Optimization of charging strategies for VRLA batteries in off-grid photovoltaic applications

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Abstract

1 Introduction

Over the last decades the market for off-grid photovoltaic applications has been raised steadily 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 off-grid photovoltaic applications have already a valve-regulated lead acid VRLA battery.

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.

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.

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. In practice, it has turned out that a properly designed AGM battery with relatively short plates and an adopted internal design, like modified absorbed glass-mat can also avoid significant acid stratification [1, 2]. There is no problem with acid stratification in case of all gel batteries even if rather tall plates are used. The reason is that the diffusion coefficient in gel is a little bit higher as in liquid fluid, which means that acid stratification nearly do not occur or rather will be balanced after some days [3, 4]. This is another advantage of gel batteries in comparison with the flooded batteries.

To charge the battery in PV applications a charge controller is used, see fig. 1. It connects the PV module with the battery and the loads. It protects the battery from overcharging and deep discharge. If the system contains a motor generator for backup a separate charger is used.

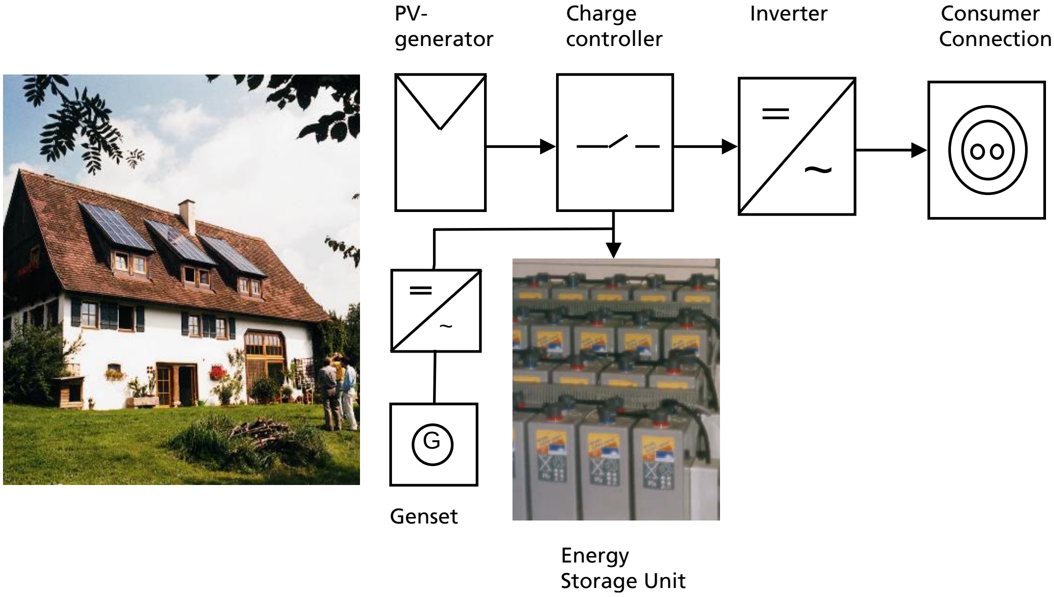

Fig. 1: Picture (Talhof) and schematic of a typical hybrid PV system with AC appliances.

To charge lead acid batteries the following charging regimes are usual, see fig. 2:

a: constant current / constant voltage charge ==> cc-cv
b: constant current / constant voltage charge with two end-of-charge voltage limits ==> cc-cv-cv
c: constant current / constant voltage charge followed by a limited constant current phase ==> cc-cv-cc

