in micro-hybrid vehicles in the last years up to now, which mainly are enhanced flooded or AGM batteries, seem to withstand these additional requirements.

In parallel to the investigation of micro-hybrid vehicles, we developed a laboratory battery test to simulate a micro-hybrid battery load profile reproducibly under controlled conditions.

2.1. Investigation of micro-hybrid vehicles

Micro-hybrid vehicles available on the European market from 2006 to 2010 were investigated, with a strong focus on battery load patterns and battery performance requirements. The scope of micro-hybrid functions (engine start/stop, regeneration of braking energy, charge voltage control and passive boost) was examined, as well as the type of battery installed (flooded/AGM). The battery operation SoC range was of special interest. Within the regular operation range there is a lowest SoC limit and a highest DoD limit, in such a way that all the micro-hybrid functions are activated within these limits. Outside these limits the cars normally work like conventional cars, but without any micro-hybrid functions activated.

In total, 15 vehicles were investigated, whereof 10 vehicles were of European brands, 5 of Asian brands. The European brands' vehicles predominantly are equipped with AGM batteries of EN container size, the Asian brands' vehicles predominantly with JIS-type flooded batteries. There are only a few exceptions from this general rule.

All 15 vehicles comprise an engine start/stop function. Six of the investigated cars do not offer any further functions in addition to start/stop. The remaining 9 cars can be divided into two groups: besides engine start/stop, they offer either a combination of regenerative braking and passive boost functions (4 vehicles), or a charge voltage control function (5 vehicles). No car was found with an implementation of all four functions in combination. Roughly, European brands' cars tend to use regenerative braking and passive

Table 1
Functions and battery types found in investigated micro-hybrid vehicles.

Vehicle number	European brands (1–10)										Asian brands (11–15)				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Engine start/stop	√	√	√	√	√	√	√	√	√	√	√	√	√	√	√
Regen. of brak. energy		√		√					√						√
Charge voltage control					√		√				√		√	√	
Passive boost		√		√					√						√
Battery technology	AGM	AGM	AGM	AGM	AGM	AGM	Flood	AGM	AGM	AGM	Flood	Flood	Flood	AGM	Flood
Number of batteries	2	1	1	1	2	1	1	1	2	1	1	1	2	1	1

Flood, flooded battery.

boost functions, while Asian brands' cars tend to use charge voltage control function. However, this assignment is not unambiguous. In detail, all these functions are implemented slightly different in each car. An overview of functions and battery types found in the investigated vehicles is given in Table 1.

The motivations for the implementation of different types of lead-acid batteries in the investigated micro-hybrid vehicles are probably at least twofold: there are pure technical reasons as well as doubts due to historical experiences. From a technical point of view, all of these micro-hybrid functions require a battery with higher cycling ability; therefore a standard flooded battery is not recommended. The question whether an enhanced flooded battery is the right choice or an AGM battery is the best solution, is regarded slightly different by the various car manufacturers worldwide. On the one hand, this decision depends on the technical requirements like charge throughput and target SoC for the intended functionality. On the other hand, there are doubts that AGM batteries withstand the elevated temperature levels when installed in the engine compartment. Especially Japanese car manufacturers seem to be more doubtful, this may be one of the reasons why in Asian cars predominantly flooded batteries were found. These findings seem to be independent on the location of car assembly—there are also some Asians brands' cars with micro-hybrid functions, manufactured and sold in Europe, which are equipped with a flooded battery.

Nevertheless, recent investigations have shown that the temperature resistance of AGM batteries may be higher than expected in the past. In a taxi fleet test performed in the United Arab Emirates AGM batteries have proven to be more temperature resistant under high-heat conditions compared to flooded batteries even when installed in the engine compartment [3]. In addition, a new generation of AGM batteries even more suitable for high-heat applications is under development [4,5].

2.2. *Results of the micro-hybrid vehicle investigation*

In late 2005, the first "new generation" start/stop vehicles entered the European market, intended to be the first step to reach the European "CAFE" climate goals announced in 2001. However, there had been a lot of start/stop vehicles a long time before, beginning in the 1980s, but these never penetrated the market widely. Prototype cars of these years and serial products of the late 1990s never found a sufficient acceptance by the customers. Possible reasons may be the level of oil price which was comparative lower than today in combination with the relative high retail price of these cars at that time. In our investigation of micro-hybrid vehicles we focused on cars available in Europe from 2005 to 2009, but keeping in mind that there have been some other technical solutions before.

The results are shown in Fig. 2. When sorted by the lowest SoC value we observed during regular micro-hybrid operation, two groups of micro-hybrid cars offering different functionality streams were identified. Starting in late 2005, an AGM type battery was operated at a very high SoC in a "start/stop only" car. Later on, two groups emerged:

Vehicles in group 1 operate the battery at a high SoC level of 90% or above. In most of these cars a flooded battery (most probably an enhanced flooded battery) is implemented. The average fuel saving of these micro-hybrid cars in comparison to their corresponding models without micro-hybrid functions is 6% in average, calculated from the NEDC data (New European drive cycle) published by the car manufacturers. The cars in group 1 generally offer a start/stop function, but in most cases no additional micro-hybrid functions.

Vehicles in group 2 are operating the battery in a significantly lower SoC range between about 60 and 80%. The first models entering the market in 2007 allowed battery operation in a quite challenging low SoC range. Over the time, some more micro-hybrid cars were developed operating the battery a somewhat higher or lower in SoC, but the observed operating SoC range still is significantly lower compared to the cars in group 1. Cars in group 2 are predominantly fitted with an AGM battery. The average fuel savings when comparing the micro-hybrid car with the same car model without micro-hybrid functions is 12%, referred to NEDC data again. The cars in group 2 mostly offer some additional micro-hybrid functions besides to engine start/stop.

