

Utilizing the full potential of UPS systems with lead-acid batteries as flexible stationary storage systems: How a 3D battery model can help

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Abstract

UPS systems are installed all over the world in various applications. This type of battery energy storage system (BESS) can provide additional services, such as load leveling or peak shaving, in an electrical grid with an increasing number of fluctuating energy sources. The concept of dual-use or double purposing describes the utilization of one storage system on two distinct markets. Compared to a single purpose BESS, a considerable business case is established through the shared investment cost and the diversified risk.

However, the operation scenarios do impose significantly more stress on the lead-acid battery than the constant charging in UPS applications. The partial state of charge operation (pSoC) that is typical for dual-use of UPS systems does require additional overcharging phases for capacity recovery and equalization of cells in a string. Compared to UPS operation, a reduction in lifetime is currently inevitable, but can be significantly minimized by the means of smart operation strategies. The revenue flow is expected to outbalance the cost of earlier battery replacement.

A 3D physico-chemical model based on first principles was developed to simulate battery performance and ageing. It allows a spatially resolved analysis of several parameters indicating ageing in a lead-acid cell. Lead-sulfate crystal size and distribution, vertical and horizontal current distribution on the electrodes and the intensity of side reactions can be identified for different operation strategies. This model approach enables a comparative study that determines an efficient charging method as well as optimized intervals between charging processes for given cell geometries, technologies and operating conditions.

The results presented in this paper show the importance of the right interval between check-ups, where a battery full charge can be reached. For the right timing, the duration at pSoC, the number of cycles as well as their depth of discharge (DoD) has to be considered. The 3D model allows the analysis of the diverse possible conditions of given load profiles and the evaluation of the optimum interval between check-ups.

Simulations and laboratory tests prove the important role of smart battery management algorithms that consider the effect of temperature changes and apply charging strategies according to the batteries' state of health. The gained insight is essential to develop new, fast and energy efficient charging methods for enhanced cycle life in a given application under consideration of the economic aspect of prolonged utilization periods in-between full charges.

Introduction

The amount of installed power delivered by renewable energies as well as the number of large scale data centers with uninterruptible power supply systems (UPS) are increasing worldwide [1–3]. Hence it seems legitimate to ask: Why not use the installed batteries in a data center for a second purpose? Fluctuating energy production from wind turbines, photovoltaic modules or other intermittent renewables could be equalized in durations of minutes and hours by battery energy storage systems (BESS). This idea of dual-use or double purposing has been described among others by McKoen et al. in [4]. The concept includes an addition of battery capacity to a system with existing electrical infrastructure, which is already redundant due to the 2N+1 regulation. For the UPS operator offering grid services such as load leveling or peak shaving means an additional flow of revenue in periods where there is no demand for the conventional UPS functionality.

Reduced investment cost and enhanced return on investment for the installation of additional battery capacity compared to a completely new BESS installation with only one purpose are part of this business case, which is described in more detail on the following pages.

The subsequent new operation conditions imply a partial state of charge (pSoC) operation for the installed batteries. Currently, the most common electrochemical storage systems for UPS application are lead-acid batteries. A pSoC operation and increased cycling cause diverse ageing mechanisms such as inhomogeneous hard sulfation, corrosion of the positive grid and loss of active mass¹ [5–7]. Additionally, necessary intensive charging methods, which shall recover reversible capacity loss caused by sulfation, can also result in an intensified corrosion and water loss through water electrolysis. For flooded lead-acid batteries especially, acid stratification has to be mentioned as one effect accelerating the ageing mechanisms discussed above.

The development of optimized operation strategies with improved charging methods through laboratory experiments is time-consuming and cost-intensive. The restricted reproducibility is further limiting the applicability of this approach for an elaboration of battery management algorithms. Therefore, a 3D battery model has been developed, which is based on physics' first principles, to simulate with selectable spatial resolution the complex effects of diverse parameters such as voltage limits, current rates and temperature on the performance of a lead-acid cell [8–13]. Furthermore, operation strategies and their influence on ageing mechanisms can be simulated reproducible as manufacturing deviations or the history of the battery can be set aside. In combination with a limited number of laboratory tests, this procedure allows quick analyses of diverse use cases and extreme operation conditions. The in-depth understanding of the correlated cell behavior can subsequently be used to implement operation strategies in battery management practice and energy management software in the field.

