LITERATURE SURVEY ABOUT LIFETIME EXPECTANCY OF COMPONENTS, IN PARTICULAR THE ENERGY STORAGE SYSTEMS IN EXISTING PV APPLICATIONS

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ABSTRACT: In the framework of the 'Benchmarking' project, a literature survey was conducted on the lifetime expectancy and on operational experience concerning lifetimes and problems of batteries operating in RES applications. Additionally to the recording of field experience, an inquiry of the factors that affect the ageing of batteries in RES applications was made, as found in the literature. Parallel to this, information on problems and experience regarding other RES components was collected. The results of this survey are presented in this paper.

Keywords: Batteries, Lifetime, PV System.

1 INTRODUCTION

Lead acid battery technology is the main storage technology used in RES systems, due to its maturity and low cost, and will be for the next years. Manufacturers design specific products to meet the requirements of the operation of batteries in small to large RES systems. It is often stated however that batteries in RES applications exhibit shorter lifetimes than those expected by manufacturers' data or those experienced in traditional applications.

In the framework of the EC founded project ENK6-CT2001-80576 entitled "Development of test procedures for benchmarking components in RES applications, in particular energy storage systems" (short name "Benchmarking"), a literature survey was conducted on the lifetime expectancy and on operational experience concerning lifetimes and problems of batteries operating in RES applications [1]. A large number of references are included in the report available on the internet site www.benchmarking.eu.org. Parallel to this, information on problems and experience regarding other RES components was collected. The collected information is focused on PV systems as they are more widely used than wind or hydro in small to large stand-alone systems. Especially in small-scale stand-alone systems the basis is always solar electricity, while wind energy is considered as an auxiliary power source. Wind energy is targeted to large-scale applications, concerning direct connection to the grid. So operation of lead-acid batteries under solar conditions was mostly considered.

2 LEAD ACID BATTERY AGEING

The main ageing processes that finally limit lead acid batteries lifetime are corrosion of positive grid, irreversible sulphation, degradation of active mass structure, and loss of contact between active masses and grids. These are briefly reviewed.

The metallic lead of the positive plate grid is oxidised slowly to lead oxide due to the potential of the positive plate. A lead dioxide layer is formed on the grid surface which penetrates slowly into the grid, combined with growth of volume. Corrosion is a side effect that occurs continuously in lead-acid batteries and finally limits the useful life. The rate increases with increasing temperature and strongly depends on the positive electrode potential.

Corrosion leads to grid and plate expansion, increase of ohmic resistance and capacity loss due to loss of contact between the active material and the grid.

Irreversible sulphation is the formation of large lead sulphate crystals on the plates of a lead-acid battery.

When a battery is discharged fine crystals of lead sulphate which are reconverted during recharge are formed on both electrodes. The size of the crystals increases with increased time spent at low acid concentrations, occurring at low state of charge. Large crystals reduce the true surface area and result in longer charging periods and lower efficiencies during recharging. The part of the active mass that is irreversibly sulphated results in loss of active material and loss of capacity.

Measures against sulphation are to have a surplus of electrolyte and a frequent full charge of the battery.

During cyclic operation of batteries the conversion of lead and lead-dioxide to lead sulphate and the reverse is combined with changes in the structure of the active material and changes in electrolyte volume. They cause the positive active material to lose its initial structure and mechanical strength, lose contact between individual particles of active material, and reduce electrical performance, as parts of the active material become electrically isolated.

Finally the effect is manifested by capacity loss due to a decrease of available active material.

Batteries with antimony grids and tubular plates are known to be more resistant to degradation of positive active material.

Other degradation and failure modes of batteries involve degradation of the negative plate, 'leading through' of separator and drying-out due to water loss (mainly relevant for VRLA batteries).

The rate of each failure mechanism and which will finally dominate is greatly influenced by the operating conditions, but also by the specific design and manufacturing details of each battery type. Regarding operating conditions, corrosion is the most critical parameter for batteries at float applications and at operation in high temperatures, while sulphation and degradation of active material are mainly related to cyclic operation of batteries.

3 OPERATING CONDITIONS OF BATTERY IN PV

APPLICATIONS

Batteries in PV systems often operate on a daily cyclic basis, which results in active mass degradation, and therefore batteries with good cycling performance are required for such applications. In applications where a long period of autonomy is required and there is a large seasonal variation of load or generation, batteries are sometime kept in almost floating operation for months.

Operating conditions of batteries in PV applications, however, feature some characteristics that are not usually met in other applications. In most conventional applications after a discharge there is always energy and time available to recharge the battery.

