European Association for the
Development of Renewable Energies, Environment
and Power Quality (EA4EPQ)

International Conference on Renewable Energies and Power Quality
(ICREPQ'12)
Santiago de Compostela (Spain), 28th to 30th March, 2012

Ageing estimation for the batteries of the Pierre Auger Observatory

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Abstract. Batteries have been used in a lot of different applications for a quite large time period, in particular in solar photovoltaic energy. In spite of this fact, their ageing mechanisms turn out to be still deeply out of control.
We show in this paper the results of applying the evolution of a preliminary method for the estimation of lead-acid batteries state of health which is based on the Root Mean Square Error (RMSE) between voltage distributions throughout a time period of nine years. A complete set of batteries, concerning the main parameters that could influence their lifetime, was analised.

Key words

Photovoltaics, accumulation, lead-acid, ageing, quality check.

1. Introduction

The Pierre Auger Observatory's (PAO) is the highest experiment on cosmic rays ever carried out and its surface detectors energy supply is obtained by means of stand-alone photovoltaic systems and thus batteries state of operation determines a lot both this detector functioning and the technical staff work. Furthermore, there are huge amounts of data in the PAO concerning the main magnitudes of these systems, actually the highest all over the world, so there is a highly outstanding opportunity of setting up methods for surveying ageing mechanisms for this kind of batteries and hence predicting their failures.
Taking advantage from such a great opportunity, the paper presents an experimental study of batteries ageing which is based on simple and standard measurements. Batteries ageing description is a challenging and essential issue concerning a lot of areas and fields in which they are used and different attempts were carried out [1] but not exempt from different intrinsic difficulties, inaccuracies and problems of implementation in the current systems. The main difficulties in batteries studies are caused by the intrinsic mixture of uncontrolled parameters that they accumulate during their manufacturing processes, installation and operation. Therefore, an empirical analysis of current systems is unavoidable both for concerning the PAO and the own batteries field, in which it could lead us to take useful and important conclusions.

2. Methodology

The effective experimental setup is a huge grid made up of 1600 identical stand-alone photovoltaic systems, each one composed of two series connected photovoltaic modules of 53Wp (Isofotón) and two series connected lead-acid batteries of 105 Ah (Moura). The data from the corresponding main magnitudes are taken and saved every 10 minutes, which is translated into a daily amount of up to 10^5. These data were used in the present study from a quite long time period.

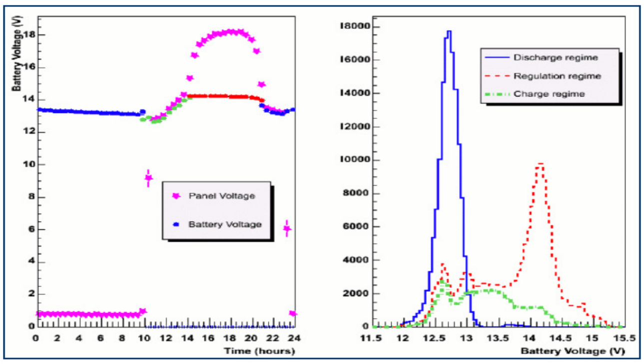

Fig. 1. . On the left voltage vs time (for comparison, solar panel voltage is also shown in pink dots) whereas on the right figure the corresponding distribution function of these values.

A. Voltage function and distribution.

The batteries voltage function is defined as the voltage values that the batteries present throughout the time (fig. 1. left). [2] The main operation values correspond to regulation regime (highest values in the plot) and discharge one (lowest ones). As a result, the voltage distribution function could generally be outlined by means of two pronounced peaks that correspond to the discharge time period and the regulation one. They are jointed by means of the charge values. In addition to these basic sectors, there are two extra possible operation regions concerning the battery that, in any case, should never be reached: deep discharge regime (lower values than 11.8V) and overcharge one (higher than 15V), as it can also be observed in Fig. 1

B. Root Mean Square Error (RMSE) estimator.

The RMSE between two voltage distribution functions on discharge regimen separated in time could be used [3,4] as an estimator of batteries ageing process during this time period, since the modification that the distribution shows as the time runs is translated into a increasing RMSE (see equation (1)) . The RMSE is defined as:

$$RMSE = \sqrt{\sum_{1}^{N_V} \frac{\left[f_A(V_i) - f_R(V_i)\right]^2}{N_V}} \qquad (1)$$

where V_i represents the voltage intervals used to obtain the voltage distribution, N_v is the total number of intervals, and $f_R(Vi)$ and $f_A(V_i)$ refer to the reference and actual probability densities of each V_i interval.