Some of the investigated micro-hybrid vehicles comprise a system of two lead-acid batteries instead of one single battery in order to ensure a more stable voltage level. During engine restart, the electrical system is supplied by the second battery. Hence, the voltage level is not negatively influenced of the voltage drop caused by the starter motor usually. This means that no electronic control unit experiences a low voltage phase with the risk of logical reset. This also means a higher level of comfort for the vehicle driver, because all other electronic devices are also protected from low voltages. The radio or CD player as well as the route guidance system and telephone devices are not showing any malfunction due to low voltage levels during warm crank. Usually this second battery is a lead-acid battery, usually of AGM type, and in the $C/20$ capacity range of 4–12 Ah. The number of batteries found in each of the investigated micro-hybrid vehicles can be read from Table 1. In general, a two-battery electrical system is more often found in cars

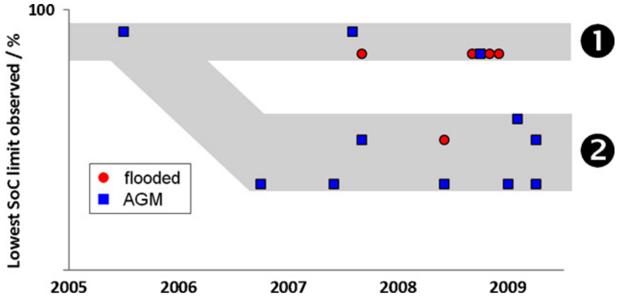

Fig. 2. Results of micro-hybrid vehicle investigation: lowest SoC limit which is allowed by the vehicles' systems, in chronological order of vehicles' market introduction.

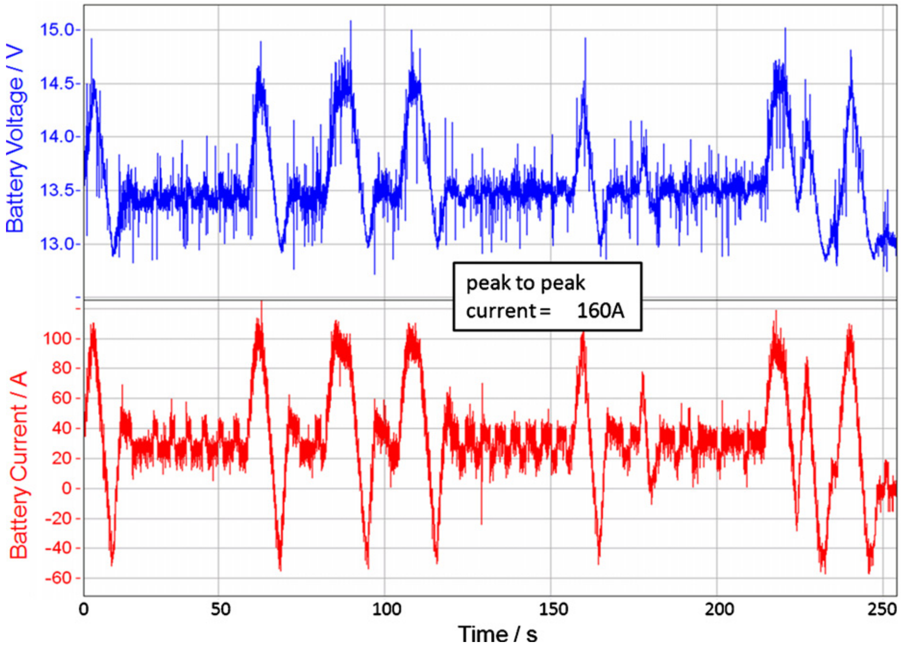

Fig. 3. In-vehicle measurements of battery voltage and currents during micro-hybrid operation.

offering some more micro-hybrid functions in addition to engine start/stop.

Fig. 3 illustrates a load profile found in one car of our micro-hybrid vehicle investigation. Quite challenging discharge and recharge currents have been observed during micro-hybrid operation. The AGM battery is operated in a pSoC mode and has to withstand a heavy cycling caused by regeneration of braking energy and passive boost as well as significant additional cycling generated by the discharge phases from engine start/stop. A remarkable value of 160 A was found as the difference of typical charge and discharge currents in this vehicle (caused by passive boost and regeneration of braking energy). In a comparable micro-hybrid vehicle of another car manufacturer, values of below 100 A were found in the same driving situation. This higher dynamic is caused by the system design, predominantly by the lower target SoC strategy. The batteries in these micro-hybrid vehicles experience a load profile completely different to the load profile of batteries in conventional cars. Both micro-hybrid vehicles mentioned above are equipped with AGM batteries, which are recommended for pSoC operation, especially at a low target SoC level.

To allow for a deeper insight into micro-hybrid battery operations, a laboratory test was developed to compare batteries under controlled ambient conditions and reproducibly. The test parameters were adapted to observations of real micro-hybrid vehicles to simulate a battery load profile close to real-life applications.

2.3. Dynamic pulse cycling test

To simulate a micro-hybrid application similar to the operating mode of “group 2” vehicles in a battery lab, the dynamic pulse cycling test sequence (DPC) was developed. Starting in 2006, the first experiments were performed and lead to a test which is able to examine a lead-acid battery according to some special requirements of a micro-hybrid vehicle. The target SoC in the test is about 80% to be in a realistic range. This value of 80% is not fixed, but swings up and down by ±10% to represent a real-life SoC range—influenced either by SoC adjustment of vehicle electronics or by ambient conditions (e.g. temperature) or by the actual driving profile determined by the vehicle’s driver. Within this cycling phase, the battery is intentionally not fully charged. After some days of cycling, two $C/20$ capacity tests are performed. The residual capacity provides information about the SoC balance during the preceding cycling phase and therefore is an estimation for the charge acceptance of the battery under the test conditions, the second capacity test is used to track the available capacity of the battery during the test run. In most cases a decrease of available capacity is observed. The course of the test is similar to other well-known life-cycle tests, but the main differences are the exclusive usage of micro-cycles with superposition of a defined SoC swing.