In the following section, the economic concept behind the dual-use of UPS systems is described. In addition, the influence of temperature and charging parameters is illustrated based on laboratory measurements and simulations. These selected results shall represent some aspects that have to be considered when UPS systems provide additional services.

¹ shedding especially of the positive active mass

The economics of dual-use for UPS systems

UPS systems are installed to provide power to critical loads during phases of grid outages. In the concept of dual-use the battery capacity is still available and guaranteed for this service. In this period of power supply the second purpose, which is an assistance of a functional grid, is not relevant. If the grid requires load leveling or comparable services, the battery is not needed as UPS. Therefore, the concept of dual-use allows a complementary utilization of capacity.

UPS systems are especially interesting for this business model as the electrical infrastructure such as the grid connection, inverters, cables and connectors as well as the major battery capacity have already been installed. Under these circumstances, the upfront investment to enable UPS systems for the provision of grid services is the installation of surplus battery capacity through an additional battery string. With this investment, the depth of discharge (DoD) per string decreases, which is accompanied by a longer cycle life (Figure 1). The outcome is lower cost per kWh. In this configuration, individual and ageing anticipating charging algorithms can be applied to each string without compromising the UPS capacity. Furthermore, the possible individual treatment can even increase the possible number of cycles.

To illustrate the reduction in price, a simple calculation example is depicted in Figure 2. Herein, the following cases are compared:

- A. BESS for grid services alone with a DoD of 100%
- B. BESS for grid services alone with a DoD of 20%
- C. Additional capacity installation for an existing UPS system with a subsequent DoD of 20%

In this example, the system cost for the electrical infrastructure in case A and case B are not considered.

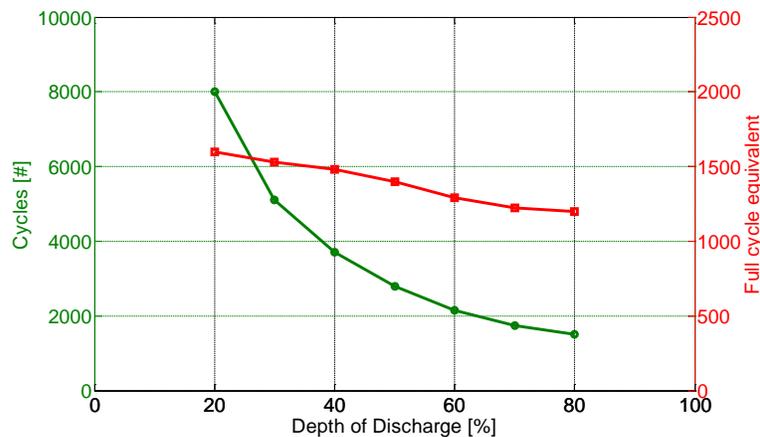


Figure 1. Dependency of cycle life on the depth of discharge. Values are given by manufacturer for a 200Ah 2V flooded cell with tubular plates.

Even with looking just at the cell price level, case A and B are not economically attractive as the price per kWh is too high in comparison to conventional electricity prices. However, case C reaches a competitive electricity price. The calculated prices shall be understood as cost per delivered kWh while the investment prices represent the cost per installed kWh.

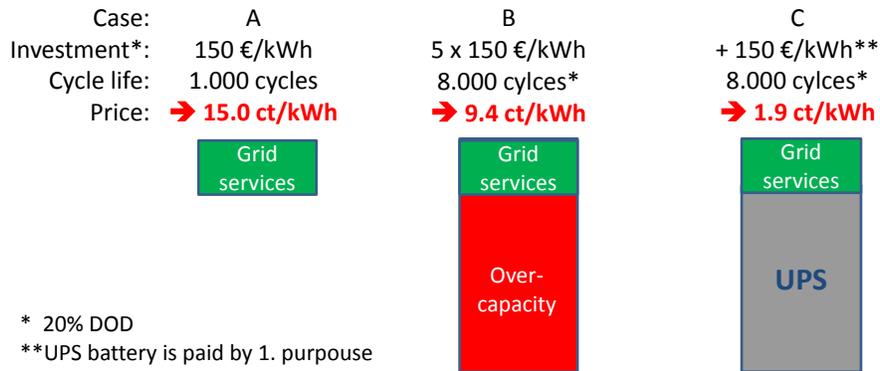


Figure 2. Schematic explanation of dual-use and its economic benefit. Comparison of three investment cases:

A: BESS for grid services alone with a DoD of 100%

B: BESS for grid services alone with a DoD of 20%

C: Additional capacity installation for an existing UPS system with a subsequent DoD of 20%

With dual-use, an underutilized system can gain additional profit from electricity sale. In the long run, even regular maintenance cost can be shared. The investment risk is at the same time low as the market for UPS persists even if grid service cannot be sold. Providing one MW per week is worth approximately 3.000 € on the German primary control market. A 60 V UPS system with a capacity of 2.000 Ah and an inverter sized for current rates of 0.1 A/Ah could offer 12 kW. On the one hand, the 20% added capacity for grid services equals an investment of 3.600 €². On the other hand, the possible revenue equals 2.000 €/a. BESS can easily fulfill the prequalification test of the primary control market. Several installations will then be pooled locally to a 1 MW system. BESS can and will play a major role in balancing supply and demand in low-voltage distribution grids, especially in Germany. The implicit change of conditions has to be tested to estimate the influence on lifetime. Coupled with simulations performed with a highly accurate battery model, optimal operation strategies can be developed that increase the cycle life and thus further reduce the cost per kWh.

Influences of new conditions on ageing

Several measurements have been conducted to investigate different effects of the new operation strategies on the lifetime of lead-acid cells. Additionally, simulations performed with the 3D battery model allow a deeper analysis of influencing factors arising under the given conditions. In the following, a selection of findings is presented, which all are relevant for the dual-use case described above.

Basic information on measurements

For the measurements, special test cells were built out of two negative Fauré plates³ and one positive tubular electrode. Both electrodes were taken from standardly manufactured cells for stationary applications with lead grids containing 1.8% antimony (Sb) for the OPzS (stationary battery with tubular plates and diluted acid) and calcium (Ca) alloy for the OPzV (like OPzS only with gelled electrolyte).

The dimensions are listed in Table 1. The cells were filled either with diluted sulfuric acid (OPzS, acid density of 1.24 kg·l⁻¹) or with a gelled electrolyte (OPzV) as can be seen in Figure 3. The cells are in total rated with a 25 Ah capacity at a 10 hour discharge rate (0.1 A/Ah).

² Considering a price per kWh of 150 €

³ standard pasted grid

		Positive Electrode	Negative Electrode
Electrodes per cell	#	1	2
Weight of active mass of one electrode	[kg]	0.367	0.178
Theoretical Capacity ⁴ (C ₁₀)	[Ah]	28.79	32.29
Dimensions (HxWxL)	[mm ³]	208x 98x 9.4	212x100x 2.8
Porosity	[%]	~50.0	~60.0

Table 1. Geometry of the tested cells.



Figure 3. Special built test cells. Left: sealed design with gelled electrolyte (OPzV). Right: vented design (OPzS)

In the laboratory, different cycle conditions were tested. For the analysis of ageing behavior capacity check-ups were performed after specified intervals, which will be discussed later. These check-up consists of either two or three full discharge/full charge cycles. The first discharge is used to measure the residual SoC level after one cycling unit. End of discharge is set in all cases to 1.75 V at a discharge rate of 0.2 A/Ah. As the last step the cell is recharged in three steps. The first step includes a charge with 0.25 A/Ah to the previous SoC level. Secondly, the cell is charged with 0.25 A/Ah to 2.4 V for a maximum of 6 hours if the voltage limit is not reached. The last step is a constant voltage phase at 2.4 V for 3 hours. This procedure is called operational charge (OP). Every second unit the cell is charged for a prolonged period of 24 h; named after the European standard EN-charge. The capacities taken after the OP and EN charge for the tested batteries are depicted in the following paragraphs.