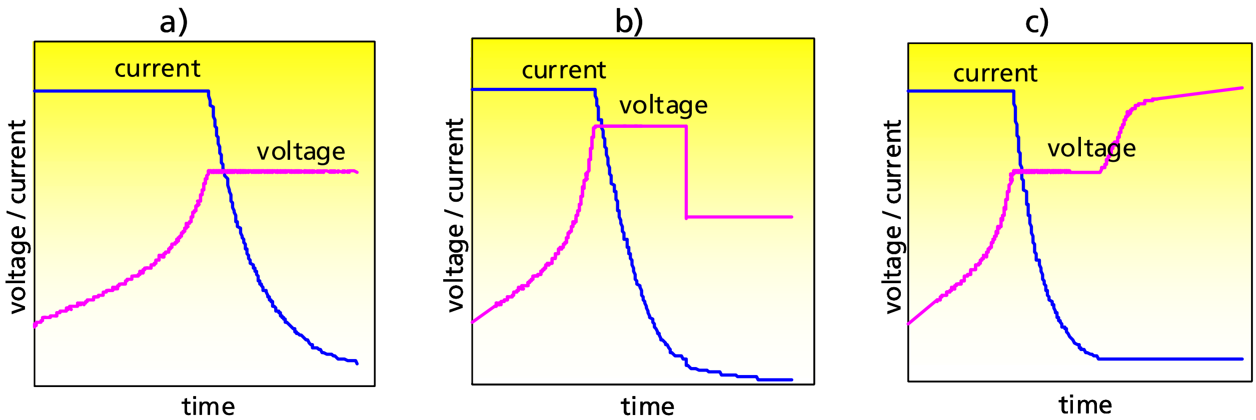

Fig. 2: Different charging regimes for lead acid batteries

In PV applications normally the charging regime a) or b) is used, in the following text called solar charging. Up to now the charging regime c) is used in fork lift applications but not in PV, in the following text called intensive charging.

In the past there was a lack of knowledge about the best way to charge VRLA batteries in PV applications as well as about the complete charge / discharge strategy. This was the background of a combined project between Fraunhofer ISE and Sonnenschein (Part of Exide Technologies) which was funded by the German Federal Ministry of Economics and Technology [5]. The project lasted from 1998 till 2001 and had the objective to investigate the current charging 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 result where different suggestions how to charge VRLA batteries in PV applications [6], see chapter 2 of this paper.

But up to now there was still a gap between the knowledge gained in this project and the charging regimes in existing charge controllers. To close this gap a combined project between Fraunhofer ISE and the charge controller manufacturer Steca GmbH was launched in 2007 by funding of German Federal Ministry of Environment. The aim of this project is to verify the knowledge of the project described above and to implement a suitable charging regime for VRLA batteries into a commercially available charge controller.

2 Field and laboratory investigation on optimum charging strategies for VRLA batteries

2.1 Field investigation

In an extensive field and laboratory test programme between 1997 and 2001 the battery manufacturer Sonnenschein and the Fraunhofer-Institute for Solar Energy Systems ISE analysed and examined different charging strategies for VRLA batteries in PV off-grid applications [6]. The investigation includes the study of different charge / discharge strategies for systems with and without a back-up generator (hybrid system). Tubular plate batteries with gel as well as flat plate batteries with gel and AGM were under investigation. The capacities of the cell / modules ranged between 35 and 300 Ah (C_{10}) and from 12 V to 168 V nominal battery voltages.

2.2 Capacity test to determine the difference between available capacity after solar charging and intensive charging

During normal operation in the field, different end-of-charge and different maximum depth of discharge regimes have been investigated. Every six month the capacity of the batteries in the field has been tested by one discharge after a typical “solar charging” regime followed by a second discharge after a rather intensive charging regime. This means that before the first discharge occurs there is a charge according to what is possible during a sunny day with the PV generator or within acceptable operating periods with a motor generator (“solar charging”), see fig 2b and 3.

