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Charge strategies for valve-regulated lead/acid batteries in solar power applications

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Abstract

In order to investigate the behaviour of valve-regulated lead/acid batteries in solar power applications, gel and AGM batteries were installed in different solar power systems. Each system is divided into several groups and each group has the same battery type, the same loading and the same solar generator. The only difference is the charge/discharge strategy. A key result after 2 years of testing is that the charge strategies which are typically used today in the field cannot charge the batteries completely. However, if the batteries were charged intensively afterwards they returned to full capacity. This means that there is a problem of undercharging in the field. Improving the charge/discharge strategy can, therefore, extend the service life and the energy turnover of VRLA batteries in solar power applications. Moreover, some existing VRLA battery types were modified with regard to the amount of electrolyte and phosphoric acid. These versions were investigated in the laboratory and are included in the field tests.

Keywords: Lead/acid batteries; Solar power; VRLA batteries; Charge/discharge

1. Introduction

Over the last decades the market for solar photovoltaic energy systems has increased steadily [1] and it is expected that it will continue to grow significantly. Often, for such an application a storage system is needed and in most cases it is a lead/acid battery. In the past in many cases flooded batteries were used, however, there has been a clear tendency to replace this type by the valve-regulated design. Actually, nowadays, a significant portion of all solar energy systems have already a valve-regulated battery [2–4].

This design has many advantages. Topping up with water is not necessary over the whole life of the battery and, therefore, frequently the term "maintenance-free" is used. Moreover, there is no risk of acid spillage and this has made it possible to use lead/acid batteries for new applications where a standard battery with flooded cells cannot be used because a "clean" battery is needed. Sometimes, the term "sealed" is also used, however, it has to be taken into account that this can give rise to some misunderstanding. This name ignores the fact that there is always some hydrogen produced at the negative electrode (although, usually, at a very low rate). This hydrogen leaves the battery either through the container walls or during opening periods of the pressure-release valve, which opens for a short time when the pressure inside the battery becomes too high.

A low level of both, self discharge and gassing rate in comparison to the flooded design are further advantages of valve regulated batteries. With regard to the solar power application the better tolerance to deep discharge is also an important point.

Solar batteries of the flooded type can suffer from the well known problem of acid stratification. A way to overcome this problem is either to overcharge the batteries significantly, resulting in a marked gassing that can re-mix up the electrolyte, or by using an electrolyte agitation system [5].

Many studies on valve-regulated batteries have been published in recent years; some examples are given as [6–20]. There are two types of valve-regulated batteries, the gel and the absorptive glass-mat (AGM) design. Both technologies have many similarities, but there are also some differences. For example, it is well known that for tall cells only gel can be used, otherwise acid stratification cannot be avoided. For short cells, however, both gel and AGM design can be used. In practice, it has turned out that a properly designed AGM battery with relatively short plates can also avoid any significant acid stratification [14,18,21]. There is no problem with acid stratification in case of all gel batteries even if rather tall plates are used. This is another advantage in comparison with the flooded batteries.

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Growing markets for VRLA batteries include UPS, telecommunication systems, consumer batteries and various traction duties. For all these applications special charge strategies were developed and tested. It has turned out that the use of an optimized charge regime can significantly extend the service life of VRLA batteries [14,21–27]. However, it seems that such charge strategies cannot be directly transferred to solar energy system application and the fact that this has been done frequently in the past could be one of the most important reasons that VRLA batteries rather often had a shorter service life than expected.

Actually, there is a lack of knowledge about the best way to charge VRLA batteries in solar energy systems as well as about the complete charge/discharge strategy. This is the background of our project which has the objective to investigate the current strategies and then to improve them with regard to the battery life and the achievable energy turnover. Most of the tests are performed in the field in order to be as close as possible to the actual application. However, it is completed by some laboratory tests with well defined parameters and conditions.

The investigation started in spring 1998, when the batteries were installed in the field and the study will be finished in autumn 2001. This paper gives a description of the different systems in the field and first results after about 2 years of service. The investigation includes the study of different charge/discharge strategies for systems with and without a back up system. Probably more than one strategy is needed in order to cover the complete range of solar power application where different battery types are used with and without a back up system [28].

2. Work program

For all investigations VRLA batteries are used of both the AGM and the Gel type. This includes 6 or 12 V monoblocks with flat positive plates of the gel and AGM design as well as 2 V gel cells with positive tubular plates. The batteries were installed at four different places in Germany.

2.1. Talhof

At Talhof there is a PV hybrid system with a 1.8 kWp PV generator, a gas engine with generator and a 48 V gel battery of 300 A $h_{10\ h}$. The system is divided into four parts, each as a 12 V unit with a 12 V battery, a 450 W_P solar generator, a charge controller and a rectifier for the gas engine. A schematic of the complete system is given in Fig. 1. Each of the 12 V units consists of six gel cells with tubular plates. The capacity is 360 A h at the 100 h rate and 300 A h at the 10 h rate. All cells are connected in series, this means the complete 48 V battery is one string so that for all cells the discharge load is the same. However, the four part systems can be charged individually both from the solar generator/ charge controller as well as from the gas engine/rectifier.