Basic information on simulations

To clarify in-depth the influence of operation conditions on cell performance, a battery model with a multi-scale and multi-physical approach has been developed. The model is based on an equivalent electrical circuit (EEC) and volume element approach. The assumptions, functionality and connection of both models are described in more detail in [8–13]. The simulations were performed with the geometries and basic data of the laboratory test cells used for the cycling tests, summarized in Table 1. The parameters for an OPzS cell with an acid density of 1.24 kg*l⁻¹ were set.

In the simulation, charge degree is used to describe the status of the electrodes. The charge degree χ stands for the proportion of existing molar mass of active material n_{AM} in a volume element compared to its initial value n_{AM}^0 and is described by equation (1).

$$\chi = \frac{n_{AM}}{n_{AM}^0} \quad (1)$$

With $\chi = 1$ the full state of charge with no lead-sulfate is described while $\chi = 0$ equals a theoretical full transformation into lead-sulfate. It is thus a form of SoC where the exact utilization rate of active mass is not a necessary parameter.

⁴ This value is calculated with a mass utilization of 35% and 3.87 g*Ah⁻¹ and 4.46 g*Ah⁻¹ for the negative and positive mass respectively.

Influence of temperature on cycle lifetime

In the new dual-use operation of UPS systems with higher current rates and intensified cycling conditions, increases of the maximum temperature of more than 10°C compared to standard conditions can be expected [4]. The temperature rise will be unequally spread over the cells of one string. The total influence of temperature on battery's cycle life is very complex. On the one hand, the limiting step of lead-sulfate dissolution during the charge process is favored at higher temperatures so that less capacity loss due to sulfation is expected. The effect of acid stratification is reduced at increased temperatures as the diffusion controlled mixing is elevated, resulting in a better equalization of gradients. On the other hand, side reactions as gassing and corrosion with subsequent water loss are intensified. Additionally, the temperature within one battery string can be very inhomogeneous and does depend on the air conditioning and packaging of the system. Even a small temperature deviation of 2°C can cause additional problems due to inhomogeneous capacity loss [14].

In the laboratory, single cells were tested with the same current profiles and check-up intervals at three different ambient temperatures: 10°C, 25°C and 40°C. For comparison, check-ups were always performed after the battery was tempered to 25°C.

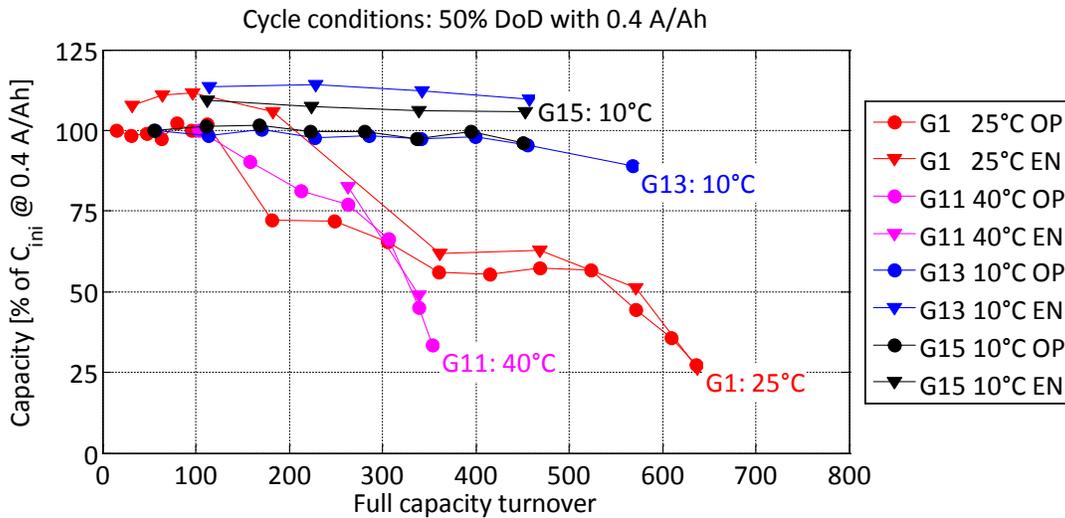


Figure 4. Influence of temperature on the cycle life at three different ambient temperatures: 25°C, 40°C and 10°C.

