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Analysis of the performance parameters of lead/acid batteries in photovoltaic systems

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Abstract

A systematic effort is made to define analysis and performance parameters for lead/acid batteries in photovoltaic (PV) systems. In this paper, results from the data analysis are presented, showing typical current and voltage profiles and time series of state-of-charge. Four major classes of battery operating conditions in PV systems and another four classes of temperature conditions are identified. Typical results from all classes are shown as examples. These results should help system engineers to choose the right control strategies and the battery industry to choose and develop appropriate batteries for PV applications especially for Central Europe, where most of the systems under investigation are located.

Keywords: Lead/acid batteries; Photovoltaic systems; Operating conditions

1. Introduction

Why are batteries so important in photovoltaic (PV) systems? Almost all remote PV systems need a battery as a storage unit to provide the energy load during the night and periods of low insolation or to meet certain peak loads. The most common battery type is the lead/acid accumulator because of its relatively low cost and high energy efficiency. The heavy weight of lead/acid batteries is not a significant disadvantage for applications in PV systems.

The lifetime of batteries in PV systems is usually between three and eight years. Table 1 shows lifetimes of batteries in different PV systems. In most cases the actual condition ('state-of-health') or the remaining capacity of the battery is not known at the time of replacement. Performing capacity tests in remote PV systems is very difficult. Therefore, very little information on batteries at the end of their lifetime and the reason for replacement is available for PV systems in Europe. Even today, information on the strains on the batteries during their lifetime is very limited. However, lead/acid batteries in PV applications reach neither the cycle number nor the shelf-life of lead/acid batteries in other applications such as uninterruptable power supplies or electro-traction.

Fig. 1 shows the impact of the batteries on the costs of PV systems. The left-hand graph shows the share of the installation costs of a PV system (with a diesel generator as a back-up) for the PV generator, installation and maintenance, the system and the battery. While the battery's share is about one eighth of the installation costs, it is about one third of the lifetime costs, assuming a 24 year lifetime for the PV generator and a battery lifetime of four years. Regarding the system lifetime, battery costs are almost three times as high

Table 1
Lifetimes and operating periods of batteries in different PV systems

Landenberger	3 years	Replaced	Oberlinhaus	6 years	Replaced
Street lamp	3 years	Replaced	Rappenecker Hof	4.5 years	Replaced
Self-sufficient house	3 years	C_{10} <75%	Brunnenbach	5 years	In use
	3.5 years	C_{10} <40%	single cells replaced		
Haus Langer	5 years	In use	Biohof Stein	3 years	In use

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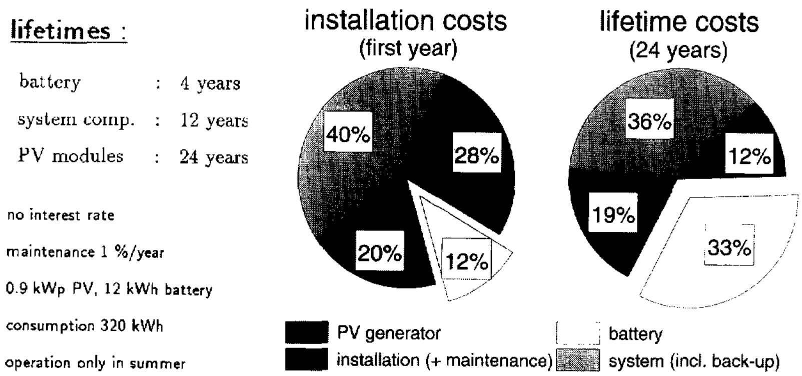

Fig. 1. Relative shares of the installation and lifetime costs for different components of a PV stand-alone system. Life times: battery, 4 years; system comp., 12 years, and PV modules, 24 years. No interest rate; maintenance 1% per year; 0.9 kWp PV, 12 kWh battery; consumption 320 kWh, and operation only during summer.

as those of the PV generator. To reach equal shares for the battery and the PV generator within the lifetime (assuming the data from Fig. 1), batteries should operate for at least 11 years.

The future of PV systems depends very much on their price and it is, therefore, very important to reduce battery costs by extending battery lifetimes.