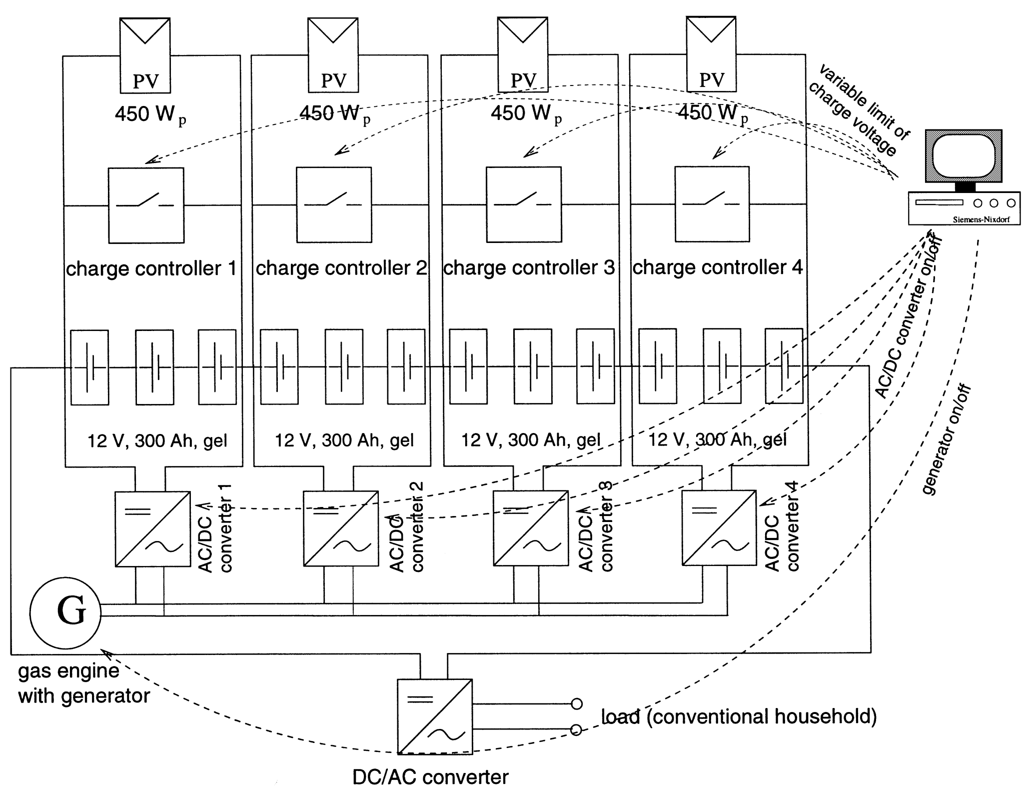

Fig. 1. Schematic of the solar power system with a 48 V 300 A $h_{10\ h}$ battery of the gel design with tubular plates and four partial systems with a back up system in Talhof.

Table 1
Differences in the charge/discharge strategy of the solar hybrid system at Talhof

	System 1	System 2	System 3	System 4
Battery type	Gel tubular	Gel tubular	Gel tubular	Gel tubular
Max. DOD (%)	70	70	70	90
Max. charge voltage (V/cell)	2.35 (no time limit)	2.45 max. 2 h per day, then 2.35	2.30–2.45 depends on DOD	2.35 (no time limit)
Duration at maximum voltage until "solar full charge" is assumed	5 h	2 h	Depends on voltage	5 h

The charge controllers, the rectifiers and the gas engine are controlled by a computer. This computer is also used for the measurement and storage of all relevant data. This includes the individual cell voltage and all currents flowing into or out of the battery, the solar generator, the gas engine and the load.

For the four part systems there are four different charge strategies. This means mainly the use of a different limitation of the charge voltage. The voltage limitation is between 2.30 and 2.45 V per cell. The max. DOD is in three part systems 70% and in one part system 90%. The different charge/discharge strategies are given in Table 1.

At least every 30 days there is a "solar full charge" of the battery according to the parameters given in Table 1 either by normal operation of the PV generator or by an extra operation of the gas generator. After such a "solar full charge" the recharge charging unit is stopped and the DOD calculation (based on an A h balance) is set to 0%.

2.2. Solarhaus Freiburg

At Freiburg there is also a PV hybrid system which is similar to that of Talhof. Instead of a gas generator it is connected to the electricity grid which is used as the back up system. A 192 V VRLA battery with flat positive plate design is used. Similar to Talhof, the system is divided into four parts, each as a 48 V unit with a 48 V battery, a 1000 W_P solar generator, a charge controller and a rectifier for the back up by the electricity grid. Fig. 2 shows a schematic of the complete system. A total of three of the 48 V units consists of gel monoblocks each of 12 V and 155 A $h_{10\ h}$, whereas the fourth 48 V unit has AGM monoblocks each of 6 V and 144 A $h_{10\ h}$. The

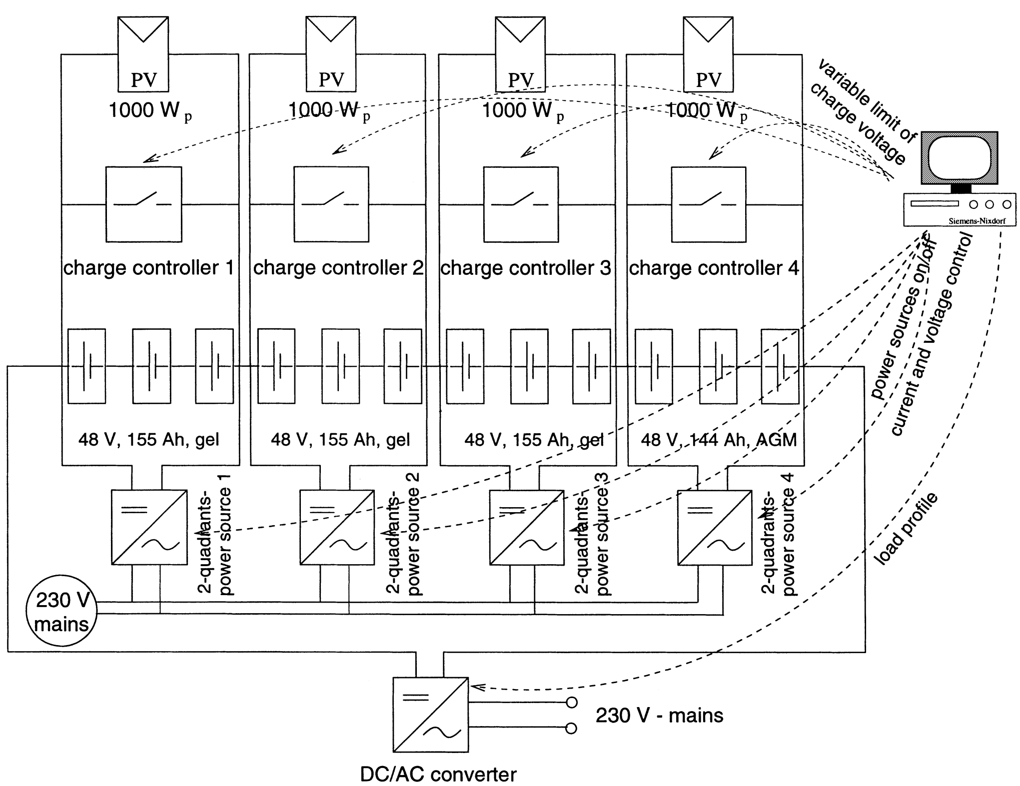

Fig. 2. Schematic of the solar power system with a 192 V 155 A $h_{10\ h}$ battery with flat positive plates and four partial systems (three with the gel design and one with the AGM design) with a back up system in Solarhaus Freiburg.

Table 2
Differences in the charge/discharge strategy of the solar hybrid system at Solarhaus Freiburg

	System 1	System 2	System 3	System 4
Battery type	Gel flat plate	Gel flat plate	Gel flat plate	AGM flat plate
Max. DOD (%)	70	70	70	70
Max. charge voltage (V/cell)	2.35 (no time limit)	2.45 max. 2 h per day, then 2.35	2.30–2.45 depends on DOD	2.35 (no time limit)
Duration at maximum voltage until "solar full charge" is assumed	5 h	2 h	Depends on voltage	5 h

capacity of the gel monoblocks is 185 A h at the 100 h rate and 155 A h at the 10 h rate. In case of the AGM design the capacity is slightly lower, 170 A h at the 100 h rate and 144 A h at the 10 h rate. All monoblocks, this means the complete 192 V battery, are in one string so that for all cells the discharge load is the same.