NOTE: The capacity tests are always performed at 25°C. Cycling between check-ups is defined by 50% DoD with a discharge and charge rate of 0.4 A/Ah for all cells but G15, which is cycled with 0.4 A/Ah discharge and 0.1 A/Ah charge rate. One cycling unit equals 55 FCE for all cells.

The capacity values of cells in the temperature test are compared in Figure 4. It becomes evident that under equal conditions higher temperatures lead to a faster capacity loss in the continuous cycling test. Furthermore, the change in charge rate during cycling, as it is done for cell G15, does not yet show a significant better behavior compared to its pendant G13.

This test highlights the importance of temperature control in a battery system. Here an increase by 15°C resulted in a reduction of cycle life by 60%. A continuous cycling with such a temperature increase would mean a reduction of a standard operation time of 5 years down to approximately 2 years. The 3D model thus includes such temperature influences emerging from the operation strategy for a valid recommendation.

Influence of charging conditions

Charging conditions can be defined by their current rate, voltage limits, temperature, durations and intervals of occurrence. The latter is normally determined by measurement of time or Ah-throughput. The following sections describe the importance of the full charge interval as well as the effect of high voltage limits in full charges.

Timing of full charges

Cycle tests were performed with two different charge and discharge rates during cycling, namely (a) 0.4 A/Ah and (b) 0.2 A/Ah. The depth of discharge (DoD) was set to 50% of the rated capacity and the SoC range started at 80% as maximum SoC. This scenario represents an extreme case of cycling in a BESS with dual-use. The cells were either cycled for a mean value of 55 full cycle equivalents (FCE=full cycle equivalent=one 100% capacity turnover) or 19 FCE before they were submitted to a check-up⁵. Mentioned numbers of full cycles will further be addressed as one cycling unit. An uncontrolled SoC drift during cycling is outbalanced by voltage controlled recharges every 2 FCE for all cases.

The capacities taken after an operational charge (OP) and prolonged for the tested batteries are depicted in Figure 5. In total, faster capacity decay is investigated in the case of 55 FCE in on cycling unit. The results of battery G1 illustrate the effect best. This battery is first cycled with 19 FCE rate and is switched to 55 FCE after around 100 capacity turnovers. The first check-ups showed a similar behavior as G9. After the switch, a sudden capacity loss occurred.

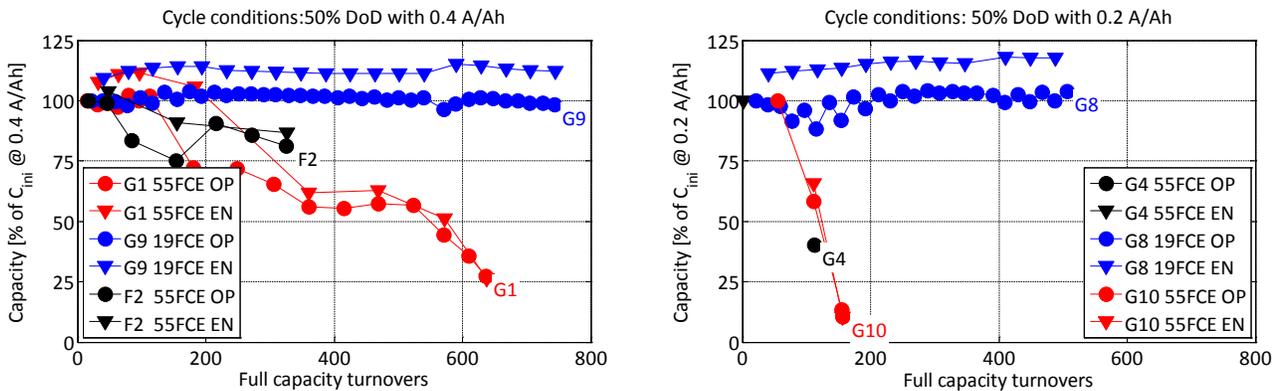


Figure 5. Comparison of capacity development over full capacity turnovers for tests with different cycling unit length in between check-ups and at two different current rates during cycling.