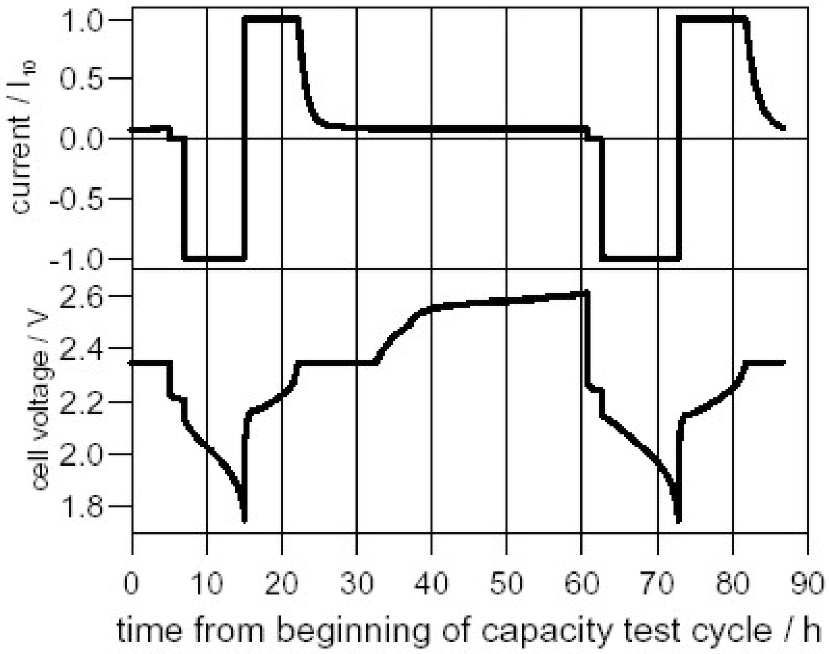

Fig.3: Typical current and voltage profile during the capacity test cycle with a "solar" charging (here 5 hours in the constant voltage charging regime at 2,35 V(cell)), a I_{10} discharge, a 112% cc-cv-cc charge ("intensive" charging) and a second I_{10} discharge.

The intensive charging 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, what ever is higher) has been recharged. The exact charge program for the cc-cv-cc charge is: cc = I_{10}, cv = 2.35 V/cell , cc = 0.08 x I_{10}, together up to a total charge of 112% of nominal or actual capacity, see fig. 3.

The aim of this time consuming procedure is to show the difference between the available capacity for the user (1^{st} discharge) and the state of health of the battery (2^{nd} discharge). The differences are very important with respect to the available capacity of the system on the 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% occurred between the 1^{st} discharge and the 2^{nd} discharge varying with the time of the year and the battery technology used.

2.3 Results from the field tests

Fig. 4 shows the development of the capacity before and after an intensive charging over a time period of two years for a tubular plate gel battery in the PV system Talhof. The results are shown for two different battery systems which were operated with different maximum depth of discharge during normal operation (left hand graph: max. DOD = 70%, right hand graph: max DOD = 90%). It can be seen that there is constantly 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.