2. Data analysis programme

There are three main classes of PV systems:

I. PV systems without storage and back-up, e.g. water pumps;

II. PV systems with storage for electrical energy,(e.g. lighting systems, telecom receivers, solar home systems, and

III. PV systems with storage and a back-up generator, e.g. remote houses and villages, applications with high reliability.

The current investigation deals with systems from classes II and III. To identify typical operating conditions, strains and ageing processes for batteries in PV systems, a database was designed with special emphasis on the battery data. Data from more than 30 battery systems were collected over periods from two to six years. This database serves as a basis for the investigations leading to the results shown in this paper. Correlating operating conditions and ageing processes is a second aim of the project, but there are no final results available at the moment.

The systems selected for the database represent a wide range of PV battery applications. The smallest system is a 4 W lamp for a bus shelter with a storage capacity of 650 Wh and the largest system provides power to a small settlement, including a storage capacity of 475 kWh. For comparison and evaluation of the operating conditions, a standard analysis programme was developed. Within the standard analysis, all values were normalised to I_{10}, nominal capacity C_{10} and cell voltage to make the different system sizes comparable. The following list shows the main features of the analysis program:

1. data availability;
2. battery current versus voltage, plot of all data points, cf. Fig. 2;
3. charged and discharged Ah per month and year, charge coefficient, energy efficiency, cf. Table 4, charge coefficient = 1/(Ah efficiency);
4. mean, maximum, minimum on a monthly basis and frequency distribution on a yearly basis for voltage, current and temperature, e.g. frequency distribution of temperature, cf. Fig. 6;
5. charge transfer as a function of mean cell volltage and as a function of battery current, cf. Fig. 3, and
6. calculated state-of-charge as a time series and frequency distribution on a yearly basis, cf. Fig. 5.

The state-of-charge was calculated from the collected data on the basis of an Ah balance, taking into account a voltage- and temperature-dependent loss current. The algorithm is calibrated by an algorithm which searches for the points with maximum state-of-charge [1].

All analysis of the data is performed on the basis of hourly mean values of battery current, voltage and temperature.

3. Classes of operating conditions

After analysing all data according to the catalogue presented above, the systems were assigned to four major classes of operating conditions. Table 2 gives an overview of the main characteristics of the battery operating conditions. While class 1 is identical with the special class II of PV systems, class III divides into the three operation classes 2, 3 and 4. Regarding the operating conditions from the battery's point of view, values like currents and the mean depth-of-discharge (DOD) per cycle are most important. From the point of view of the system engineer's decision, variables like solar fraction and storage size in terms of load demand are more common. However, as Table 2 shows, both points of view result in identical classes.

To illustrate typical operating conditions of batteries in the four classes, one system for each class is chosen as an example. Table 3 gives an overview of the selected systems with a short description of the system configuration. These systems will be referred to within the text and graphs as classes 1 to 4.

Table 4 summarises the charge transfer, charge coefficient, energy efficiency and voltage efficiency of the four selected systems. The values are typical for the systems in these classes, even though there are margins around the given values for different systems within the same class. The decreasing charge coefficient and the increasing energy efficiency from class 1 to class 4 are results of the decreasing solar fraction within the classes. High values of the solar fraction result in long periods of fully charged batteries at the end-of-charge voltage and therefore in high gassing losses. The high voltage efficiency in class 1 is due to the low end-of-charge voltage and the small discharge currents, resulting in a small voltage gap between charging and discharging.

Figs. 2–5 show results of the selected systems representing the four classes.

Battery current is plotted versus cell voltage in Fig. 2. It is obvious that load currents (negative battery currents) increase from class 1 to class 4. The phase–space spread of voltage and current increases in the same way. (Note that negative currents at voltages above 2.2 V/cell are a result of the averaging methods.) More informative averaging methods are already developed and tested [1], but they have not yet been implemented in the systems. Voltages are regulated during charging with charge controllers in all systems. Nevertheless, there is no clear break in the voltage distribution in classes 2, 3 and 4, due to the effect of gassing cycles, different voltage limits for PV, wind and diesel generators or temperature-dependent end-of-charge voltages.