Left: 0.4 A/Ah for discharge and charge. Gx: OPzV cells. Fx: OPzS cell. 55 FCE: G1 and F2, 19 FCE: G9
 Right: 0.2 A/Ah for discharge and charge. Gx: OPzV cells. 55 FCE: G10 and G4, 19 FCE: G8

The capacity loss during the first cycles is depicted in Figure 5 and can be compared to the simulation results. After 107 FCE the EN capacity decreased by 15.9% (F2). The OPzV type (G1) lost during the same amount of FCE around 30.3% of its capacity.

⁵ The intervals were previously set to 16 and 50 FCE. Due to changes in the test setup the given mean values were reached.

These tests reveal the positive influence of high current rates on cycle life in the continuous cycle profile with 55 FCE per cycling unit. The Ah-based and voltage controlled recharges during cycling hinder a reduction of charge periods for higher currents. This averts a possible increase in sulfation. One explanation for this deviation is the change in active mass utilization with different current rates. Higher current rates exploit more of the upper electrode region and the outer electrode area, which is closer to the electrolyte, while lower current rates lead to a more homogenous and more intense active mass utilization. The lower current does also result in bigger sulfate crystals per active mass volume. The extreme capacity loss is seen for G4 and G10 (Figure 5). G4 was the first cell under these cycling conditions so that less capacity tests have been performed. But the given check-ups deliver the same behavior as G10. Tear down analyses will be conducted for all tested cells to further investigate the cause of failure.

A similar profile of 16 FCE and 50 FCE at a SoC range of 100% down to 50% built the basis for a cycling simulation. The charge degree is evaluated at different points of the electrical profile. The average charge degrees reached in both electrodes at the end of each cycle block's last discharge and charge step are listed in Table 2. The loss in capacity can be seen in the values given in the full charged state. In the end, the mean charge degree for the 50 FCE case is reduced by 5.1% and 7.2% for the positive and negative electrode respectively. The difference between the two cases is of course also a result of the higher number of overall capacity turnovers reached at this point for 50 FCE cycling. However, a difference in ageing can already be seen in the comparison of the second full charge of the 16 FCE case (after overall 36 FCE) and the first full charge of the 50 FCE case.

	Cycle Block	Last Discharge		Last Charge		Full charge	
		1	2	1	2	1	2
Positive Electrode	16 FCE	83.1%	83.2%	98.3%	98.3%	100.0%	100.0%
	50 FCE	79.1%	71.4%	94.2%	86.2%	99.5%	94.9%
Negative Electrode	16 FCE	84.4%	83.6%	98.0%	96.8%	99.6%	98.5%
	50 FCE	69.9%	70.2%	83.5%	83.4%	91.8%	92.8%

Table 2. Mean charge degree for positive and negative electrode in discharged and charged state after the two cycle blocks and in charged state after 24 hour charge. A comparison of the values in full charge reveals the loss of capacity.

In addition, the charge degrees for both electrodes at four distinct points of the electrical profile are plotted in Figure 6. For both electrodes the difference between the minimum and maximum charge degree over the electrode is higher when exposed to longer cycle units (compare blue and red lines). Furthermore, the negative electrode is shown to have a larger spread between maximum and minimum charge degree compared to the positive electrode. This indicates a deeper discharge and less sufficient recharge. Its average charge degree decreases faster than the one of the positive electrode although the capacity of the negative electrode is bigger by a factor of 1.12. The reason is that the current rate per volume is lower for the negative electrode. Larger sulfate crystals are built at lower current rates, subsequently leading to reduced charge acceptance.