The depth of discharge (DoD) of every single discharge phase during cycling is at least 0.1% and at most 1.0%, with an average DoD of approximately 0.3%. This is close to the average DoD in some real-life stop/start vehicles, according to the average length of the start/stop cycles in urban traffic. In this test, the DoD is not related to the battery size, but to a fix value. This means that the highest DoD may be even higher than 1% if small battery sizes are tested. The usual battery size investigated in this DPC test is 70 Ah. This approach was chosen due to the fact that a certain minimum load current is required during the stop phase of every micro-hybrid car, independent on the size of the battery or the car. To simulate smaller or larger vehicles with significant lower or higher load requirements, the test has to be adapted accordingly. This has been done to test very small automotive batteries with less than 40 Ah, under the assumption that vehicles using these very small batteries do not comprise many electric devices besides lighting and basic vehicle functions.

There are three different cycling phases in the dynamic pulse cycling test (DPC): starting with a SoC of 80%, in the first phase of test the SoC decreases to 70%. This is done by a micro-cycling pattern of 12 micro-cycles which comprise more discharging than charging (charge balance is negative). The next phase increases the SoC by 20% and uses 94 micro-cycles in which charging predominates over discharging (positive charge balance), until 90% is reached. The third cycling phase is the same as the first phase and decreases the SoC of the test battery from 90% back to 80% again within 12 micro-cycles. One entire cycling unit consists of 50 of these cycling patterns describes above (i.e. 12 + 94 + 12 micro-cycles each), followed by two capacity tests (Fig. 4). The cycling

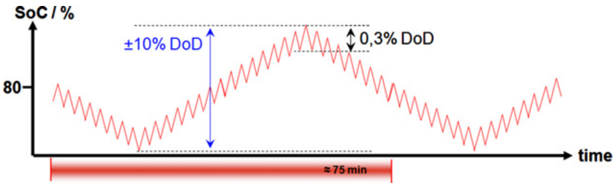

Fig. 4. Schematic depiction of dynamic pulse cycling test (DPC).

test simulates stop phases of a micro-hybrid car in urban traffic. Additionally, battery recharging is done by simulated regenerative braking only. The recharge voltage during micro-cycling is fixed to 14.8 V (as found in real-life micro-hybrid vehicles) independently on the battery technology and on ambient temperature, which is fixed to 25 °C in a water bath.

The DPC test can be carried out at standard laboratory equipment with a charging and discharging capability of ±50 A. This ensures that the test is easily set up in different labs and the results are comparable and reproducible. A high-rate discharge is not part of the original DPC test pattern, but may be implemented [6]. The pre-treatment schedules a series of $C/20$ tests prior to the first cycling unit to estimate a capacity baseline unaffected by the subsequent cycling test. Recharge after $C/20$ test is done at the regular charging voltage according to the battery technology (16 V for flooded, 14.8 V for AGM batteries).

There are two end-of-life criteria in the test: either the available capacity of the battery falls below 50% of its nominal value, or the voltage during 50 A discharge drops below 10 V. In both cases the battery is regarded as no longer suitable for a real-life application. The detailed test schedule is depicted in Appendix A. As described above, the pretest phase comprises several $C/20$ tests and in one cycling phase 50 cycles are performed, each with a SoC swing from 80% down to 70%, up to 90% and back to 80%. In the standard DPC test, the duration of one entire cycling unit is about one week.

The DPC test results strongly depend on the battery technology (Fig. 5). While flooded batteries exhibit a heavy decrease of capacity within the first cycling units, mainly caused by effects of acid stratification, the available capacity of AGM batteries is very stable even after many cycling units. The enhanced flooded battery (EFB) exhibits a performance level in between the standard flooded and the AGM battery. Effects of acid stratification are observed with EFB also, but the battery is designed to be more robust against acid stratification. According to this design, EFB ensures a higher lifetime of at least 170 capacity turnovers in comparison to standard flooded batteries with a lifetime of about 110 capacity turnovers until their $C/20$ capacity drops down to 50%. However, EFB do not reach by far the excellent performance level of AGM batteries with more than 1100 capacity turnovers until failure (Fig. 6).

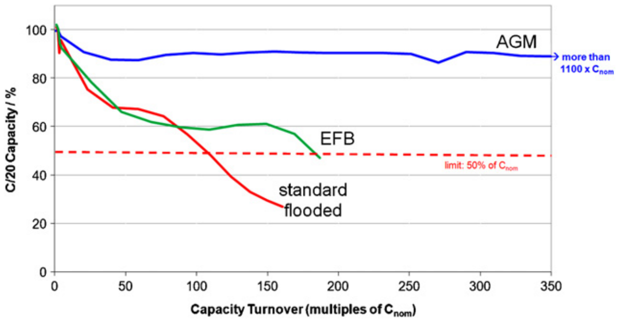

Fig. 5. Results of dynamic pulse cycling test (DPC).

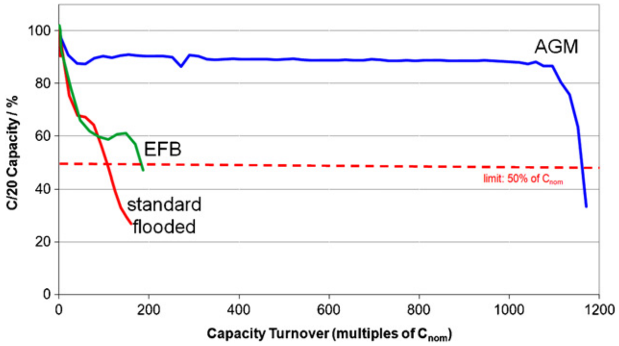

Fig. 6. Complete view of DPC test results.

2.4. *Modification of DPC test: influence of rest time*

In the standard test configuration, each cycling unit consists of 50 cycles at 80 ± 10% SoC followed by two capacity tests. The test does not contain any rest phase longer than 60 s. In reality, most cars are used in a considerable different way: in the morning the car is used to travel to work, in the evening for driving home (typical commuter duty). At weekends the usage may be different, but usually a private passenger car is not operated around the clock. To simulate this kind of operation pattern, the DPC test profile was modified. After every 75-min cycling phase (which means one complete SoC-swing from 80% to 70%, up to 90% and back to 80% again) a rest time of 10 h and 45 min is implemented. So a 24 h-day comprises 2 “driving phases” of 75 min each and two rest phases of 10 h and 45 min each. The battery has to withstand the extended rest phases in a partial SoC, meaning not being fully charged. This is strongly related to real-life applications, because in a real car the battery will also not be recharged after a 1-h drive. In the modified DPC lab test, one cycling unit with 50 cycles and the additional rest phases now takes approximately four weeks instead of one week. Charge throughput per week is 4.9 C_{nom} instead of 20 C_{nom}. After this micro-cycling phase, two capacity tests are performed as usual for reference. The detailed test schedule of the modified DPC test is depicted in Appendix B.