A main characteristic of battery operation in PV systems is operation at partial state of charge (SOC). The battery is subject to cycles of discharge and partial charge at intermediate SOCs. Due to the limited energy and time available it may not reach full SOC and gassing voltage for a long time. This mode of operation leads to stratification of the electrolyte, to the formation of large lead sulphate crystals which are difficult to recharge and to the development of differences between single cells.

Stratification is the development of concentration differences between the electrolyte at the top and the bottom of the battery. The concentration differences are growing from cycle to cycle, especially in tall cells. The problem of stratification is mainly related to flooded batteries. In VRLA type the problem is reduced (but with no ability to recover).

Stratification is a serious problem. It causes uneven current distribution and stresses the lower parts of the plates, which experience higher active mass utilisation. By simulations it has been calculated that stratification in conjunction with small currents leads to undercharging of the lower parts of plates, with differences in ‘local’ SOC up to 30%. This means that the lower part of the electrode is cycled at a lower SOC without full charge for extended periods, with increased risk of suffering sulphation [2].

During partial cycling, the size distribution of crystallites changes to fewer and larger lead sulphate crystals. This leads to mechanical stress, and more importantly to longer charging times as the dissolution rate of lead sulphate crystals is the limiting factor at the end of charging. Sulphated batteries still have lead sulphate material left even after the charge has been terminated [3].

Another consequence of operation at partial state of charge is that differences between single cells develop over time. If there is no equalisation process, these differences grow from cycle to cycle, causing deep discharge of the weakest cell and overcharge of the other cells. Especially in high voltage battery banks, which are often met in PV-hybrid applications, there is an increased probability for a single cell failure.

Measures against the problems encountered due to operation at partial state of charge are the periodic overcharge of the battery at a higher voltage. As the battery SOC in PV-hybrid applications is affected by solar irradiation, during periods of low sunshine, the battery can remain in low SOC for a long time. The SOC can be very low (deep discharge) due to the low currents, if no proper end-of-discharge criteria either by SOC or voltage is defined. This situation gives rise to the failure mechanism of sulphation. The accumulated sulphation is not easily removed, due to inadequate charging related to solar irradiation. Analysis of battery plates after operation in PV applications has shown that sulphation of both plates is the most common problem.

Field experience has shown that in PV applications a battery is charged inadequately without reaching full SOC even in periods of high sunshine. This leads to a gradual decline of the ‘useful’ capacity to the user and operation of the battery at lower ‘true’ SOC. Initially this is not a true capacity loss, as full capacity can be recovered by an extra charging, but it affects the ageing mechanisms and long-term performance if these extra charging events are not performed frequently. This incomplete recharge and decline of capacity can be explained by the limited available charging time (few sunshine hours per day) which is not sufficient to restore the battery to a high SOC. Under constant voltage charge the current decreases as SOC approaches 100%. Full recharge of a battery requires several hours, and is also hindered by the development of any stratification and sulphation due to operation at partial state of charge. This is shown in Fig.1, where the time for the recharge by a factor of 1.2 of a discharged flooded battery, before and after a cycling period of approx.1 month at partial state of charge, is plotted [4]. The same parameters were used for both charge procedures (IUIa charge). As it can be seen, the time to reach 100% charge increases by several hours after a cycling period. So in many PV applications full charge of a battery is not easy to be achieved.

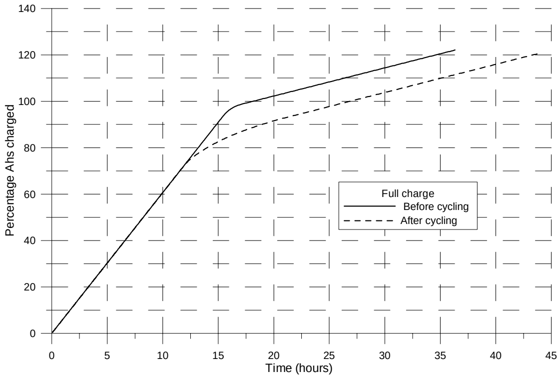

Fig.1. Recharge of a battery before and after cycling.

Moreover, the type of the solar charge-controller (ON-OFF or PWM type) and the voltage thresholds used, play an important role in the efficient charge of the battery.