As well as at Talhof the four part systems can be charged individually both from the solar generator/charge controller as well as from the electricity grid/rectifier. There is the same computer control system as at Talhof. There are four different charge strategies where limitation of the charge voltage is between 2.30 and 2.45 V per cell as it can be seen in Table 2.

At least every 30 days there is a "solar full charge" of the battery according to the parameters given in Table 2 either by normal operation of the PV generator or by an extra operation of the charging unit. After such a "solar full charge" the recharge is stopped and the DOD calculation (based on an Ampere-hour balance) is set to 0%.

2.3. Small systems

These systems are significantly different from those at Talhof and Freiburg. There is no back up and the batteries are rather small. Whereas the load at Talhof and Freiburg can vary strongly and depends mainly on the decision of the people living in this house, the load is rather constant for the small system. There are in total 16 individual systems each with a 100 W_P solar generator, a charge controller, a light as a 7 W load and a 24 V VRLA battery. A total of eight systems have a gel battery with a capacity of 41 A h at the 100 h rate and 34 A h at the 10 h rate and the other eight systems have an AGM battery with a capacity of 44 A h at the 100 h rate and 39 A h at the 10 h rate. All batteries consists of 12 V monoblocks of the flat positive plate design.

Four of the part systems are shown in Fig. 3. The computer controls the charging and disconnects the load when the voltages becomes too low. Additionally the monoblock voltage as well as all currents are measured and stored

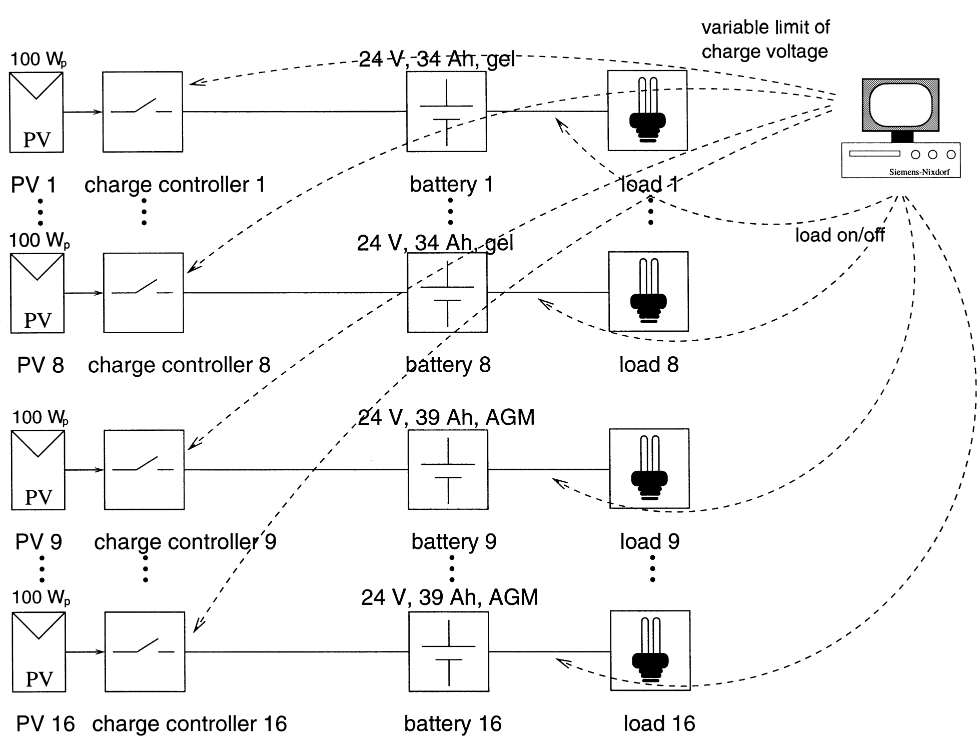

Fig. 3. Schematic of four of in total 16 small solar power systems, each with a 24 V battery with flat positive plates. Total eight partial systems have the gel design (34 A $h_{10\ h}$) and eight partial systems have the AGM design (39 A $h_{10\ h}$).

Table 3
Differences in the charge/discharge strategy of the small systems

Operating strategy	1	2	3	4
Number of test systems	4	4	4	4
Battery type	Gel/AGM flat plate	Gel/AGM flat plate	Gel/AGM flat plate	Gel/AGM flat plate
Max. DOD (%) (detected by voltage)	~70	~70	~50	~70
Max. charge voltage (V/cell)	2.35	2.40 max. 2 h per day then 2.30	2.40 max. 2 h per day then 2.30	2.40 max. 2 h per day then 2.35
Max. charge voltage after load disconnect (24 h, accumulated)	2.35	2.45	2.45	2.45
Duration at maximum voltage until "solar full charge" is assumed	5 h	2 h	2 h	2 h

by this computer. The different charge/discharge strategies are shown in Table 3.

After about 1.5 years the monoblocks from four selected systems with different operating strategies have been completely replaced by a modified gel version.

2.4. *Rotwandhaus*

This is again a hybrid system which includes both, a solar generator and a wind generator. There is also a diesel engine for the back up. A 162 V gel battery is used with tubular plate design and a capacity of 720 A h at the 100 h rate and 600 A h at the 10 h rate. A schematic of the complete system is given in Fig. 4. There are two strings in parallel, each of 300 A $h_{10\ h}$ and the same 2 V cell type is used as for the Talhof system. This time there is just one charge strategy and the only difference between both strings is the use of a CHargeEQualizer in one string. The development of CHargeEQualizers was started in 1992 at Fraunhofer ISE. It can transport some energy from cells having a high voltage to cells having a low voltage during both charge and discharge periods. This results then in virtually the same voltage for all cells or cell groups in a string. More details about the CHargeEQualizer system can be found in the literature [29,30]. The CHargeEQualizer has been included to this investigation program in order to find out whether such a system can give a higher energy turnover and a longer battery life. The charge strategy includes a voltage limit of 2.35 V per cell and the DOD is restricted to 80%. As this charge/discharge strategy is the same for both strings any difference in performance of the string can directly be related to the use of the CHargeEQualizer. All important parameters are controlled, measured and stored by a computer system.