2.5. *Results of the modified DPC test*

During DPC testing, in both regular and modified test versions, the batteries are kept in a partial SoC. Acid stratification is one of the main issues for flooded batteries in these tests. The operation of a stratified flooded battery in a lab test comprising extended rest phases is even more challenging. The stratified flooded batteries undergo an internal charge equilibration effect, which decreases the extent of acid stratification, but leads to imbalances in the active masses of the battery (details shown in Section 3.1).

Standard flooded, EFB and AGM batteries were tested according to the DPC test profile with additional rest phases (Fig. 7).

Both flooded batteries (standard flooded and EFB) failed within the second cycling unit, after successful completion of the first unit (after the first four weeks) of the modified DPC test. The decrease of $C/20$ is even steeper in the modified test (marked with triangles) compared to the standard DPC test of standard flooded batteries (marked with circles). Generally, all types of flooded batteries suffer from extended rest phases under pSoC operation conditions. This can be observed from the difference of $C/20$ levels of each battery type in both tests. The higher decreases of $C/20$ capacities of both flooded battery types in the modified test compared to the standard DPC test are marked with broken arrows in Fig. 7.

AGM batteries are not influenced significantly by pSoC operation with extended rest phases. The levels of available capacity of both

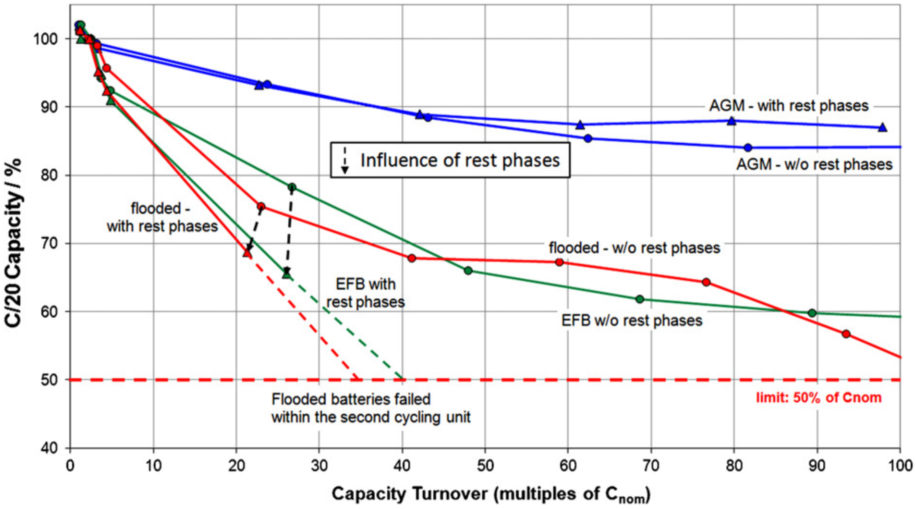

Fig. 7. The modified DPC test comprises some rest periods between micro-cycling phases.

AGM batteries, undergoing the regular and the modified test profile, do not differ significantly. Even after five cycling units, which means after 5 months, both blue graphs do not differ too much. The small differences observed after 3 months are regarded as variances of single battery individuals. The modified DPC test at the AGM battery was stopped after 5 cycling units without observation of any battery failure.

In real-life applications with pSoC operation mode implemented, the batteries are intentionally not fully charged during a certain time period. The modified DPC test suggests that under these severe operating conditions flooded batteries are not recommended.

3. Batteries in pSoC operation mode

In lead-acid batteries, the acid density is directly linked to the SoC, as discharge processes consume sulfate anions from the electrolyte, and recharge processes release sulfate anions back into the electrolyte again. Hence, in the left part of Fig. 8, the “normal” process is shown—discharge of a fully charged flooded battery leads to a completely discharged flooded battery with low acid density. In theory, the reverse process of recharging the battery should lead back to the initial state of the battery. In reality, this is not always the case. While recharging occurs, sulfuric acid is formed in the porous structures of the active masses. The density of this newly formed sulfuric acid is higher than the density of the remaining electrolyte outside the porous active masses. Hence, the high-density sulfuric acid will sink down to the bottom of the battery cell due to gravity, directly after is poured out of the porous active masses. This effect is even more important the lower the SoC of the battery is (e.g. low target SoC of micro-hybrid operation mode). Therefore deeper discharges and low SoC targets are even more harmful to flooded batteries than shallow discharges are. The result of the high-density sulfuric acid dropping down to the bottom parts of the battery cells is depicted in the right part of Fig. 8. The acid density is not homogeneously distributed over the height of the battery cells, but there is a gradient of acid densities—low density at the top of the battery cell, high density at the bottom. This unbalanced acid density distribution is called acid stratification [7–9].

Most of the commonly known laboratory battery tests specify a recharge voltage of 16 V for flooded batteries. This high charging voltage does not only recharge the battery, but also causes a significant amount of overcharging. The effect of water decomposition, as one part of the overcharging process, is the generation of gas bubbles rising from the battery plates up to surface of the electrolyte. The electrolyte is mixed by the rising gas bubbles, and during this process the acid densities are equalized to a certain extent (but mostly not completely). In addition, during this 16 V recharge phase both water loss and corrosion of the positive grids occur. Therefore, to minimize battery deterioration, this procedure cannot be recommended too often.