In order to achieve fast and efficient charge, and at the same time to prevent the battery from harmful conditions for lifetime expectancy, such as extensive overcharge, stratification etc., more complex charging algorithms are required. These may include the utilisation of several voltage thresholds, fixed or adjustable, combined with timers, to allow e.g. for various steps in the charging procedure, regular overcharge etc. Third generation charge controllers which allow for a monthly IUIa charging of the battery would be required.

4 BATTERY LIFETIME EXPECTANCY

Various types of batteries are used in PV applications, though the so called solar batteries are usually preferred.

Solar batteries in developing countries are mainly modified SLI batteries, designed with thicker plates, to meet the special conditions occurring in small PV applications. In Europe solar batteries are also often modified stationary batteries with tubular plates. Therefore, it needs to be examined very carefully, what the manufacturer means by “solar battery”.

The lifetime of a battery in cycling applications is mostly determined by its cycle life, i.e. the number of cycles a battery can withstand before the end of its life. Battery capacity gradually decreases with cycles, with an end of life to be reached when the capacity falls below a given value, usually 80% of the rated capacity.

Manufacturers usually give cycle-life data via values of cycles at specified depth of discharge (DOD). This gives the battery cycle-life when operating with repeated cycles of discharges at the same specified DOD and full recharge.

Lead-acid batteries are designed to meet specific application requirements, and so a variety of cycle-life characteristics exist. SLI batteries have a cycle life of about 100 nominal cycles, while with solar design cycle life is improved to 200-300 nominal cycles. Most solar batteries, of the modified stationary type, have cycle-lives in the range of 700-1200 nominal cycles. Traction batteries usually have cycle-lives of over 1200 nominal cycles, but this would require full charging every day.

The calendar lifetime of a battery under floating conditions is another limit of battery lifetime, related to corrosion. Due to the corrosion’s dependence on temperature, the battery lifetime is strongly related to temperature operating conditions. Battery floating lifetime is usually considered to half for each 7 to 10 K rise of operating temperature. Solar modified SLI batteries have a floating lifetime around 5 years. Solar modified stationary batteries usually have lifetimes under floating conditions of more than 10 years for average ambient temperatures of 20°C.

Working conditions of batteries in PV-hybrid systems can have large variations, depending on the type of system, the design, the weather conditions and load.

The number of equivalent battery cycles per year can be from as small as 15 cycles/year, in pure PV systems with high autonomy, up to more than 150 cycles/year, in hybrid systems.

As the operating conditions in RES applications have large variations, and so have battery characteristics, lifetime can be limited by either the cycle-life of the battery or by its floating service-life, so both should be considered.

The data given by manufacturers, however, refer to optimum conditions and should be considered as upper limits only. Incomplete recharge results in reduced cycling performance, while operation at various temperature and voltage values results in shorter service-life than the stated floating lifetime. On the other hand, in practice in most PV applications the battery can be used far below the strict theoretical end-of-life criterion of 80% actual capacity without major complaints from the user. Remaining capacities of 60% with respect to the nominal capacity are no problem, especially in hybrid systems with a diesel generator as additional power source.

Based on manufacturers data a wide range of operational lifetime may be estimated depending on battery type and operating conditions. Lifetime may be from 1.5 year for a low cost battery in PV battery systems, up to more than 8 years for high cycle-life batteries in hybrid systems.

Theoretical estimations however usually overestimate battery lifetime. A more accurate estimation would require time-step simulation and implementation of a model that takes into consideration effects such as stratification, sulphation, corrosion rate etc. according to operating conditions. Such a validated model is not currently available. Work on this is under way as part of the Benchmarking project.

5 FIELD EXPERIENCE

Information on lifetime of batteries in PV applications is not very often presented in the literature. The information is difficult to acquire as systematic long-term monitoring of the plant is required. The end of life of a battery usually is not determined by the criterion of an actual capacity value lower than a preset threshold, as this requires a capacity test which is not easy to perform in the field. Therefore, the end of life is determined empirically, usually when the battery cannot fulfill its scope anymore.

The reported lifetimes also are difficult to evaluate and compare without knowing the battery history concerning all factors affecting lifetime, as battery lifetime is greatly influenced by operating conditions. Special operating conditions such as daily DOD (DDOD), temperature, charge-controller limits and charging strategy, malfunction of any peripheral component etc. may lead to large variations of the resulting lifetimes. That is why a wide range of reported results are often found and sometimes contradictory to each other.

Some of the collected information is presented in Table1.