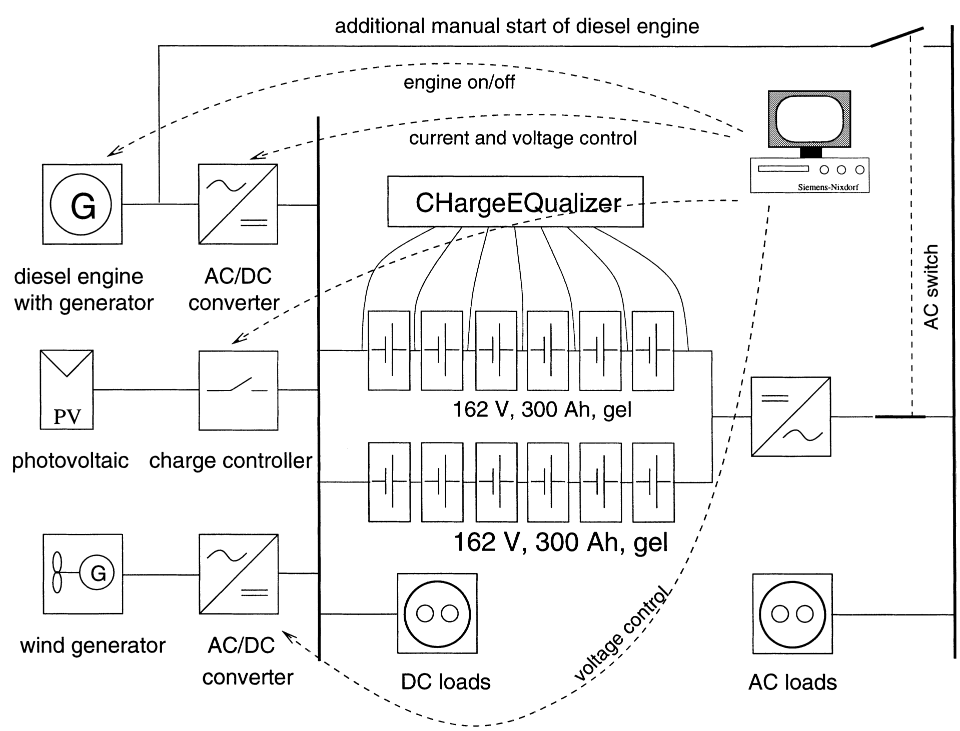

Fig. 4. Schematic of the solar power system with a 162 V 600 A $h_{10\ h}$ battery of the gel design with tubular plates at the Rotwandhaus in the Alps. There are two strings, one is equipped with a CHargeEQualizer and the other is not.

2.5. Summary of the work program

Our investigation includes PV-battery and PV-hybrid systems with daily loads between 150 W h and more than 25 kW h. There is a measurement of all cell and block voltages, as well as of the current in and out of the battery and of many other parameters. In total there are 26 groups with more than 200 cells and monoblocks which are continuously measured over a time period of 3.5 years.

2.6. Capacity tests

Every half a year the capacity of the batteries are tested by one discharge after a typical "solar charge" regime followed by a second discharge after a rather intensive charge regime. This means that before the first discharge occurs there is a charge according to the criteria given in the tables above. The intensive charge before the second discharge is an IUI_a charge where at the final stage the battery voltage is significantly higher than during normal operation. The charge is terminated when 112% of the nominal capacity (or of the previous discharged capacity, if it is higher than the nominal capacity) has been recharged. The exact charge program for the IUI_a charge is: $I = I_{10}$, $U = 2.35$ V/cell, $I_a = 0.08\times I_{10}$, 112% of nominal or actual capacity.

Afterwards the battery is charged again with the solar typical charge regime and can be used again in the solar power system.

The aim of this time-consuming procedure is to show the difference between the available capacity for the user (first discharge) and the state of health of the battery (second discharge). The differences are very important with respect to the available capacity of the system on one hand and with respect to guarantee periods given by the battery manufacturer on the other hand. As the results have shown, differences of up to 20% between the first discharge and the second discharge occur.

This has also implication on the definition of the state of charge and the full state of charge. According to the definitions given in [31] the "solar charge" regime gives the "practical full state of charge" $FULL_p$ and the corresponding state of charge is the "practical state of charge" (SOC_p). These definitions take into account, that the user of the system has no access to the complete capacity of the battery because the charging conditions in PV system do not allow a complete recharge of the battery. The second charge regime with the "112% charge" gives a "full state of charge" FULL and this corresponds to the "relative state of charge" SOC_r. This is the capacity which is defined on the basis of the actual state of health of the battery. But as mentioned above, this does not correspond to the available capacity for the user. With respect to the definitions of maximum values for the depth of discharge during operation or state-of-charge displays it is very important to define, which definitions are used for the state of charge and for the full state of charge. A complete list with definitions on state of charge

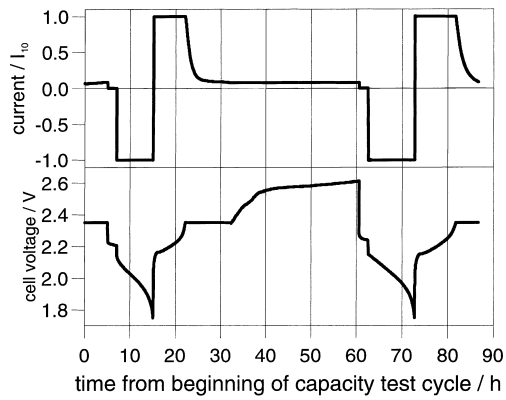

Fig. 5. Typical current and voltage profile during the capacity test cycle with a "solar" charge, a I_{10} discharge, a 112% IUIa charge ("intensive" charge) and a second I_{10} discharge. This test profile is used in all field tests performed within this project.

and related parameters under various operating conditions is given in [31].

Fig. 5 shows a typical current and voltage profile of the capacity test cycles with the "solar" IU charge (duration of I charging depends on state of charge of the battery at the beginning of the test), a first discharge (10 h rate), a IUI_a recharge to 112% of the previous discharged capacity or the nominal capacity (called the "intensive" charge), a second 10 h rate discharge and an IU recharge to bring the battery into operation once again.

As a consequence of the capacity tests the batteries get twice a year an intensive recharge. This intensive charge is not available in the field with todays technology of PV systems. It is difficult to predict the influence on the overall lifetime of the batteries in the field tests within this project. Investigations into this questions are planned during the next year.

3. First results and discussion

3.1. Talhof

Fig. 6 gives, as an example, the discharge curves of all cells of the part system 1 after an intensive IUI_a charge as described above. The test was performed after 2 years of service. All cells have a capacity of more than 100%. The development of the capacity before and after an intensive charging over a time period of 2 years from the beginning is given in Fig. 7 (left graph), again for the part system 1. It can be seen that there is all the time a lower capacity before the intensive charge and that this difference is significantly larger in spring after the winter period. On the other hand, in autumn the difference is much smaller probably due to less undercharging during summer time when there is much more sun shine. Obviously, there was some undercharging during the normal solar application and a typical solar charge could not recharge all sulfation which had been

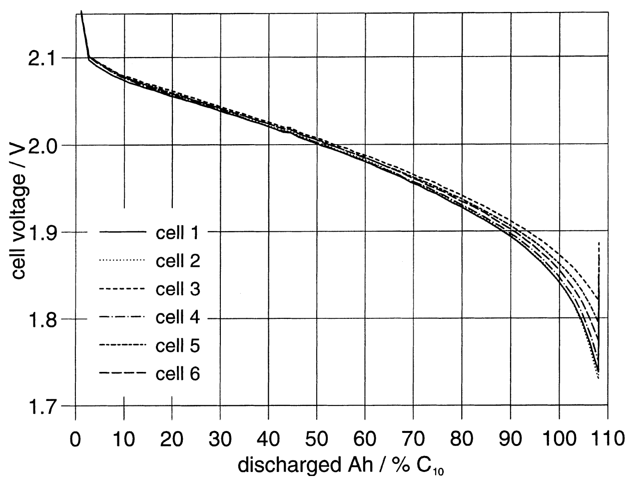

Fig. 6. Discharge curves at 10 h rate of system 1 at Talhof after 2 years service with tubular plate gel cells after an intensive charge.