In vehicle applications, the applicable recharge voltage is limited. System electronics, bulbs and technical standards limit the maximum voltage to an upper limit of approximately 15 V. And even this voltage level is higher than usual—often recharge voltages of about 14 V or slightly above are found in standard cars. In general these values are controlled dependent on the temperature, but the recharge voltage measured at the battery hardly reaches more than 14.4 V at 20 °C in standard cars. This is not high enough to reduce acid stratification by gassing, and additionally, car manufacturers intend to minimize the water loss during battery operation, surely not to maximize it for reasons of acid mixing.

Lab tests and fleet trials have proven that usual vehicle movement is not sufficient to mix a stratified flooded battery. In a lab test we carried out four cycling units of the DPC test with standard flooded batteries (Fig. 9). Battery 1 did not experience any movement during testing, while batteries 2 and 3 were accelerated and decelerated on a rocker, 9 or 18 times per hour, respectively. The duration and extent of acceleration was chosen accurately to represent a real vehicle's acceleration in urban traffic as well as possible. Typical acceleration values in real-life cars in urban traffic have been measured to be 0.2–0.5 g both in direction of driving

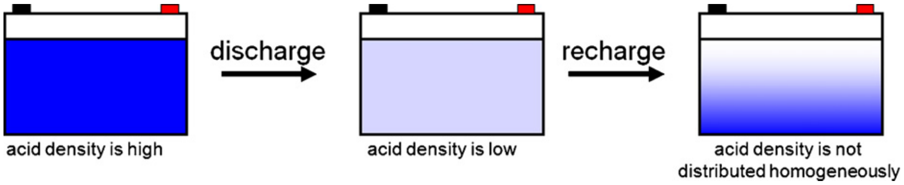

Fig. 8. Distribution of acid densities in flooded batteries.

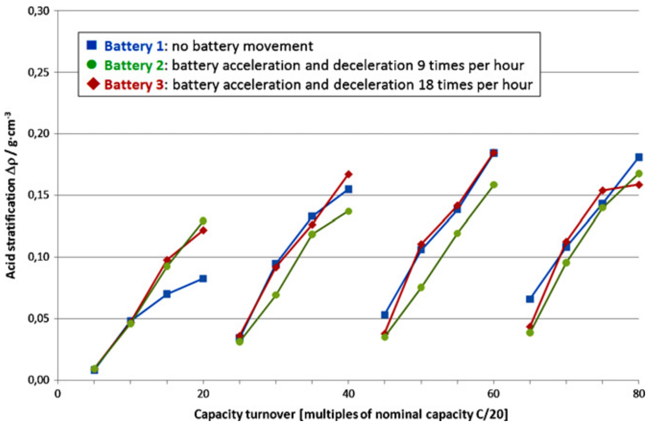

Fig. 9. Acid stratification of standard flooded batteries during four cycling units of DPC test: no significant influences of battery movement have been observed.

(acceleration and braking) as well as transversal to that (turning left and right). In the DPC test, the acid stratification was measured four times within each cycling unit. The test showed that the extent of acid stratification is not influenced significantly from battery movement (which represents vehicle movement in urban traffic). Neither the movement prevents acid stratification, nor does it reduce an existing stratification. In the lab tests – with or without battery movement – the severe acid stratification is reduced at the end of each cycling unit by 16 V recharge following the $C/20$ capacity test.

Hence, the slow decrease of acid density imbalances in the vehicle, which can be observed after a few days of rest time, is not the result of acid mixing from vehicle movement, but from an internal charge equilibration process described in Section 3.1.

AGM batteries do not show any acid stratification, and therefore they do not suffer from rest phases in pSoC operation like flooded batteries do. AGM batteries allow for deeper cycling (i.e. higher SoC swing) and for lower SoC targets in real-life applications without the risk of deterioration from extended rest phases.

3.1. *Influence of rest phases on stratified flooded batteries*

In a stratified, partially discharged flooded battery the acid density is unbalanced. From a electrochemical view, the high acid density at the bottom of the electrode stack is linked to a higher electrochemical potential in comparison to the lower potential caused by the low acid density at the top of the stack, as depicted in Fig. 10. An equilibration effect takes place in the electrolyte and changes composition of active masses locally [10]. Driving force of these equalization processes is the difference of electromotive forces.

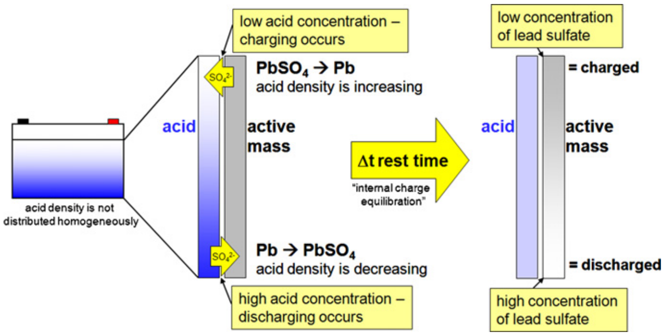

Fig. 10. Influence of rest phases on stratified flooded batteries, acid stratification is converted to mass stratification after extended rest phases.

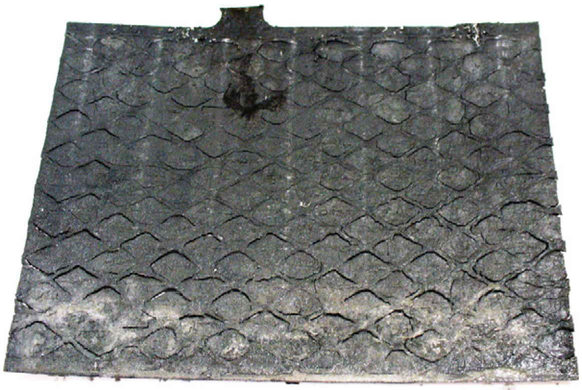

Fig. 11. Negative battery plate with lead sulfate on lower plate surface.