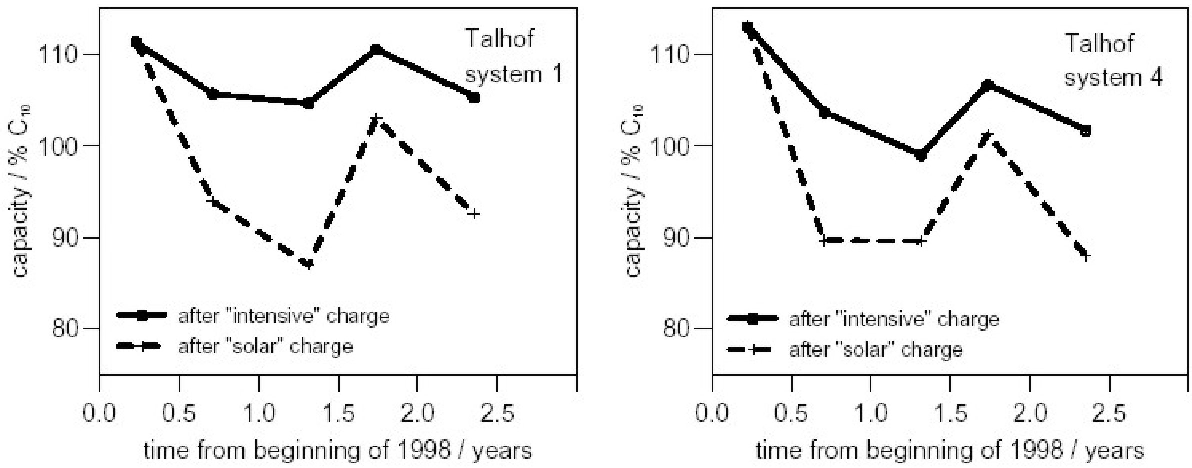

Fig. 4: Development of the ten hours capacity for tubular plate gel cells after two years service with maximum DOD during normal operation of 70% (left hand graph) and 90% (right hand graph) before and after an intensive charging.

Obviously there was some undercharging during the normal solar application and a typical solar charging could not recharge all sulfation which had been accumulated in the plates. This means that the solar typical charging 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 it back to full capacity. It turned out that the charge factors for the batteries, even with a maximum charging voltage of 2.45 V/cell during normal operation, were as low as 1,02 and less on an annual basis. This already includes the two 112% rechargings per year within the capacity tests.

After the end of the project in January 2002 the charge controller was replaced by a specific modified charge controller which has used a continuous intensive charging regime. The exact charge program for the intensive cc-cv-cc charge is: cc = I_{10}, cv = 2.37 V/cell, cc = I_{50} up to 2.6 V/cell. Because of the end of the project the monitoring stops.
In autumn 2008 the end of lifetime of the batteries was reached, because in some cells short circuits occur because of deep discharge. At selected cells capacity tests after solar charging and intensive charging was done. Table 1 shows the comparison of the capacity tests in autumn 2001 and in autumn 2008. It is obvious that the capacity after solar charging in autumn 2008 is about 10 % higher in comparison to autumn 2001 and the capacity gained by intensive charging is only about 2 % in comparison to about 10 %. The reason is the continuous intensive charging after autumn 2001 in comparison to the continuous solar charging before autumn 2001.

This means the continuous intensive charging regime is very good to avoid sulphation and to reach a lifetime of 10.5 years with only approx. 3% water loss.

capacity test	autumn 2001		autumn 2008		
cell	after solar charging [Ah]	gain by intensive charging [%]	after solar charging [Ah]	gain by intensive charging [%]	comment
6	330	11	0	0	dendrites
14	320	13	370	2.2	
13	330	11	370	2.6	
24	350	12	310	1	dendrites

Tab.1 :Capacity tests after different charging regimes. Till autumn 2001 continuous solar charging, afterwards continuous intensive charging

3 New laboratory tests

To validate the results from the field tests concerning the sulphation by the solar charging and the capacity gain (removing of sulphation) by intensive charging additional laboratory tests at 81 VRLA gel type batteries with 6V 1.2 Ah was applied [7].

The following test regime was used:

1. The battery is discharged to 1.8 V/cell (5.4 V) with I_2 (0.6A);
2. The battery is then charged with I_5 (0.24 A) until it reaches 2.4 V/cell (7.2 V);
3. The battery is kept charging with 7.2 V, until the current reaches $0.1I_5$ (0.024A);
4. A relaxation time period of 3 hours is given, for the battery to approach equilibrium and cool down;
5. The battery is then discharged with I_5 (0.24 A) until it reaches 5.4 V;
7. Another relaxation time period of 3 hours is given;
8. The batteries are charged with 0.24 A until pre-defined SOC (10, 30, 50%) levels
9. The batteries are stored at different temperature (20°, 40°, 60° C) levels for different periods (50, 85, 120 days) each group contains three samples. During the storage period no charging or discharging was done.
10. Capacity test (see step 5)
11. Capacity test (see step 5) after solar charging: step 2 and step 3
12. Capacity test (see step 5) after intensive charging: step 2 and step 3 until the current reaches I_{75} (0,014 A) continuing with I_{75} up to a total charge of 120 % of nominal capacity of the battery

Table 2 gives an overview of the different storage conditions of the different battery groups