As expected, the ageing process is quite different for the two simulations of 32 and 100 FCE of 50% DoD. From Figure 6 it can be concluded that the charging process does restore the mean charge degree for the 16 FCE case. On the contrary, even with a long 24 hour charging period the full state of charge cannot be restored for the 50 FCE case. The laboratory cell comparable to this simulation is F2. The smaller capacity loss in the simulation can be due to a better sulfate dissolution in the given SoC range.

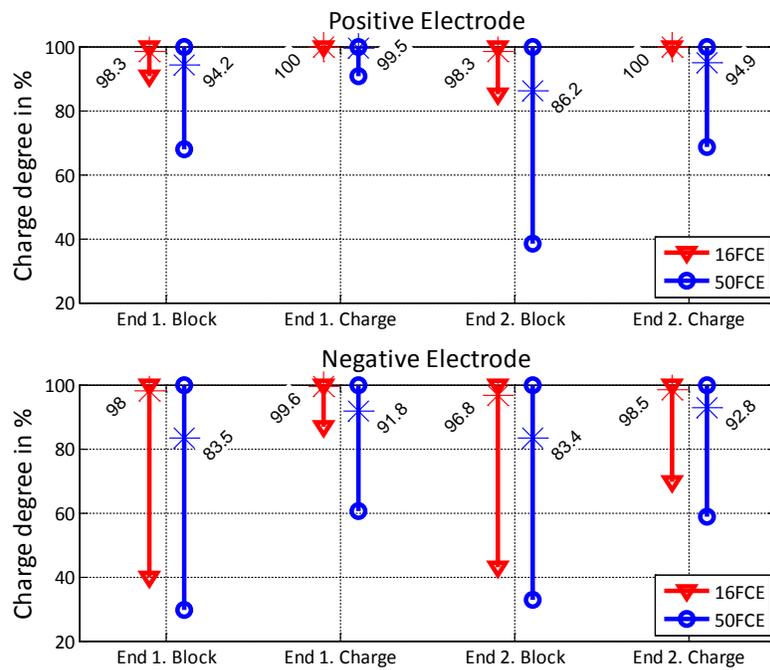


Figure 6. Differences in minimum and maximum charge degree of the positive (top) and negative (bottom) electrode in charged state after the two cycle blocks and the two full charge procedures for the simulation with 16 FCE and 50 FCE block length. The corresponding mean charge degree is marked with a star.

Intensity of full charges

First simulation results provide an insight into the influence of standard CC-CV charges with different voltage limits. A detailed description of the test setup is given in [15]. For the initial setting a highly sulfated cell was chosen and implemented through a distribution of large crystal radii and accordingly reduced charge degrees in vertical direction of the electrodes. Afterwards, the simulation starts with a discharge (0.25 A/Ah down to 1.75 V) followed by one of the two charge procedures. The maximum current rate is set to 0.25 A/Ah while the charge voltage limit is either 2.45 V (case 1) or 2.67 V (case 2).

A charge voltage limit of 2.67 V instead of 2.45 V results in a 2.25 times higher water loss over the simulation period of a 24 hour charge step. The accompanied gas development has resulted in a better mixture of the electrolyte hindering a built up of acid gradients in the 2.67 V case (Figure 7 (right)). The 2.45 V do not lead to increased gas evolution so that the acid densities⁶ start to disperse in the CV phase (t=10 hours, Figure 7 (left)). Even though higher gassing rates occur in the 2.67 V charge, the time until 100% of the nominal capacity is recharged to the main reaction of the negative electrode is decreased by 29.04%. This suggests the possibility of reduced charge periods with smaller water losses in the end.

⁶ here taken from the free electrolyte beside the electrodes

A homogenous acid density distribution is essential for a homogenous and efficient utilization of active masses. The simulation suggests that stratification can be hindered by a high voltage charge. It is now possible to evaluate the cost of water loss and surplus energy against the increase in cycle life. Besides, the influence of pulses within the charge period with no voltage limitation can be investigated. In UPS, where a voltage limit per cell is given through the system configuration, charges of smaller units in one string can have beneficial effects. The split allows an iterative charge of smaller cell blocks at higher voltages and thus, increases the chance to equalize cells in one string.