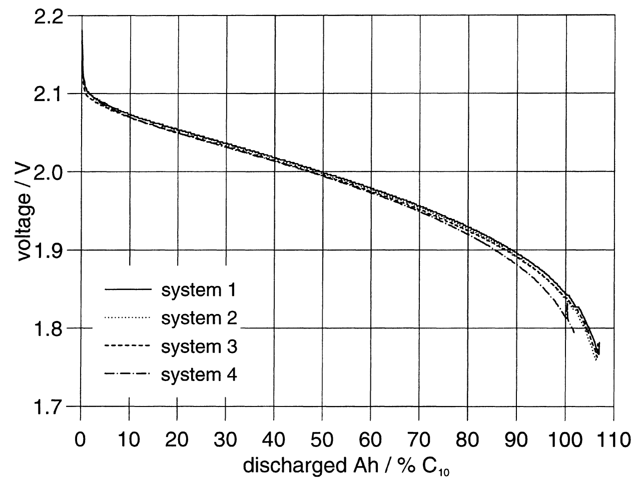

Fig. 8. Influence of the different charge regimes on the tubular gel cells in Talhof after 2 years service. The curves represent the average cell voltage during discharge with the 10 h rate after an intensive charge.

accumulated in the plates. This means that the solar typical charge did not recharge the gel cells completely and that a relatively high voltage over a special period of time is necessary to recover the battery and to bring them back to full capacity. There is not much deviation of the individual cell voltage both before and after the intensive charge. This shows that all cells suffered similarly from the same amount of undercharging. The behaviour of the part system 1 shown in the Figs. 6 and 7 is typical for all four part systems.

There is always some undercharging especially during the winter period and even the relatively high voltage limit of part system 2 could not avoid this problem completely. It is interesting that the cells of part system 4, where a markedly higher DOD was accepted (90% in comparison to 70% of the other systems) had a relatively high capacity before an intensive charge after the first winter time period (Fig. 7, right graph). This would mean that in the battery with a sometimes rather low DOD the undercharging was lower than that of the other systems. However, after an intensive charge this difference disappeared.

The influence of the different charge regimes on the tubular gel cells at Talhof can be seen in Fig. 8. So far there is not much difference with regard to the capacities after an intensive recharge. Even the relatively high voltage limit of 2.45 V per cell cannot avoid some undercharging. However, it is a reversible effect and the capacity can be recovered by an extra charge with higher voltage. It is also obvious, that the relative high voltage of 2.45 V applied for a controlled time period per day does not harm the batteries at all.

3.2. Solarhaus Freiburg

The behaviour of the flat positive plate batteries at the solar power system in Freiburg is quite similar to that of the tubular plate batteries at Talhof. However, the difference in the capacities after the "solar charge" and the intensive charge is significantly less than at Talhof. This deviation in the charge characteristics might be due to the different electrode technologies (tubular at Talhof and flat plate at

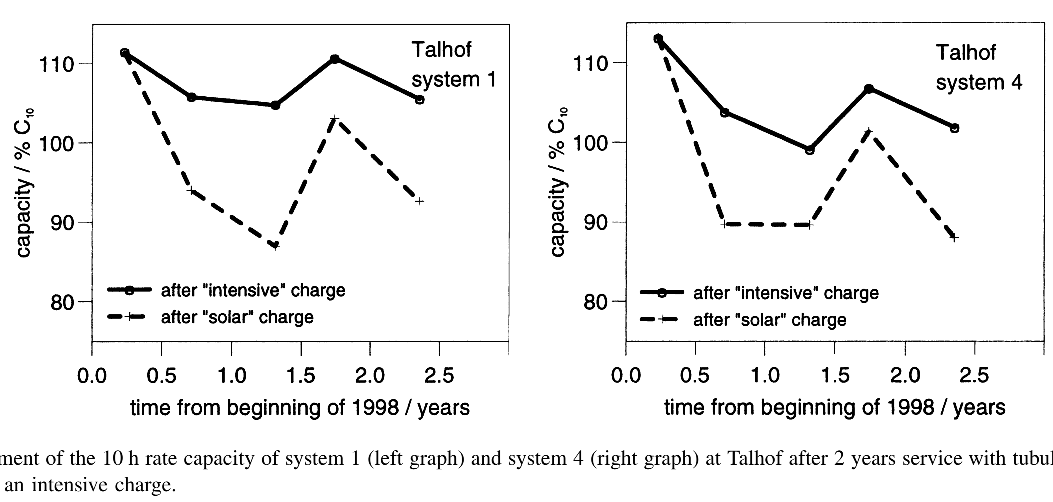

Fig. 7. Development of the 10 h rate capacity of system 1 (left graph) and system 4 (right graph) at Talhof after 2 years service with tubular plate gel cells before and after an intensive charge.

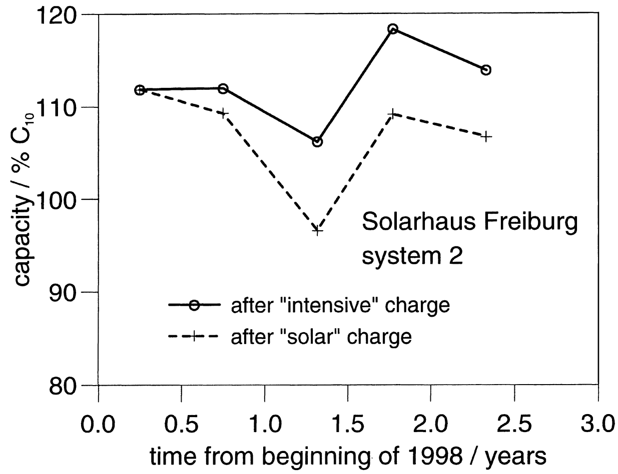

Fig. 9. Development of the 10 h rate capacity of system 2 at Solarhaus Freiburg after 2 years service with flat plate gel batteries before and after an intensive charge.

Solarhaus Freiburg). Fig. 9 shows the capacities after 2 years of service for the system 2 at the Solarhaus Freiburg.

The deviation of the capacities of the individual gel monoblocks is quite low whereas there is markedly more deviation of the AGM monoblocks.