C. Influent factors to be studied.

In the PAO, and in the main part of the stand-alone photovoltaic systems, such systems deal with different causes of breakdown, different ages and different initial conditions (depending on if they were installed in winter or summer, in a more humid zone or not and so forth). The deployment details and conditions are not important for solar modules and regulators, whereas they could be decisive for the batteries lifetime. They are summarized in what follows:

1) *Weather conditions.* During winter, batteries are quite often not filled enough because of the low irradiation and even snow effect. This has been suggested as a cause of deficient plate formation [3].
2) *Period of storage.* The amount of time that batteries remain stored influences their subsequent way of functioning since the electrolyte becomes inhomogeneous.
3) *Eventualities during batteries lifetime*. There are some incidents that may happen during batteries operation such as problems on solar panels, regulators, connections, dust, snow and even water flows.
4) *Different manufacturing processes*. During the PAO deployment time period, the batteries manufacturer modified the production procedures (2006).
5) *Causes of breakdown.* Under normal operation conditions, the main factor that determines batteries deterioration is the cycling process, in which a slight portion of active chemical material is progressively disappearing. In addition, stratification, overcharging, deep discharge and the corresponding corrosion are accelerated mechanisms of reaching the end of their lifetime.

3. Results.

Ten cases were analysed, among which there are batteries that were stored for different amounts of time, under different initial weather conditions, different manufacturing processes, different lifetimes, and different anomalies (see Table I). The RMSE evolution throughout nine years of data taking was calculated for these stations so that it is possible to draw any conclusions about both ageing in general and the above listed parameters.

Table I - The battery sample.

Station Type	Season of Installation	Production differences	Storage (before installation)	Life Accidents	'Death' possible causes	Lifetime
I Tank 152	Summer	Old	Short	No	Corrosion	Long
II Tank 146	Winter	Old	Prolongate	No	Corrosion	Normal
III Tank 149	Winter	Old	Prolongate	No	Sulphation	Long
IV Tank 243	Summer Winter	Old	Medium	Broken regulator	Corrosion Sulphation	Short
V Tank 109	Summer	Old	Medium	No	Corrosion	Long
VI Tank 168a	Winter	Old	Prolonged	Panel with failures	Corrosion	Normal
VII Tank 168b	Winter	Old	Prolonged	Panel with failures	Sulphation	Changed before
VIII Tank 204	Summer	Old	Medium	Panel with failures	Corrosion	Long
IX Tank 1400	Winter	New (after 2006)	Not evaluated	No	Not evaluated	Not evaluated
X Tank 1450	Summer	New (after 2006)	Not evaluated	No	Not evaluated	Not evaluated

A. The RMSE slope.

In Fig. 2, the RMSE evolution for three batteries that were installed in one station is shown. The first observation is that, after an initial short period in which they are stabilising, there is a clear temporal increase of RMSE. It is worth also noting in this case that the first battery presented a quite different lifetime than that of the others, whereas the standard slope is even lower than theirs. In any case, the second battery's lifetime was also not so high. It is worth also mentioning that the sensitivity of the slope to eventualities that may occur during the battery lifetime is slightly present (in this case, a period of time in which the solar modules were partially covered with snow, which is translated into a slight increase of slope)

In this situation of linear RMSE increase over time, the slope under which it does could be thought to be by itself a good predictor of battery 'death', as it is schematically pointed in the plot, but the above mentioned kind of circumstance started suggesting the difficulties of doing so.

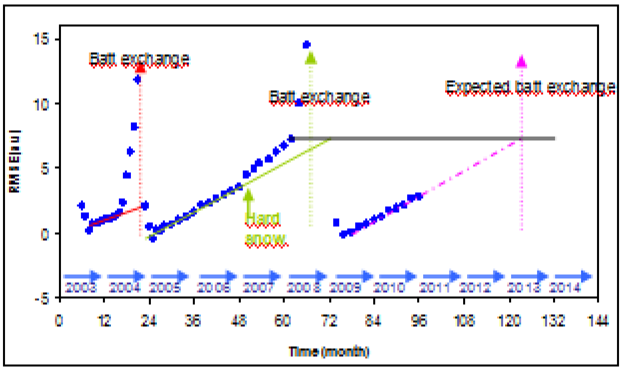

Fig. 2. RMSE during nine years for three batteries of the PAO's station 243.