At the bottom of the plates, the high acid concentration facilitates the discharge process. Sulfate anions from the electrolyte react to lead sulfate precipitating onto the surface of the electrode. At the top of the electrode stack, the low acid density facilitates the recharge process. At this reaction site, sulfate anions are released from the electrode plate into the electrolyte. As both reaction sites are electrically connected by the electrode grid, an equalization current from one reaction site to the other occurs. From this process, the acid density at the bottom of the plates decreases, and it increases at the top of the electrode stack. In total, acid density imbalances are reduced. But this reduction of imbalances in the electrolyte is directly connected to an increasing imbalance of lead sulfate distribution in the electrode plates. As described above, the amount of lead sulfate which was equally distributed in the partially discharged electrode prior to the electrolyte equilibration process, afterwards is imbalanced. At the bottom of the plate stack where discharge took place, the content of lead sulfate is higher compared to the average of the plates' lead sulfate content. At the top of the plates, the content of lead sulfate is lower, correspondingly. The process of internal charge equilibration takes some time in the order of a few days at room temperature. The "disappearance" of acid stratification after a rest time is caused by the equilibration effect, not by diffusion, which would take much longer with such high differences in acid density and these long distances of many centimeters within the battery cells. If many of these stratification/rest phase cycles are carried out one after the other, the effects are accumulating. Over time, the lead sulfate content of the lower parts of the plates is getting larger. The result of such treatment both in lab tests and in real-life applications can be observed after battery teardown. Fig. 11 shows a negative battery plate with strong appearance of sulfation, which means a high content of lead sulfate in the lower parts of the plate. The process of internal charge equilibration in stratified flooded batteries can be described as a transition from acid stratification to mass stratification.

The more discharged bottom areas of the plates cannot be recharged easily. During extended rest phases without any recharge in between, the smaller lead sulfate crystals have the opportunity to grow to larger crystals. Due to the higher ratio of volume to surface, the larger crystals are thermodynamically preferred. These larger crystals cannot be dissolved quickly, so that the battery cannot be recharged easily [11–13]. This can be observed predominantly at the negative electrode due to the differences in pore diameters of negative and positive mass of a lead-acid battery, which in average is less than 2 μm for positive, but 5–10 μm for negative active masses [14,15]. Therefore the size of lead sulfate crystals in the positive plate is more limited, which means a higher recharging ability, in consequence. The effect of sulfation is described as a concept of "hardening crystals" by Thele et al. [16,17], and literature cited there.

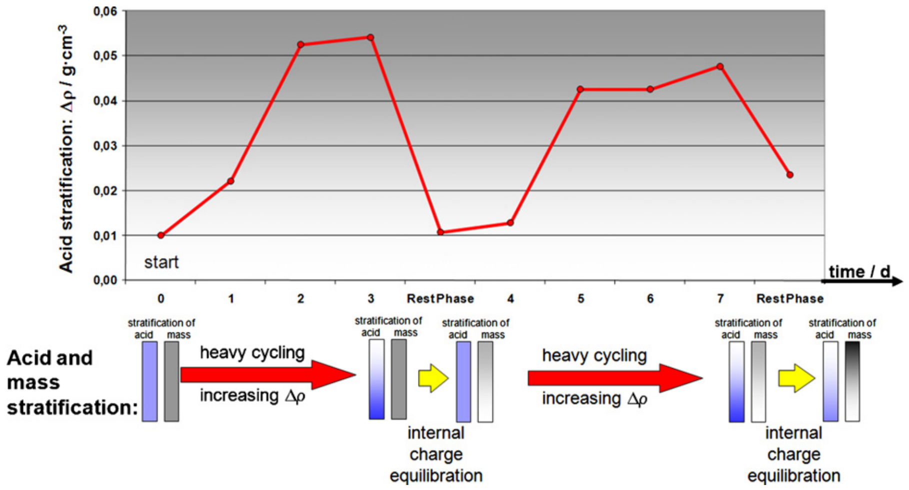

Fig. 12. Acid stratification of a flooded battery during a micro-hybrid vehicle test. During rest time, acid stratification is converted to mass stratification by internal equilibration processes.

In the modified DPC test, there is a second point of view to sulfation: both AGM and flooded batteries undergo the same test procedure. While the AGM batteries seem to be not affected by the extended rest times, the flooded batteries show significant decreases in the available capacity. This means that the sulfation processes do not differ from the regular DPC test conditions to the modified test in case of the AGM battery. For this battery type, one full recharge every four weeks has been found to be sufficient under the ambient conditions of the DPC test. In contrast, flooded batteries have to be recharged more often—one full recharge in four weeks seems to be not sufficient. But after recharge, independent on the frequency of recharge, a flooded battery may be still in a somewhat stratified state, mainly dependent on the DoD of cycling.

3.2. *In-vehicle experiment: acid stratification of flooded batteries and rest phases*

In addition to the lab test described above, another experiment has been performed with a standard flooded battery in a real micro-hybrid vehicle. This vehicle usually operates the battery in a pSoC mode and is equipped with an AGM battery, regularly.

Starting with a fresh battery, the difference of acid density from the top to the bottom of the battery cells is about 0.01 $\mathrm{g\,cm^{-3}}$. Acid stratification data (difference of acid densities at the bottom and top of the plates) are plotted as average values of all six battery cells in Fig. 12. The car was operated with a quite heavy urban driving test profile with a few hours of driving (20 km distance) every day (charge throughput of each test drive was approximately 0.5 C_{nom}). Acid stratification increases significantly within the first 3 days of testing up to 0.05 $\mathrm{g\,cm^{-3}}$ on average. After 3 days of driving, 3 days of rest time were allowed without operating the car: the battery experienced an uninterrupted rest time. The acid stratification observed afterwards was 0.01 $\mathrm{g\,cm^{-3}}$ again. In the subsequent week, battery cycling was performed on 4 days according to the same driving profile as one week earlier. Again the acid stratification increased to about 0.05 $\mathrm{g\,cm^{-3}}$. After this second cycling phase, a second rest phase was allowed. Again, afterwards a significant decrease of acid stratification was observed.

N.B.: the absolute degree of acid stratification after the end of the test was at 0.025 $\mathrm{g\,cm^{-3}}$, this is slightly higher than the initial degree had been. The acid stratification has not been removed completely during the second rest phase.

