ELECTRICAL ENERGY STORAGE

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Summary

This paper gives an overview of electrical energy storage systems used in photovoltaic applications. The demands for storage systems are explained and the most important systems are described The working principles of lead-acid, nickel-cadmium, and redox-flow batteries and gas-accumulators are shown. Advantages and disadvantages of the discussed systems are listed and the further developments are discussed.

The paper shows that it is useful to separate between systems with internal and systems with external storage. Systems with external storage, e.g. gas-accumulators, have the advantage that the storage size and the power size can be sized separately. In this case seasonal storage, the use of energy generated in the summer months for use in the winter months, is possible.

Up to now in most cases batteries with internal storage are used. In case of photovoltaic systems lead-acid batteries are used for most applications. The reasons are the low price, the high state of development and simple operation.

1. Introduction

For a continuous energy supply of photovoltaic operated and off-grid loads, the storage of the solar produced electrical energy is necessary. About 60 per cent of world-wide manufactured solar cells are used for such stand alone systems.

In case of photovoltaic systems, mainly electrochemical storage systems, also called accumulators, are used. Partly water pumping systems in combination with a water tank are also used.

Inside of an accumulator the electrical energy is converted into storable chemical energy by use of an electrical-chemical converter. In case of need, the stored chemical energy is converted into electrical energy by the chemical-electrical converter. The converters are electrochemical cells. The mode of operation is shown in Figure 1.

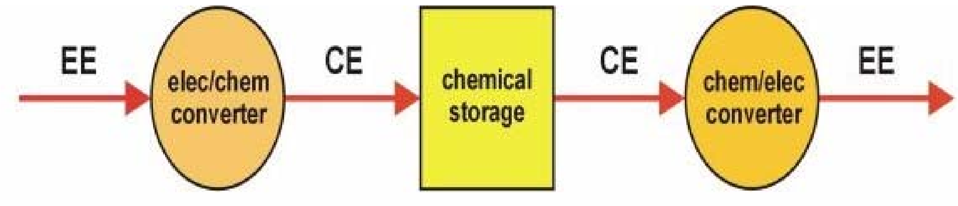

Figure 1. Mode of operation of accumulators (EE, electrical energy; CE, chemical energy).

In the case of accumulators, the power is given by the electrochemical cell and the capacity is given by the storage unit. The following different systems are possible:

(a) *Systems with internal storage (e.g. lead-acid battery)* The storage is done in the electrodes of the electrochemical cell. In this case capacity and power are nearly proportional to the battery weight. The storage medium (active mass) is in most cases in a solid state. The construction of these systems is relatively simple.
(b) *Systems with external storage (e.g. gas-accumulator)* The storage and the electrochemical cells are divided into different units. The capacity can be adjusted by sizing of the storage tanks to nearly any size. By this method it is possible to store the energy produced by the PV generator during the summer months and to use in the winter. It is also possible to separate the storage unit from the electrochemical cells and to transport this unit individually. The storage medium is normally liquid or gaseous. The construction of these systems is relatively complex. The systems are partly commercial available, but the costs are very high.

For this reason, the priority of this chapter is storage systems with internal storage. The most important aspects for batteries in PV applications are described for storage systems with internal storage.

Further information about this thematic can be found at Köthe (1991) and Lambert (1990).

2. Systems with Internal Storage

2.1. Demands on the Battery

The following demands are important for a battery used in PV applications:

- Low specific energy costs

- High lifetime
- High overall efficiency
- Low self-discharge
- Low maintenance
- Simple installation and operation
- (high power)

Specific energy costs (\$ kWhΣ^{-1})

In normal cases the specific energy costs are given by the sum of capital and operation costs of the accumulator divided by the total amount of stored energy for the whole battery lifetime (\$ per kWhΣ^{-1}), this means energy throughput. In the example the specific energy costs take the battery lifetime into account, as well. Table 1 shows the specific energy costs (without operation costs) for different battery types.

System	**Lifetime cycles (80% DOD)**	**Prize (\$ per kWh)**	**Specific Wh-prize (\$ per kWh$_\Sigma$)**	**• I**	**Self-discharge (% month)**	**Operating temperature (°C)**
Lead-acid						
Flooded grid	500	100	0.20	83	3	-15°…+55°
Tubular	1500	225	0.15	80	3	-15°…+55°
VRLA grid	>600	200	0.30	>90	4	-20°…+50°
Tubular	1300	300	0.23	>90	4	-20°…+50°
Ni-Cd						
Flooded pocket	2000	725	0.36	71	6	-40°...+45°
Sinter	>2000	1400	0.70	71	10	-40 ° ...+45°
Sealed pocket	1500	1100	0.73	71	20	-40°...+45°
Sinter	1500	1700	1.13	71	20	-40°...+45°
Fiber	3500	1700	0.49			-40°...+45°
Ni-Fe	3000	1100	0.37	55	40	0°...+40°

Table 1. Parameter of different accumulators.