In the last stage of charge the voltage of the individual monoblocks varies significantly, a phenomenon which is well known from other application especially in the early stage of the battery life. It can be explained by some differences in the recombination behaviour of VRLA batteries and contrary to flooded cells it does not mean that there is a failure of the battery. Fig. 10 shows the voltage dispersion at the end of charge of one of the 48 V part system in Freiburg with 6 V monoblocks of the AGM design. Some of the monoblocks had a relatively early increase of the charge voltage returning to lower values later, whereas other monoblocks had the voltage increase much later. This different behaviour during charging does not influence the

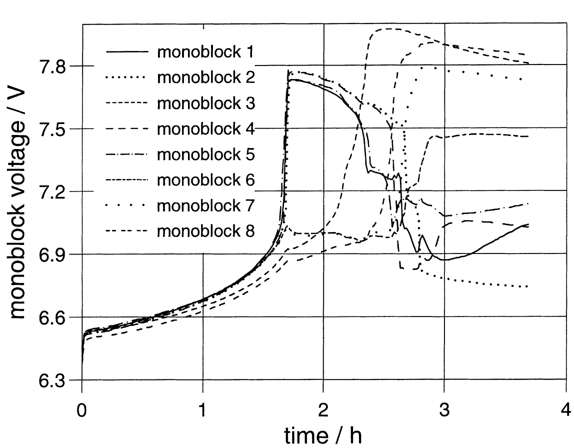

Fig. 10. Voltage dispersion at the end of charge of system 4 at Solarhaus Freiburg with 6 V monoblocks of the AGM design.

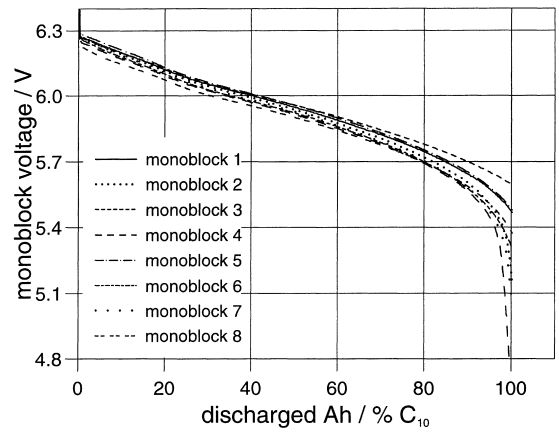

Fig. 11. Discharge with the 10 h rate of the same 8 AGM blocks after the charge as shown in Fig. 10.

capacity of the cells as it can be seen by the next 10 h rate discharge of the same eight AGM blocks in Fig. 11.

The different charge regimes on the flat positive gel batteries in Freiburg are compared in Fig. 12. So far there is no large difference with regard to the capacities after an intensive recharge but the capacity of the system with the highest charging voltage (2.45 V/cell in system 2) is significantly higher than those of the other systems. All used charge regimes cannot avoid completely some undercharging and again it is a reversible effect and the capacity can be recovered by an extra charge with higher voltage.

3.3. Small systems

For the gel batteries the differences between a solar typical recharge and an intensive recharge are even higher in case of the small systems. The difference is between 10

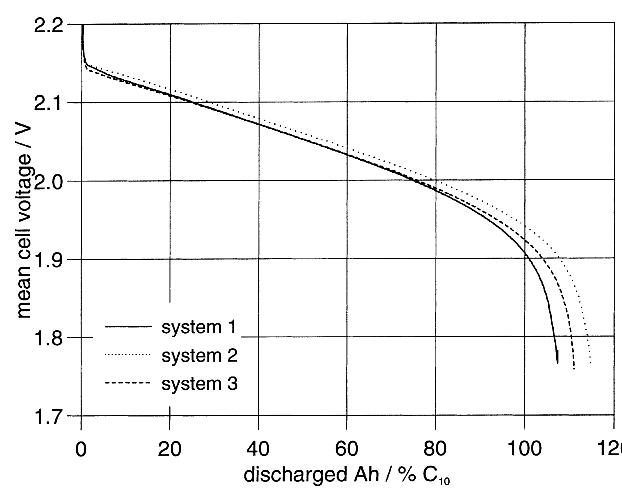

Fig. 12. Influence of the different charge regimes on the flat positive gel batteries in Solarhaus Freiburg after 2 years service. The curves represent the average cell voltage during discharge with the 10 h rate after an intensive charge.

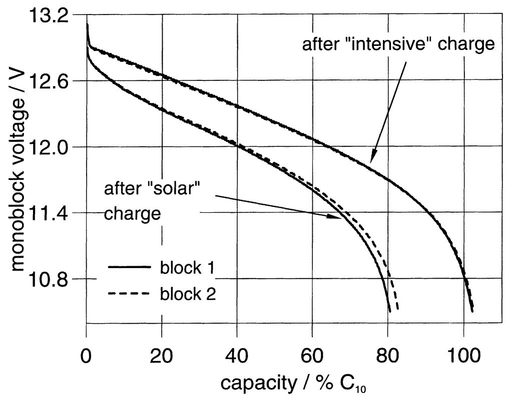

Fig. 13. Discharge curves at 10 h rate of two 12 V gel monoblocks of the small system 1 after 1 year service before and after an intensive charge.

and 20%. A typical example is given by Fig. 13. There are the discharge curves at 10 h rate of the two 12 V gel monoblocks in one of the small solar power systems with charge regime 2 after 1 year service before and after an intensive charge. It can be seen that after the solar typical recharge the capacity is only about 80% whereas the intensive recharge gives again more than 100%. The result with the other small systems is similar. There is always a differences of up to 20%, which shows that the small systems suffers even more from the undercharging under normal solar typical charge regimes.

The deviation of the capacity of the individual gel monoblocks is quite low whereas there is markedly more deviation of the AGM monoblocks. On the other hand, for AGM the difference between the capacity before and after intensive charge is less in comparison with the gel batteries. This could be explained by a better charge acceptance of the AGM batteries when the same charge regime is used. It means that probably gel and AGM design need different charge strategies in solar power application to avoid undercharging.

The influence of the different charge regimes on the flat positive gel batteries in the small solar power systems is shown in Fig. 14. It can be seen that there is not much difference between the different charge regimes after an intensive charge. Fig. 14 shows that the lowest capacity is available in system 3. System 3 has a similar charging strategy as system 2 but has a lower maximum DOD (approximately 50% instead of 70%). Considering the results given in Figs. 13 and 14 there is the same interpretation and conclusion as for the systems at Talhof and Solarhaus Freiburg.

It is necessary to mention, that at the small systems the maximum voltage is reached almost every day between April and October, whereas in the hybrid systems the maximum voltage is reached much less frequently even during the summer.

The weight of the monoblocks from these systems was measured at the capacity tests. The weight loss is very low until now.