Fig. 3 shows the charge transfer as a function of the battery current within one year. The accumulated charge transfer increases from class 1 to class 4 according to the values given in Table 4. While very little charge transfer occurs at discharge currents above $0.25I_{10}$ in classes 1 and 2, higher discharge currents are common in classes 3 and 4. It is very important to be aware of the most common discharge currents for proper adjustment of a voltage-based end-of-charge dis-

Table 2

Classification of batteries in PV systems according to their operating conditions with special respect to the currents and the state-of-charge cycles. The solar fraction is the amount of energy produced by the PV generator divided by the energy produced by all energy sources within the system (including e.g. wind and diesel generators). The storage size is given in units of battery capacity divided by the mean daily load

	Class 1	Class 2	Class 3	Class 4
Characteristics	Small currents Few cycles (mainly one cycle per year)	Small currents Large number of partial cycles (at different states of charge)	Medium currents Large number of partial cycles (at good states-of-charge)	High currents Deep cycles (0.5 to 1 cycles per day)
solar fraction	100%	70–90%	about 50%	<50%
storage size	>10 days	3–5 days	1–3 days	about 1 day

Table 3

System design of the systems selected as examples for each of the four operating condition classes (time series for voltage, current and temperature were taken from 1995 for all systems)

Class	System	System design
1	Bus shelter [2], Bernburg	AGM battery, 2.5 years in operation, 12 V, 54 Ah, lighting system with about 4 W load, no back-up, includes an energy management system
2	Self-sufficient solar house [3]	Tubular plate positive electrode, 3.5 years in operation, less than 40% capacity remaining, 48 V, 2×200 Ah, household with low consumption appliances, H_2/O_2 seasonal storage and back-up
3	Biohof Stein [4]	Tubular plate positive electrode, 3 years in operation, 100 Ah, 42 V, farmhouse with animals, biogas back-up generator, string 3 out of a multiple voltage system (12, 24, 42, 84 and 162 V)
4	Terschelling [5]	Flat-plate electrodes, 2.5 years in operation, 360 V, 250 Ah, PV–wind–diesel hybrid system

Table 4

Charge-transfer rates in units of nominal capacity, charge coefficient, energy efficiency and 'voltage efficiency' for the selected systems representing the four classes (see Table 3) over a period of 1 year [a]

	Class 1	Class 2	Class 3	Class 4
Charged Ah (C_{10})	18.0	66.2	145.4	145.8 (178.9) [a]
Discharged Ah (C_{10})	15.1	58.6	137.9	139.7 (171.4) [a]
Charge coefficient	1.19	1.13	1.05	1.04
Energy efficiency (%)	78.7	80.0	86.9	87.7
'Voltage efficiency' $\left(=\frac{\text{Wh efficiency}}{\text{Ah efficiency}}\right)$ (%)	93.7	90.4	91.2	91.2

[a] For 2.5 months of the year, the battery was kept almost on float-charge operation because of work on the system (see time series of state-of-charge in Fig. 5, class 4). Therefore, the marked values were calculated from the remaining months and extrapolated to the complete year.

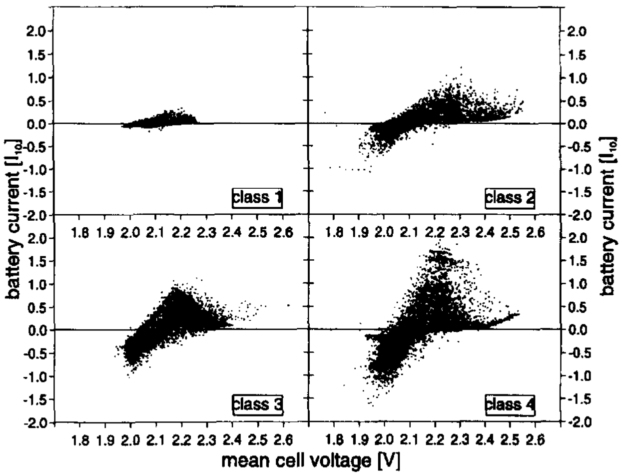

Fig. 2. Battery current in units of I_{10} vs. cell voltage for all data points within 1 year for the classes 1 to 4 for the systems characterized in Table 3.