	20°C			40°C			60°C		
50 days	10 % SOC	30 % SOC	50 % SOC	10 % SOC	30 % SOC	50 % SOC	10 % SOC	30 % SOC	50 % SOC
85 days	10 % SOC	30 % SOC	50 % SOC	10 % SOC	30 % SOC	50 % SOC	10 % SOC	30 % SOC	50 % SOC
120 days	10 % SOC	30 % SOC	50 % SOC	10 % SOC	30 % SOC	50 % SOC	10 % SOC	30 % SOC	50 % SOC

Tab.2: Overview of the different storage conditions of the different battery groups

Fig. 5 shows the capacity loss versus storage time and temperature at 50 % SOC. The capacity loss dependents minimal from the state of charge, especially at 20° C. At higher temperatures and long storage periods of 120 days the capacity loss increase by about 1,5 times if the SOC is 10 % in comparison to a SOC of 50 %.

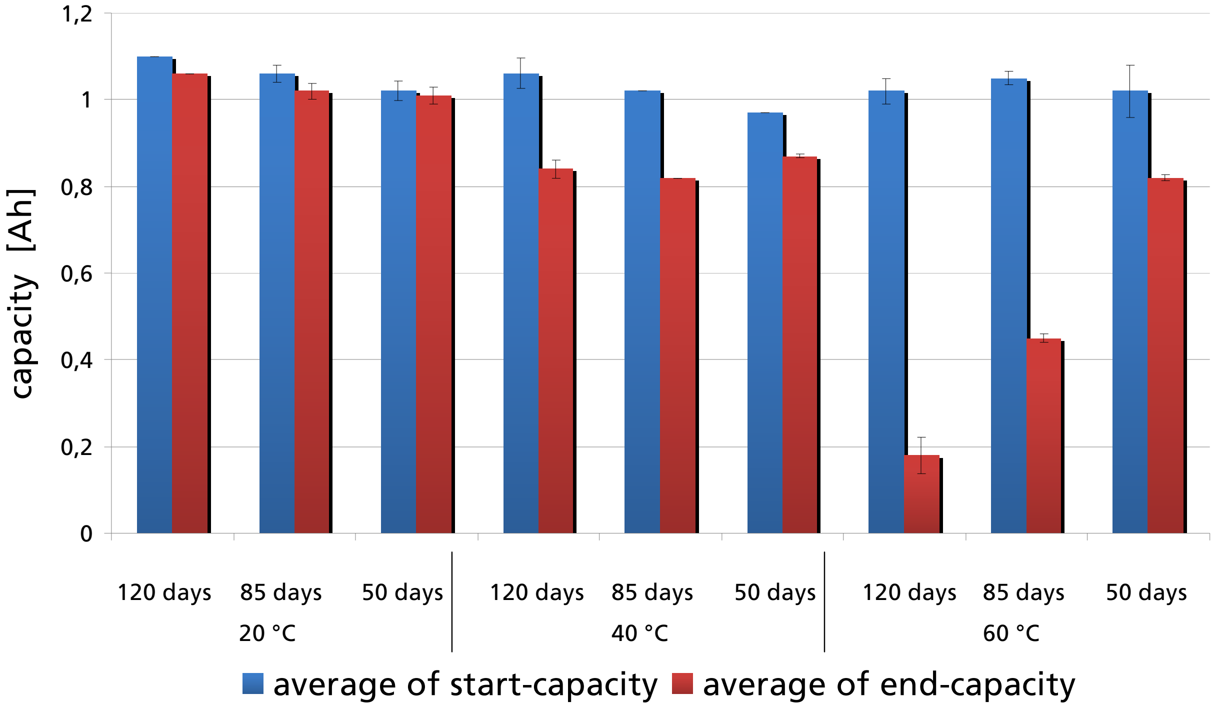

Fig. 5: The capacity loss versus storage time and temperature (SOC 50 %)

It is obviously that the capacity loss depends mainly from the storage time and the temperature. With solar charging it is not possible to recover the old capacity, but with intensive charging a capacity gain is possible, see fig.6. It is obviously that after intensive charging the battery capacity recover the nominal capacity with exception at storage periods bigger than 50 days at the high temperature of 60° C [8].

