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Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems

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HIGHLIGHTS

- Lifetime estimation of lead–acid batteries is a complex task.
- This paper compares different models to predict battery lifetime in stand-alone systems.
- We compare a weighted Ah-throughput battery ageing model with other models.
- The battery charge controller significantly affects the lifetime of batteries.
- The results show the weighted Ah-throughput model provides more accurate values.

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ABSTRACT

Lifetime estimation of lead–acid batteries in stand-alone photovoltaic (PV) systems is a complex task because it depends on the operating conditions of the batteries. In many research simulations and optimisations, the estimation of battery lifetime is error-prone, thus producing values that differ substantially from the real ones. This error can indicate that the "optimal" system selected by the optimisation tool will not be optimal. In this paper, all of the components of a PV system have been considered simultaneously to simulate the behaviour of the system. One of these important components is the battery charge controller, which significantly affects the lifetime of batteries. The results of the simulations have allowed a comparison of the most common methods of battery lifetime prediction used by simulation and/or optimisation tools with a weighted Ah-throughput method developed a few years ago. The results show that this recent method provides more accurate lifetime values. In a simulation of a real off-grid household PV system where the real battery lifetime was 6.2 years, the weighted Ah-throughput model predicted a lifetime of 5.8 years; however, the other methods obtained lifetimes of more than 15 years. In a simulation of another PV system designed to supply the load of an alarm where the real batteries lifetime was 5.1 years, the weighted Ah-throughput model predicted a lifetime of 4.4 years; however, the other methods obtained lifetimes of more than nine years.

1. Introduction

The ageing mechanisms of lead–acid batteries have been studied previously [1–5]. The most important ageing processes are anodic corrosion, positive active mass degradation and the loss of adherence to the grid, irreversible formation of lead sulphate in the active mass, short-circuit, loss of water and electrolyte stratification [3]. These processes are often inter-dependent.

Batteries subject to deep cycling regimes typically age by degradation of the structure of the positive active mass. The battery cycle lifetime shown in the datasheet of the batteries (usually 300–2000 full cycles depending on the technology) is obtained in laboratory tests under standard conditions. However, the real conditions of the cycles in PV systems are habitually very different from standard conditions and the real cycle lifetime can be much lower.

Stationary batteries, which operate under float-charge conditions (in practice, float service may also include occasional partial discharges), typically age by corrosion of the positive grid. Under optimum float voltage conditions (i.e., without cycling), a theoretical maximum service life can be achieved, called floating lifetime. Its value is between 10 and 20 years depending on the technology (manufacturers usually show this value in datasheets). However, even in the batteries of UPS systems (operating at float service) the real conditions can be different from optimal, and the real floating life can be much lower than shown in the datasheet. Float life shown in the datasheet is usually reported at 20 or 25 °C, but the effect of temperature on float life is approximately a 50% reduction for every 8.3 °C increase in temperature [6].

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Battery lifetime prediction in stand-alone systems is a difficult task as it highly depends on the operating conditions. Many factors affect the life of the batteries, including the depth of the charge–discharge cycles, the current, the cell voltage, the performance of the charge controller (e.g., voltage and state of charge limits and regulation), the length of time that the batteries are in a low state of charge, the time since the last full charge, the temperature, etc.

Many studies have been published about the simulation and optimisation of renewable stand-alone systems including batteries. However, the battery lifetime has always been estimated in fixed values based on the experience of the researcher [7–16] or it has been estimated by calculating the number of equivalent full cycles [17–20]. In the best cases, it may be estimated using the cycle counting method [21–25]. Additionally, many simulation and optimisation software tools use these methodologies to estimate battery lifetimes [26–29]. However, the real lifetime of the batteries can differ from the estimated lifetime by many years using the mentioned methods, depending on the operating conditions. A high error in the estimation of the battery lifetime would imply a great error in the estimation of the total cost of the batteries in the net present cost (NPC) of the system; therefore, a real levelised cost of energy (LCE) may be very different from the expectation. This fact can imply that, when using optimisation tools, the selected design for the system can be very far from the optimal one.