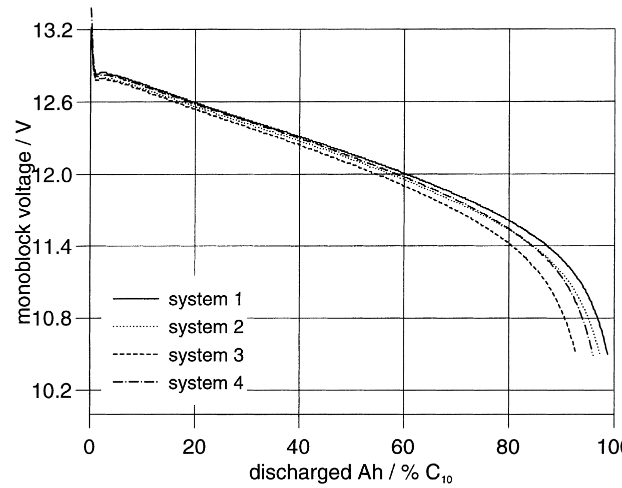

Fig. 14. Influence of the different charge regimes on the flat positive gel batteries in the small solar power systems after 2 years service. The curves represent the average monoblock voltage during discharge with the 10 h rate after an intensive charge.

3.4. *Rotwandhaus*

The battery at the Rotwandhaus was later installed than the other systems. Here it is especially interesting to see whether there is any advantage by the use of a CHargeEQualizer. Up to now there is virtually no difference between both strings. Both strings show capacities significantly above the nominal capacity.

3.5. *Revision of the charge regimes as a consequence of the current results*

In order to reduce the undercharging of the batteries the charge regime was changed at selected systems in Solarhaus Freiburg, Talhof and the small systems. In some cases the voltage limits and in other cases the maximum duration per day at the maximum voltage was increased. The ongoing experiments will show the impact of these measures.

4. Battery development

Two of the existing gel battery types, one with positive flat plates and one with tubular plates, were modified with regard to the amount of electrolyte and to the amount of phosphoric acid. The ratio of electrolyte/active mass was increased by extending the plate distance resulting in a thicker plate group and by using a larger container. The amount of phosphoric acid was varied between no addition and the value normally used for hard cycling application.

In case of the flat plate design the plate distance was increased by 1 mm giving a 30% higher amount of electrolyte and for the tubular plate design the distance increase was 1.5 mm resulting in 15% more electrolyte volume.

4.1. Positive flat plate design

The different variants are

- Standard electrolyte volume without phosphoric acid.
- Standard electrolyte volume with phosphoric acid.
- A total of 30% more electrolyte volume without phosphoric acid.
- A total of 30% more electrolyte volume with phosphoric acid.

A cycle test is running with all variants by using a discharge current of 6.1 A over a time period of 4 h. Every 10th cycle there is a complete discharge with 6.1 A and a cut-off voltage of 1.70 V per cell. The charge regime is IU with $I = 5$ A and $U = 2.40$ V per cell, the total charge time is 16 h.

Fig. 15 gives the result of the complete discharges up to 300 cycles which is the current status of this test. It can be seen that the use of phosphoric acid gave a lower initial capacity. However, the capacity of these cells was rather stable with even a small increase during cycling. The batteries without phosphoric acid already lost some capacity and, therefore, after about 100 cycles the batteries with phosphoric acid were already on a higher capacity level than the batteries without phosphoric acid. This is valid for both, the standard and the 30% higher electrolyte volume, but there is a more significant difference in case of the standard electrolyte volume.

As expected, the capacity was markedly higher by the use of more electrolyte volume. Both, the behaviour of the batteries with and without phosphoric acid as well as the influence of electrolyte volume on the capacity are known in principle and the result of this test confirms what already was found in the past. However, the influence of the electrolyte volume on cycle life has not been completely clear and this is the main reason for this part of the investigation. In the mean time in parallel these variants were also included in the field test to see any difference under real photovoltaic conditions.

The charging behaviour of the batteries is an important parameter for photovoltaic applications. Therefore, the charge acceptance has been included to the laboratory investigation. The charging time with a constant current of 5 A before reaching the voltage limit of 2.40 V per cell is given by Fig. 16. The discharge just before the charge was 6.1 A over 4 h and the same for all battery variants. There is a significant difference between the batteries with and without phosphoric acid but virtually no influence of the electrolyte volume. The charge/discharge factor before reaching 2.40 V per cell was about 84% without phosphoric acid and about 91% with phosphoric acid. There is a slight tendency to lower values without phosphoric acid and to higher values with phosphoric acid during cycling.

The variant with 30% more electrolyte volume and with phosphoric acid was included in the field test by exchanging some of the monoblocks of the small systems.

4.2. Tubular plate design

The different variants were

- Standard volume with the standard amount of phosphoric acid.
- Standard volume with 25% of the standard amount of phosphoric acid.
- Standard volume without phosphoric acid.
- Standard volume with phosphoric acid but 0.02 higher specific gravity.
- A total of 15% more electrolyte volume with the standard amount of phosphoric acid.

The cells were discharged with 4.2 A by using a cut-off voltage of 1.85 V per cell. Fig. 17 gives the discharge curves for all five variants. The discharge time was longest for the variant with 15% more electrolyte volume and shortest for the standard volume with phosphoric acid. However, there are also some differences of the voltage level during discharge.

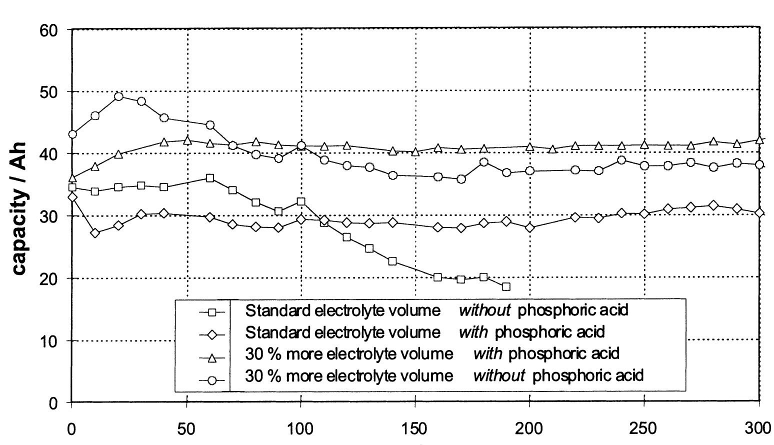

Fig. 15. Cycle test of modified flat plate gel batteries with different amounts of electrolyte and phosphoric acid.