In Fig. 3, there is an overview of the RMSE values obtained for all stations during the considered nine-year period of time. The RMSE-over-time slope is clearly battery dependent. This is caused by the fact that there are several parameters which intrinsically influence their behaviour, among which there also are some that are uncontrollable. It is also worth noting the differences of behaviour that even two batteries of a single station could show (see Type VI and VII) depending on these variables.

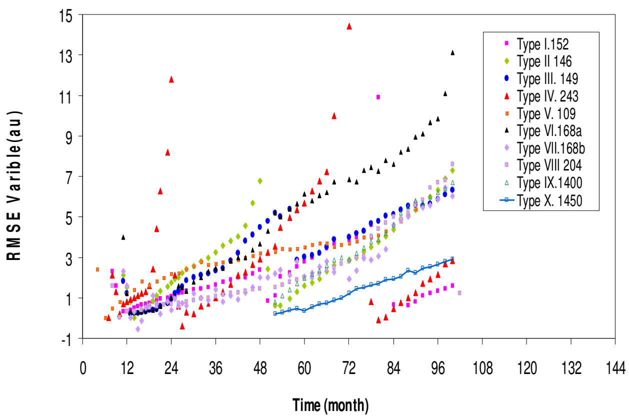

Fig. 3. RMSE evolution throughout the time for the whole set of batteries.

From the outset, the most outstanding point is a rather sudden change in RMSE time evolution which is observed a few months before the batteries final failure. This is a direct way to anticipate the breakdowns, so this method demonstrates to be a suitable procedure for the early detection of batteries failure and thus a potential effective way of a thoroughly optimisation of the most important corrective maintenance tasks.
A simple and adequate manner of implementing this method is carried out by means of the analysis of the time evaluation of the month-to-month differences for each battery (see Fig. 4.). In this way, a standard tolerance range is generated due to the linear time increasing and the values that are higher than it correspond to batteries which are on the verge of breaking down.

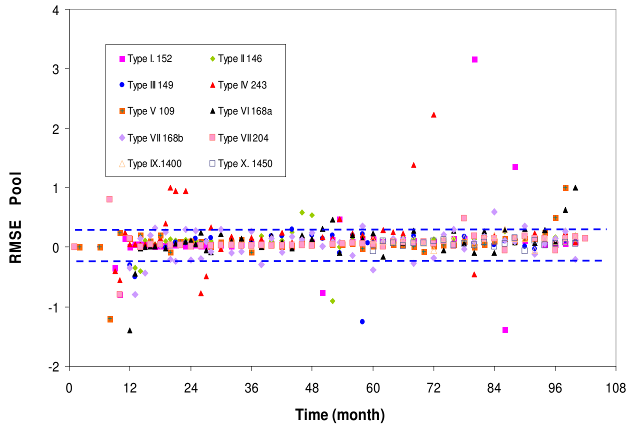

Fig. 4. Monthly mean variation of the RMSE for the studied cases.

B. Influent effects.

When Table I and Fig. 3. are considered, under the above explained assumptions about the mechanisms that influence the battery operation and hence its lifetime, some conclusions can be drawn:

If the batteries that were installed in summer (types I, V, VIII, and X -see Table I-) are compared from Fig. 3 with the ones installed during winter (II, III, IV, VI, IX), a no significantly noticeable effect on battery ageing is found. Nevertheless, a slight tendency to higher slopes is present in the winter cases, as it could be expected.
When the different times of storage are considered (short time, types I, V, VII and long time I, VI, IX, X) no essential differences are observed, but it is worth mentioning that even if the batteries suffered a prolonged storage without any recharge, their final lifetimes were still longer.
Concerning the different manufacturing procedures, no noticeable enough differences were observed but a slight trend to higher slopes for the old manufacture is present.
Finally, the causes of 'death' are practically not correlated with the RMSE slopes.

Statistics are increasing every day and further work is currently underway.

4. Conclusions.

The capacities of the RMSE between voltage distribution functions of the batteries throughout their lifetime have been further evaluated as an estimator of batteries ageing by means of ten of the Pierre Auger Observatory's stand-alone photovoltaic systems' data.

The temporal evolution of RMSE is globally translated into a rather constant increasing of its values that becomes sharply higher when the batteries lifetime is near to its end. This is a clear, simple and suitable observable for an early detection of the final breakdown. Under this analysis, the RMSE over time slope itself is not directly related to lifetime neither to the cause of failure.

The weather conditions during the deployment processes, the batteries storage time period and the kind of manufacture processes have also been studied as possible factors that determines the final lifetime and to which the algorithms may be sensitive, although a no sufficiently significant influence was found.

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