Lifetime

The lifetime of batteries should be high, especially in order to reduce the specific energy costs.

Overall energy efficiency $\eta\Sigma$

The overall energy efficiency is calculated by the charged and discharged energy:

$$\eta_\Sigma = \frac{\text{discharged energy}}{\text{charged energy}} \tag{1}$$

The coulomb efficiency is calculated by the quotient of the discharged capacity (Q_D)

and the charged (Q_c).

Especially in the summer time standard accumulators cannot store all the electricity generated by the PV modules. In order to prevent gassing and therefore to increase the lifetime of the battery, the charge current will be reduced if the charge voltage is reached in the region of the gassing voltage (see Figure 2).

This means the overall system efficiency is further decreased.

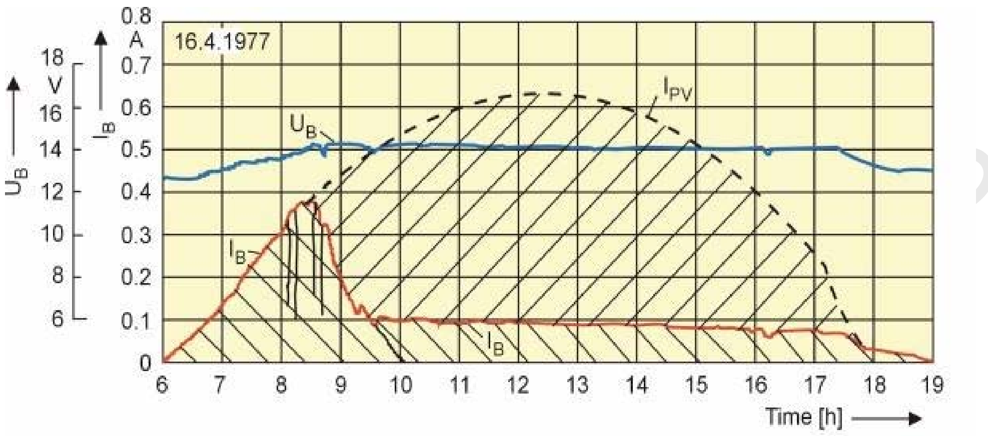

Figure 2. Charge voltage (U_B), charge current (I_B) of a lead-acid battery, and by the PV module generated current (I_{PV}) vs time (Köthe, 1991).

Self-discharge

Thermodynamic instabilities of the active masses and the electrolyte as well as internal and external short-circuits, result in capacity losses. These losses are called self-discharge and should, especially in cases of annual storage systems, be very small.

Maintenance work

The maintenance, e.g. the topping up with distilled water in case of lead-acid batteries, should be very small.

Simple installation and operation

In a lot of cases the batteries are not operated by experts. Simple installation and operation is very important in this case.

Power

In some cases the battery must be strong enough for short term high rate discharges. Examples are the starting of a diesel-engine or temporary output power increase of the PV system. Table 1 shows data of available accumulators.

The given data are approximated values and should be used as guideline.

A lot of the given values depend on the charge- and discharge-conditions. These are for solar applications changeable and up to now in case of testing not standardized. This means a comparison between accumulators and so the selection of the best suitable system is not easy.

By reason of the special operation conditions of PV applications the cycle life given by the manufacturer (Table 1) can be reduced by half. The given battery costs are the values for Germany in 1996 (*Akku Gesellschaft, D-02689 Taubenheim, Fax +49 359363 4397*).

Table 1 also shows that in most cases of PV applications, lead acid batteries will be the storage system of choice. The selection of the systems must take the application into account.

For solar home systems located in developing countries and for hobby applications automotive batteries or derivates of this battery technology are used.

For semi-professional applications, i.e. weekend houses, vented type tubular plate lead-acid batteries are used. For professional and industrial systems tubular plate lead-acid batteries in valve regulated technology are used.

At low temperatures, i.e. below -25°C, Ni-Cd batteries are to be preferred, although applications with lead-acid batteries have also been reported (Ikkala and Nieminen 1990).

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