This micro-hybrid vehicle experiment shows the impact of acid stratification on flooded batteries. In pSoC operation mode, acid stratification in conjunction with extended rest phases, leads to a deterioration of flooded batteries. After the test, the battery showed an available capacity of 84% only, compared to 100% before testing. This considerable decrease of available capacity of 16% was reached within only two weeks of micro-hybrid operation. If the battery load profile would have been less challenging than the test profile applied in this test, the battery may withstand some longer testing time, but the appearance of a general stratification issue of flooded batteries in conjunction with rest phases is evident.

From a technical point of view, for such challenging micro-hybrid applications AGM batteries are highly recommended. The high cycling ability and the possibility to allow for deeper cycling and a lower target SoC are the most important advantages of AGM batteries beyond their non-stratifying characteristics. Positive experiences of AGM batteries in real-life micro-hybrid applications are gained in the last three years with many OEM customers.

The general occurrence of acid stratification of flooded batteries in micro-hybrid vehicles seems to be not avoidable dependent on the actual driving patterns, individual usage profiles and the operation mode determined by the micro-hybrid system design. Therefore it is most important to reduce the consequences of acid stratification. The enhanced flooded battery is more robust by design, leading to a higher lifetime in micro-cycle tests. OEM introduction of EFB will be in late 2010.

4. Conclusions and outlook

More and more micro-hybrid vehicles enter the markets, as one part of the car manufacturers' strategy to fulfill environmental goals and legal requirements. In an investigation of 15 micro-hybrid vehicles available in Europe two groups were found: entry-level vehicles with engine start/stop only, and advanced vehicles with engine start/stop and additional micro-hybrid functions. Within this second group either the combination of start/stop with regenerative braking and passive boost functions or the combination of start/stop with charge voltage control functions were found. European brands tend to implement AGM batteries, Asian brands tend to implement flooded or enhanced flooded batteries.

A laboratory test was set up to simulate micro-hybrid applications under controlled conditions (dynamic pulse cycling test, DPC). The batteries are operated in a pSoC mode at a medium SoC which is not fixed, but oscillating in a range of 70–90% SoC (close to real-life applications). All charging and discharging phases are of 1% DoD maximum. Standard flooded batteries generally suffer from acid stratification in the test. Enhanced flooded batteries are more robust and exhibit a higher lifetime compared to standard flooded batteries. AGM batteries do not show any acid stratification and show excellent results in the DPC test.

As a variation of the DPC test procedure, a commuter duty was simulated, alternating 1-h cycling periods with extended rest phases regularly. In the modified test, flooded batteries suffer even more from acid stratification and fail after the first test unit. The extended rest phases lead to an internal charge balancing process, which results in an apparent reduction of acid stratification as well as in a stratification of active masses which means a deterioration of the battery, finally. AGM batteries are not affected significantly by the rest phases and passed 5 test units without any failure.

As observed in this investigation of micro-hybrid vehicles, it is expected that also in the future different micro-hybrid concepts will coexist. There may be more concepts in future aiming for an even higher efficiency of micro-hybrid vehicles. Furthermore, many other hybrid car concepts will enter the markets as well (micro-, mild-, full- and plug-in hybrid vehicles as well as pure electric vehicles). The battery selection will be done according to the system design and according to the performance requirements defined by the car manufacturers. There will be a large variety of battery technologies, beyond standard flooded lead-acid batteries there is a wide range from enhanced flooded to AGM batteries and even to Nickel-Metal-Hydride and Lithium-Ion batteries. All of these technologies are available now and are already implemented in real vehicles yet or will be implemented shortly.

Even more work has to be done in the technical assessment of different battery technologies for micro-hybrid applications. More and more laboratory tests try to simulate real-life operating conditions as well as possible. It will be valuable to correlate lab test results to real-life experiences as soon as reliable data are available. The first results published by BMW look quite promising for the application of AGM batteries in micro-hybrid vehicles [1,18].