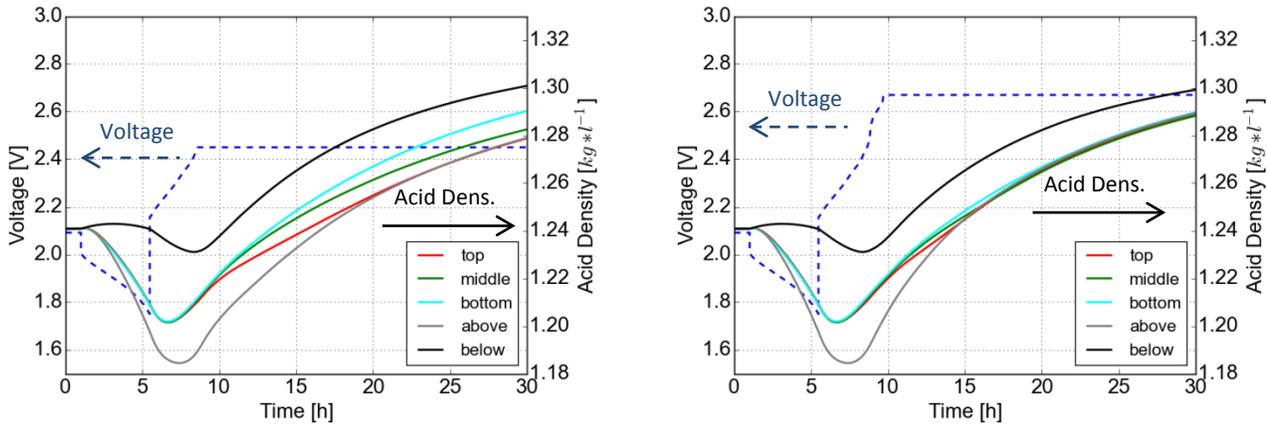


Figure 7. Acid density distribution in vertical direction over time for CC-CV charge with 2.45 V (case 1, left) and 2.67 V (case 2, right) limit. “Below” and “above” are the values for the free electrolyte below and above the electrodes. “Top”, “middle” and “bottom” describe the mean values for each third of the electrode height.

Conclusion

OPzS and OPzV test cells with 25 Ah (C_{10}) rated capacity have been built. With these cells, laboratory experiments were conducted to investigate the influence of intervals between full charges and ambient temperature on the lifetime of a lead-acid cell. The analysis suggests a drastically decreased cycle life for cells with more full capacity turn-overs between full charges. This effect is increased with smaller current rates during the cycle process. This finding was underlined by the simulation of cycle profiles. The result showed a decreased mean charge rate especially for the negative electrode. If the cell was cycled with longer intervals the charge degree could not be restored to 100% in 24 hour charge periods. Therefore, good management systems for BESS should include an algorithm for optimum charge intervals depending on time and capacity turnovers. Best effects can be achieved if two or more parallel strings are available and if strings are split into cell blocks. This allows full charges of one battery string while the parallel ones deliver the required services.

The simulation confirms that higher charging voltages do lead to an increased water loss in the same charging duration (in the chosen case 2.25 times higher with 220 mV increase) but shows also the positive influence on the acid stratification for the given cell geometry. The electrolyte mixing hinders a vertical acid gradient built up in the constant voltage phase. One result is a better charge degree of the electrodes in vertical direction compared to the cell with acid stratification after a recharge of equal capacity. Furthermore, the higher charge voltage leads to a reduction in charge time of 29.04% for the negative electrode which was prone to deep discharge.

Overall, the possibilities of the 3D model for a deeper analysis of different conditions and their effect on cell performance are illustrated. The model can be used to analyze the right timing for charge steps to consequently avoid deep discharges of parts of the electrodes, which cannot be restored during operation.

In a next step of the model development, further validation tests will be simulated and correlated with the laboratory test. The goal is an economic sensitivity analysis that allows decision making on the basis of cycle cost versus revenue per cycle. The model will further be extended to represent the side reaction of corrosion and to include the gas recombination process at the negative electrode especially for sealed lead acid batteries.

Acknowledgement

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