The values of the reported lifetimes vary and depend of course on the battery type and the working conditions. Though there is experience of very short lifetimes, there are also cases of remarkable operational lifetimes, over 8 years, mostly in systems well designed and usually maintained by experienced operators. In many cases however the actual capacity at time of battery replacement is not known. In some cases when a capacity test was performed it resulted in a value below end-of-life criterion, but there was no complaint by the user.

6 FAILURES OF OTHER PV SYSTEM COMPONENTS

Besides batteries other components of PV and hybrid systems suffer also failures.

Experience from 30 stand-alone systems indicates that inverters and charge controllers are the components with the highest frequency of faults that require repair or replacement (20-30% of systems per year) [5]. This is also confirmed by the experience from large residential PV programs, concerning grid connected systems, where a percentage of 15-30% of systems suffer a failure or trouble each year. In the majority of these failures the inverter is involved, while the solar generator has proven to be the most reliable component [6].

Besides a main component weakness, many of the problems encountered during operation of a PV plant are related to the harsh environment (outdoors) that materials and components are exposed to, and to improper installation practices for such conditions. After some years of operation it is reported that common problems are water leakage in junction boxes and defects in connectors, cabling, diodes, etc..

Table 1. Battery lifetime in existing PV plants.

Plant	**Battery lifetime**	**Battery type**	**Other information**
Europe 16 PV plants	>6	Vented, mostly flat	30-300kWp 250-3000Ah
Greece 5 PV plants	>4	Vented	3-28kWp
Vulcano (IT)	8	Vented, tubular	80kWp 40% DDOD
Zambelli (IT)	10	Vented	70kWp 15% DDOD
Refugee des Evettes(FR)	12	Vented, tubular	5kWp DDOD<10%
Gross Bessillon(FR)	8	Vented tubular	3.8 kWp +Diesel 15% DDOD
Self-sufficient house, Freiburg(DE)	3.5	Vented, tubular	
Haus-Langer (DE)	8	Vented	Isolated house, 1.8kWp,
Oberlinhaus (DE)	6		Youth center 1.5kWp
Rappenecker Hof (DE)	4.5	Flat plate	Isolated house, 3.8kWp
Brunnenbach (DE)	8	Vented, flat	10.4kWp+ Diesel DDOD 25-30%
Germany	6.6		30 Systems
Sukatani, Indonesia	4.2	Solar batteries, flat- vented	SHS (Solar Home Systems) 10% DDOD
Flanitzhuette (DE)	>9	VRLA gel tubular	40kWp hybrid 10-60% DDOD
Netherlands, house boat sector	2.5	Flat and tubular, low and high Sb	10-40% DDOD
Simonos Petra Monast.(GR)	>10	Vented, tubular	45kWp Hybrid

The PV modules are the most reliable components of a PV system. Experience from a large number of small systems but also from large PV plants show a failure rate of PV modules usually less than 0.1% per year. Faults in PV modules are usually located at module connection box.

Tests on modules from old plants have proven also only limited degradation of output power, despite any visual degradation signs that may be encountered. In recent module and array tests, a reduced power output from the early time of operation of a PV plant has been often reported, caused mainly by the fact that many manufacturers provide modules with less power at STC than stated [6].

Regarding inverters, tests in recent years show that the rate of hardware defects of inverters has been reduced in recent years, to a value of less than 20 failures per 100 inverters and year [6].

7 DISCUSSION AND CONCLUSION

Lifetimes of batteries in different PV applications can be quite different depending on quality of batteries and operating conditions.

It is difficult to extract quantitative results from the collected information, but some general conclusions can be drawn. Also a lot of results are quite old, and battery technology has been improved in recent years. However it is clear from the data, that battery lifetime of 10 years can be achieved when using high quality batteries and appropriate battery management systems.

One major conclusion is that in most PV applications the battery can be used at a significantly reduced actual capacity with no major problem for the user.

The cycle-life capabilities of batteries are usually sufficient to provide long lifetimes in most PV applications. In systems with long service-life, corrosion is a usual failure reason. So care should be taken to reduce rate of corrosion in systems where a long service life for the battery is expected. However sulphation is very often reported in PV applications as a reason for low performance of a battery. The frequent occurence of sulphation, which has been validated by plate analysis of batteries after service, is probably related to the inability of the battery to get fully charged in such applications.

Regarding other components, power conditioning equipment represent a major source of failures in PV systems. The progress in technology and the experience gained has, however, led to the improvement of products and to the increase of inverters' reliability in recent years.

Regarding PV modules, some manufactures have been found recently to provide products with less power at STC than stated. PV modules however are the most reliable components, featuring a low rate of failures and stable performance for a long time.

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