Acknowledgements

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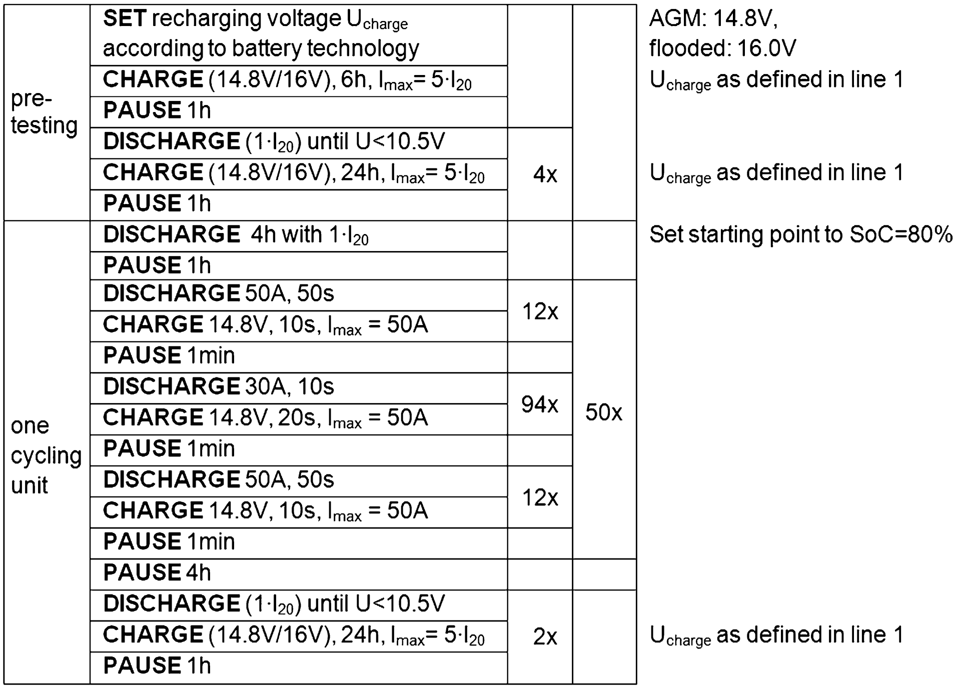
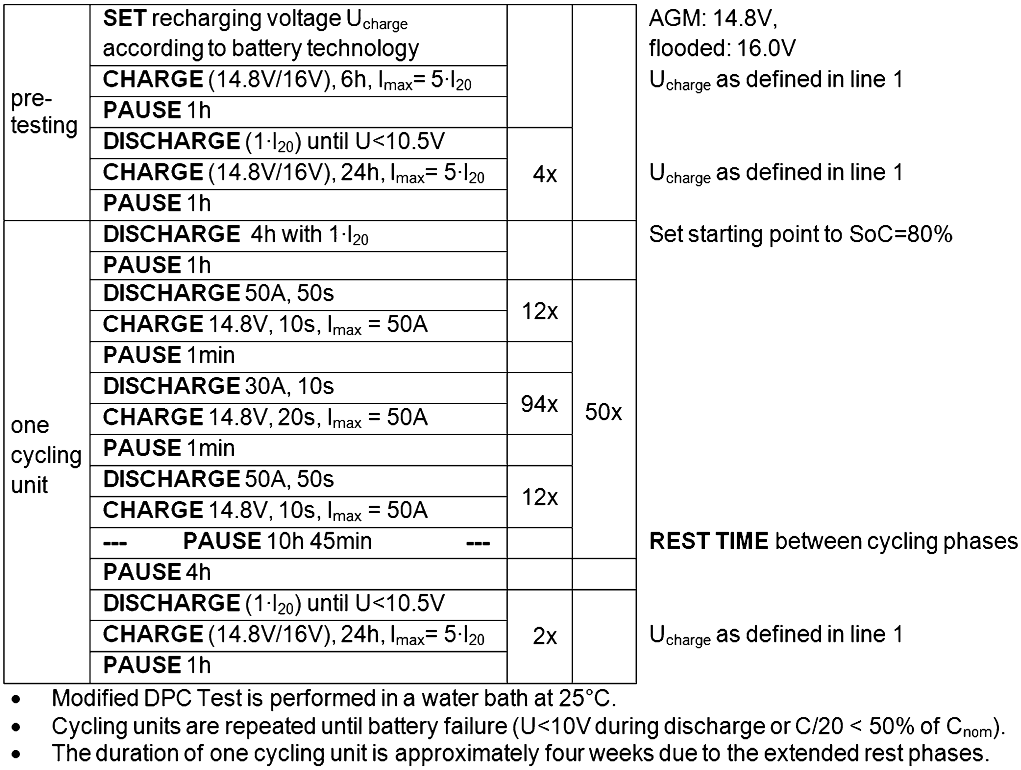
Appendix A. Detailed description of the dynamic pulse cycling test (DPC).



pre-testing	**SET** recharging voltage U_{charge} according to battery technology			AGM: 14.8V, flooded: 16.0V
	CHARGE (14.8V/16V), 6h, $I_{max}= 5 \cdot I_{20}$			U_{charge} as defined in line 1
	PAUSE 1h			
	DISCHARGE ($1 \cdot I_{20}$) until U<10.5V	4x		
	CHARGE (14.8V/16V), 24h, $I_{max}= 5 \cdot I_{20}$			U_{charge} as defined in line 1
	PAUSE 1h			
one cycling unit	**DISCHARGE** 4h with $1 \cdot I_{20}$			Set starting point to SoC=80%
	PAUSE 1h			
	DISCHARGE 50A, 50s	12x	50x	
	CHARGE 14.8V, 10s, $I_{max} = 50A$			
	PAUSE 1min			
	DISCHARGE 30A, 10s	94x		
	CHARGE 14.8V, 20s, $I_{max} = 50A$			
	PAUSE 1min			
	DISCHARGE 50A, 50s	12x		
	CHARGE 14.8V, 10s, $I_{max} = 50A$			
	PAUSE 1min			
	PAUSE 4h			
	DISCHARGE ($1 \cdot I_{20}$) until U<10.5V	2x		
	CHARGE (14.8V/16V), 24h, $I_{max}= 5 \cdot I_{20}$			U_{charge} as defined in line 1
	PAUSE 1h			

- DPC Test is performed in a water bath at 25°C.
- Cycling units are repeated until battery failure (U<10V during discharge or C/20 < 50% of C_{nom}).

Appendix B. Detailed description of the modified dynamic pulse cycling test (DPC) including extended rest phases.



pre-testing	**SET** recharging voltage U_{charge} according to battery technology			AGM: 14.8V, flooded: 16.0V
	CHARGE (14.8V/16V), 6h, $I_{max}= 5 \cdot I_{20}$			U_{charge} as defined in line 1
	PAUSE 1h			
	DISCHARGE ($1 \cdot I_{20}$) until U<10.5V	4x		
	CHARGE (14.8V/16V), 24h, $I_{max}= 5 \cdot I_{20}$			U_{charge} as defined in line 1
	PAUSE 1h			
one cycling unit	**DISCHARGE** 4h with $1 \cdot I_{20}$			Set starting point to SoC=80%
	PAUSE 1h			
	DISCHARGE 50A, 50s	12x	50x	
	CHARGE 14.8V, 10s, I_{max} = 50A			
	PAUSE 1min			
	DISCHARGE 30A, 10s	94x		
	CHARGE 14.8V, 20s, I_{max} = 50A			
	PAUSE 1min			
	DISCHARGE 50A, 50s	12x		
	CHARGE 14.8V, 10s, I_{max} = 50A			
	--- **PAUSE** 10h 45min ---			**REST TIME** between cycling phases
	PAUSE 4h			
	DISCHARGE ($1 \cdot I_{20}$) until U<10.5V	2x		
	CHARGE (14.8V/16V), 24h, $I_{max}= 5 \cdot I_{20}$			U_{charge} as defined in line 1
	PAUSE 1h			

- Modified DPC Test is performed in a water bath at 25°C.
- Cycling units are repeated until battery failure (U<10V during discharge or C/20 < 50% of C_{nom}).
- The duration of one cycling unit is approximately four weeks due to the extended rest phases.

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