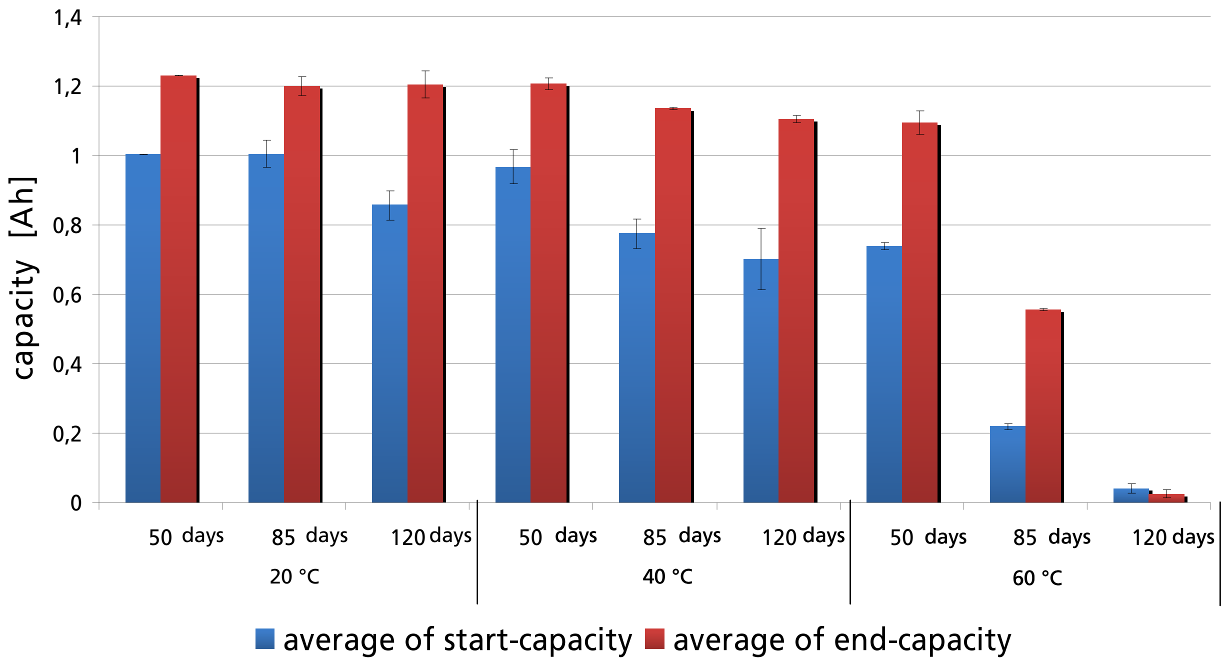

Fig. 6 Capacity gain after intensive charging

The reason of this unrecoverable capacity loss is a loss of water which was estimated by weighting the batteries, see Fig.7.