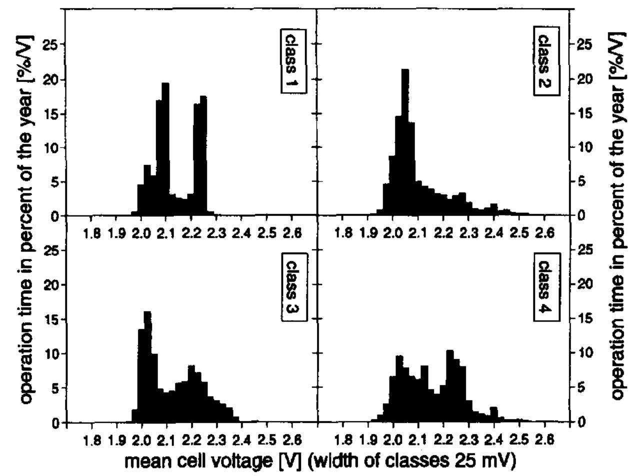

Fig. 4. Frequency distribution of battery voltage within 1 year for classes 1 to 4 for the systems characterized in Table 3.

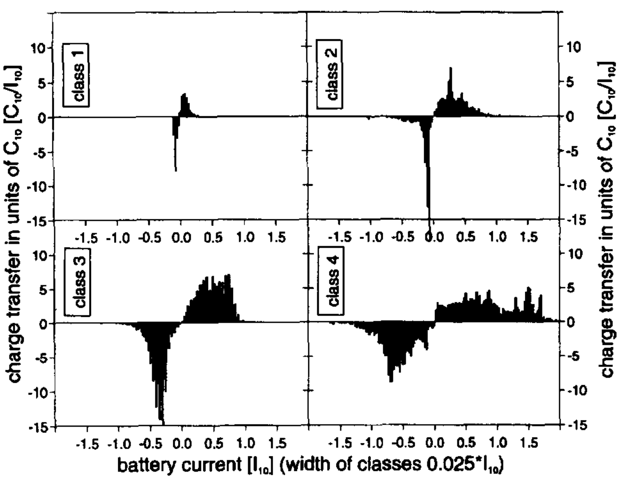

Fig. 3. Charge transfer in units of nominal capacity vs. battery current within 1 year for the classes 1 to 4 for the systems characterised in Table 3. The charge transfer is given by the cumulated Ah within a class of battery current for 1 year divided by the nominal capacity.

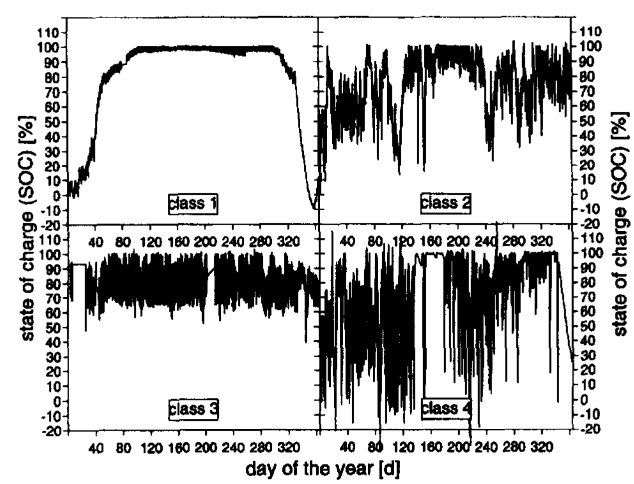

Fig. 5. Time series of state-of-charge within 1 year calculated from current, voltage and temperature using an Ah balance with a voltage- and temperature-dependent loss current, for the systems characterized in Table 3.

connect or starting of the back-up generator to avoid deep discharges. High charging currents are mainly correlated with powerful diesel engines or wind turbines, while currents from PV generators above I_{10} occur very seldom.

Cumulative frequency distributions of voltage for one year are shown in Fig. 4 for all classes. The significant peaks within the distribution of class 1 are attributed to the discharge and rest periods during the night on the one hand and on the other hand to the end-of-charge voltage during summer. During eight months of the year, the battery is at the daytime almost on a floating operation mode. The distributions widen and become flatter from class 1 to class 4 as a result of an increasing spectrum of states-of-charge and currents. No really deep-discharges happened in the four selected systems. Therefore, voltages below 1.9 V/cell do not occur very often. Nevertheless, there are still several batteries with deep-discharges at least once a year, even with periods of reverse charging of single cells in high-voltage strings [6,7].