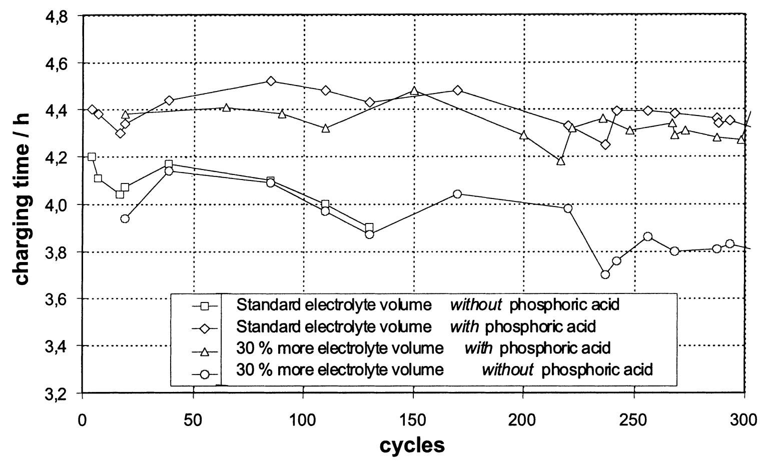

Fig. 16. Charge acceptance of modified flat plate gel batteries with different amounts of electrolyte and phosphoric acid. The curves give the charging time with a constant current of 5 A before reaching the voltage limit of 2.40 V per cell.

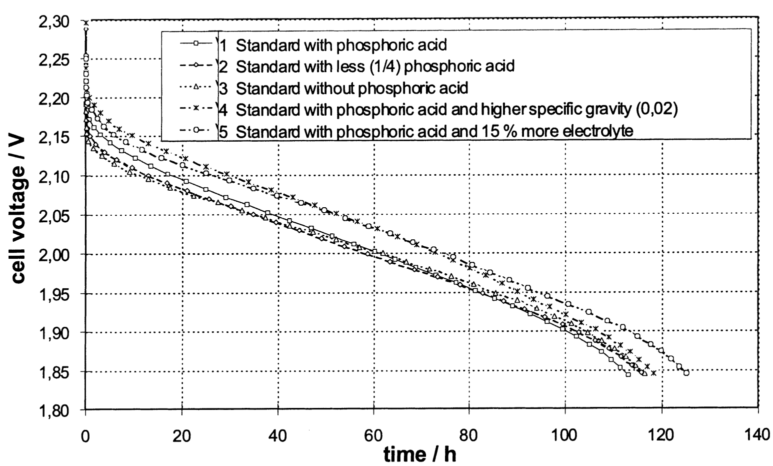

Fig. 17. Discharge curves of modified tubular plate gel cells with different amounts of electrolyte and phosphoric acid.

All the different variants were included in the field test by exchanging some of the cells at the Rotwandhaus.

5. Conclusions

In order to investigate the behaviour of valve-regulated lead/acid batteries in solar power applications, gel (tubular as well as flat plate design) and AGM batteries were installed in different solar power systems. PV-battery and PV-hybrid systems with daily loads between 150 W h and some 25 kW h are used for this test. Each system is divided into several groups and each group has the same battery type, the same loading and the same solar generator. The only difference is the charge/discharge strategy. Overall 26 groups with more than 200 cells or modules are under investigation.

This is the first time that for solar power applications the influence of charge/discharge strategies on the life and performance of VRLA batteries is investigated systematically in the field. After 2 years there are already many differences in the available capacity and deviations in the remaining capacity. Capacity tests after a solar typical charge regime reveals that the batteries could not be charged completely. However, after an intensive charge the batteries returned to full capacity. This means that there is a clear problem of undercharging with charge regimes typical for solar power application. Improved charge strategies are needed to overcome this problem.

References

[1] P.D. Maycock, PV News 19 (3) (March 2000).
[2] R. Wagner, in: J. Garche (Ed.), Elektrochemische Speicher in regenerativen Energiesystemen, Universitätsverlag, Ulm, Germany, 1994.
[3] R. Wagner, J. Power Sources 67 (1997) 163.
[4] R. Wagner, G. Bopp, D.U. Sauer, U. Theimann, in: Proceedings of the 15th Symposium Photovoltaische Solarenergie, Staffelstein, Germany, 2000.
[5] R. Wagner, M. Schroeder, T. Stephanblome, E. Handschin, J. Power Sources 78 (1999) 156.
[6] B.P. Varma, D.P. Boden, The Battery Man (December 1986).

[7] B. Culpin, J.A. Hayman, in: L.J. Pearce (Ed.), Power Sources 11, International Power Sources Symposium Committee, Leatherhead, UK, 1987, p. 45.
[8] C.S.C. Bose, N.A. Hampson, J. Power Sources 19 (1987) 261.
[9] A.M. Harman, J. Power Sources 23 (1988) 127.
[10] H. Tuphorn, J. Power Sources 31 (1990) 57.
[11] R.F. Nelson, J. Power Sources 31 (1990) 3.
[12] D. Berndt, Maintenance-Free Batteries, Research Studies Press, Taunton, Sommerset, UK, 1993.
[13] G. Baudo, in: Proceedings of the 11th International Lead Conference, Venice, Italy, 1993.
[14] R. Wagner, J. Power Sources 53 (1995) 153.
[15] B. Culpin, J. Power Sources 53 (1995) 127.
[16] K. Takahashi, H. Yasuda, H. Hasegawa, S. Horie, K. Kanetsuki, J. Power Sources 53 (1995) 137.
[17] R. Wagner, J. Electrochem. Soc. 143 (1996) 139.
[18] R. Wagner, P. Scharf, in: Proceedings of the 30th International Symposium on Automotive Technology and Automation, Florence, Italy, 1997.
[19] M. Calabek, K. Micka, P. Baca, P. Krivakk, L. Sacha, J. Power Sources 78 (1999) 94.
[20] I. Dreier, F. Saez, P. Scharf, R. Wagner, J. Power Sources 85 (2000) 117.
[21] R. Wagner, W. Bögel, J.-P. Büchel, in: Proceedings of the 29th International Symposium on Automotive Technology and Automation, Florence, Italy, 1996.
[22] U. Hullmeine, A.J.P. Winsel, E. Voss, J. Power Sources 25 (1989) 27.
[23] E. Meissner, E. Voss, J. Power Sources 33 (1991) 231.
[24] E. Meissner, J. Power Sources 46 (1993) 231.
[25] R. Wagner, in: Proceedings of the 11th International Lead Conference, Venice, Italy, 1993.
[26] E. Meissner, J. Power Sources 78 (1999) 99.
[27] F.A. Fleming, P. Shumard, B. Dickinson, J. Power Sources 78 (1999) 237.
[28] D.U. Sauer, M. Bächler, G. Bopp, W. Höhe, J. Mittermeier, P. Sprau, B. Willer, M. Wollny, J. Power Sources 64 (1997) 187–201.
[29] H. Schmidt, C. Siedle, L. Anton, H. Tuphorn, in: Proceedings of the 30th International Symposium on Automotive Technology and Automation, Florence, Italy, 1997.
[30] H. Schmidt, L. Anton, INTELEC 1999, Conference Proceedings, Copenhagen, Denmark, 1999.
[31] D.U. Sauer, G. Bopp, A. Jossen, J. Garche, M. Rothert, M. Wollny, INTELEC 1999, Conference Proceedings, Copenhagen, Denmark, 1999.