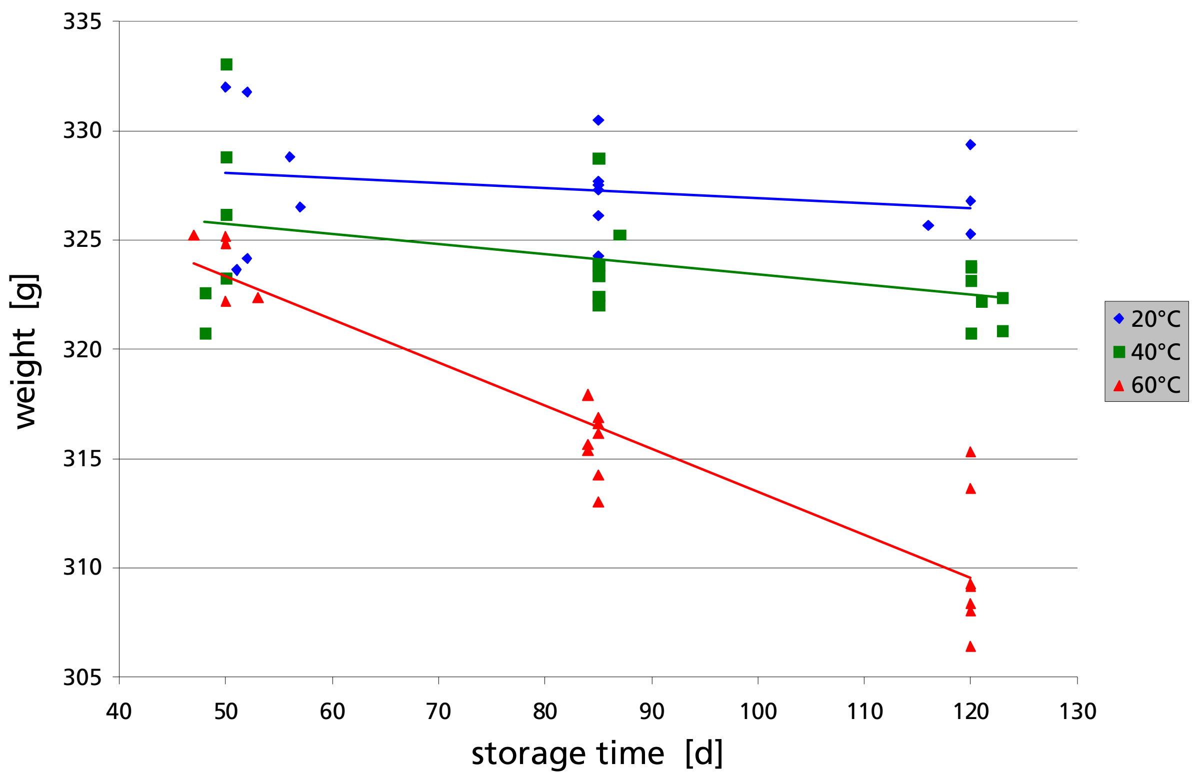

Fig.7: Water loss versus storage time and temperature

The storage at the high temperature 60° C causes at storage periods bigger than 50 days a relative high water loss. A weight loss of 15 g corresponds approximately to a water loss of about 35 %, with such a water loss it is not possible to recover the capacity. In consequence VRLA battery manufactures suggest: do not operate VRLA batteries at temperatures higher than 50° C.

4 Implementation in commercial charge controller

To apply the intensive charging regime in off-grid photovoltaic applications it was implemented into the commercial charge controller Solarix MPP 2010 from the company Steca, see fig. 8. The exact charge program for the cc-cv-cc charge is:
cc = I_{10}, cv = 2.45 V/cell , cc = I_{75} (once per month), together all up to total charge of 130 % of nominal capacity

Fig.8: Charge controller Solarix MPP 2010 with the implemented intensive charging regime from the company Steca

After some optimizations in the internal software of the charge controller during the laboratory tests the device runs now well and in autumn 2010 the field tests shall be started.

5 Conclusion

VRLA gel type batteries are very suitable for off-grid PV applications. To avoid continuous undercharging which cause sulphation a regular intensive charging is necessary. This means after the constant current and the constant voltage phase with at least 2.35 – 2.40 V/cell each month an additional limited constant current phase with I_{100} - I_{50} together up to total charge of 115 % - 130 % of nominal capacity is necessary to prevent sulphation. With such an intensive charging regime and preventing of deep discharge lifetimes greater 10 years are possible.

To avoid dramatically loss of water and very short lifetime it is necessary to avoid long periods with temperatures > 50° C.

Only VRLA gel types are inherently safe against acid stratification. To minimise the acid stratification in AGM types a well optimised internal design is necessary.

In the middle of 2011 the Steca charge controller Solarix MPP 2010 with the intensive charging regime for VRLA batteries will be commercially available

6 Literature

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