Time series of state-of-charge are shown in Fig. 5. While class 1 shows essentially a one-year cycle, including a period of three months without full charging of the battery, there is no yearly cycle for batteries in classes 3 and 4. Energy is produced by the diesel generator in these systems, leading to low solar fractions. Daily cycles are between 2 and 5% in class 1, between 10 and 20% in class 2, about 30% in class 3 and even more in class 4.

Batteries from class 1 and 2 are exposed to long periods with low states-of-charge. This is probably the main reason for shorter lifetimes than expected of these batteries, whereas batteries in classes 3 and 4 have a high energy throughput and, therefore, a high number of nominal cycles.

4. Classes of temperature conditions

Along with the operating conditions defined by currents, charge transfer and cycling conditions, the temperature conditions experienced by the batteries represent another important point. Four classes of typical temperature conditions are identified. Table 5 sums up the temperature ranges and characteristics of the locations where the batteries are installed,

Table 5
Classification of batteries in PV systems according to the battery temperature for Central European climate

	Class A	Class B	Class C	Class D
Characteristics	Almost at ambient temperature, sometimes even direct sunshine	Protected from the ambient by a shelter	Located in houses, basements or cellars	Kept at the right temperature by insulation or active systems
Temperature range (°C)	− 10 to + 45	+ 5 to + 30	+ 5 to + 20	+ 15 to + 25

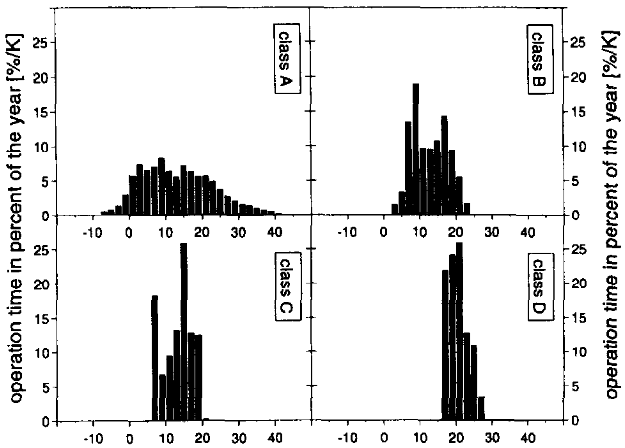

Fig. 6. Frequency distribution of battery temperature for the defined classes A–D, examples from different battery systems over a period of 1 year.

for the four classes A, B, C and D. The given temperature ranges are representative of Central European climates and may change for other climatic regions.

Fig. 6 shows frequency distributions of the temperature measured in four different systems. Results as shown for class A are very common for lighting systems and small technical applications. In these systems, the battery is often housed in a box without insulation and with direct contact to the ambient air or even direct sunshine. Temperature differences of 15 to 20 K within 24 h are very common. Also, it is most important to recognise that temperatures below 0° C are correlated with low states-of-charge during the winter, see Fig. 5, class 1.

On the other hand, there are systems with a narrow temperature range, represented by class D. Reasons for this thermal stability are rooms with a very effective insulation or special tests under laboratory conditions at constant temperature (active heating or cooling systems).

Classes B and C represent systems where batteries are housed in basements and cellars (class C) or in shelters beside the main houses or applications, which protect the batteries from the direct influence of ambient temperature and sunshine (class B).

5. Conclusions and outlook

Batteries in PV systems are exposed to very different operating conditions. Nevertheless, we found equivalent battery types and technologies in all four classes within our investigations. Choosing the right battery for a planned PV system is not as easy as it seems. The system should be assigned according to the suggestion made in this paper and the battery should then be choosen according to the typical operating conditions. Drawing on their knowledge of batteries in other, well-specified applications, manufacturers should tell the system engineers what kind of battery is best for a certain class, and system engineers have to improve the battery management to avoid overcharging and deep-discharging. Further investigations are planned to correlate the operating conditions and control strategies with the battery lifetime. Therefore capacity tests, electrochemical post-mortem analyses [8] and electrical tests are performed in the laboratory and in the field and will be intensified in the next phase of the project.

The final goal must be: battery lifetime in PV systems in the range of 10 years or at least 500 to 800 full cycles.

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