2. Background and motivation

The thermodynamics and kinetics of the corrosion of lead in lead–acid batteries were first shown by Lander in [30]. Ruetschi studied the influence of crystal structure and inter-particle contact in lead–acid batteries [31] and reviewed the ageing mechanisms [3]. Failure mechanisms of lead–acid batteries were studied also in [32], and kinetic aspects of ageing factor were shown in [1]. Garche et al. [33] studied the influence of different operating conditions (e.g., cycling, self-discharge, and floating) on the lifetime of different lead–acid batteries for solar applications. Other researchers [34] showed that ageing mechanisms in valve-regulated lead–acid (VRLA) batteries also include negative-plate deterioration and poor separator-plate contact. More recent studies of ageing of VRLA batteries can be found in [35]. A classification of battery operating conditions in PV applications in four classes can be found in [36]. In another study, Svoboda et al. [37] classified lead–acid batteries into categories for lifetime considerations of the components of renewable systems and for analysing the properties and performance of these systems. Wenzl et al. [38] described a procedure for lifetime predictions including the relationships between stress factors and ageing processes. Cherif et al. [2] proposed a battery ageing model for stand-alone PV systems based on the initial model of Shepherd [39]. In 2008, Sauer and Wenzl [5] compared different approaches for lifetime prediction for lead–acid batteries. The models compared were (i) the physicochemical ageing model, which has high precision but also high complexity and high difficulty to obtain the parameters of the model and low calculation speed; (ii) the weighted Ah ageing model (the Schiffer model [4]), which has medium precisions, medium complexity and medium calculation speed; and (iii) the event-oriented ageing models that have low precision, low complexity and high calculation speed.

In 2007, Schiffer et al. [4] showed a comprehensive Weighted Ah ageing prediction model for ranking lead–acid batteries according to expected lifetime in renewable energy systems and autonomous power-supply systems. The cycles are weighted by factors that consider the operating conditions. The model was verified by comparing the simulation results with experimental test results. However, the experimental charge–discharge tests were not the typical charge–discharge processes which occur in stand-alone PV systems. They used two profiles: “PV profile” and “Wind profile”. However, even in the “PV profile” the batteries were tested using very intense deep charge–discharge cycles, with charge currents of about I_5 (current that would fully charge the batteries in 5 h) and discharge currents of about I_{10}, performing three cycles per day, obtaining a lifetime of approximately 180 days for an OGi battery. The simulation results were verified with the tests, but the profiles used were not realistic (they were “accelerated” tests). In most real stand-alone PV systems, there is only one daily charge–discharge cycle and also the charge and discharge currents are much lower than those used in the tests. Realistic testing usually obtains battery lifetimes higher than four years, and in some cases, if the batteries perform low discharge cycles and are well-controlled by the charge controller, then their lifetime can be even higher than 15 years. Additionally, previous researchers did not model the PV output current nor did they account for the effect of the charge controller on the lifetime of the batteries, which is a very important issue as it prevents overcharge and over-discharge. Using a good charge controller (e.g., PWM with state-of-charge calculation algorithms) with appropriate settings for the battery technology, the same battery exposed to the same charge/discharge cycles can have a much higher lifetime than one using a bad charge controller with incorrect settings.

In this paper, we have modelled the whole integrated system (including PV, batteries, charge controller and inverter), taking into account the characteristics of the most common charge controllers. Additionally, we have compared four different models for the performance of the batteries (the model proposed in [4] and three others); and we have compared three models for the calculation of the lifetime of the batteries (the model proposed in [4], the equivalent full cycles counting model and the “rainflow” cycle counting model, which are widely used by engineers, technicians, and in software tools). We have simulated two realistic stand-alone PV systems and we have compared the real lifetime of the batteries with the lifetime predicted by the different models. We conclude that the Schiffer model shown in [4] is the only one that gives good results. The results show that, in many cases, the approximations of the equivalent full cycles or the rainflow cycle counting methods can be very inaccurate. In some cases, the expected lifetime is more than two or three times the real lifetime.

3. Mathematical modelling and simulation of the system

The stand-alone PV system model used in this work is described in this section. Fig. 1 shows the system, composed of the PV

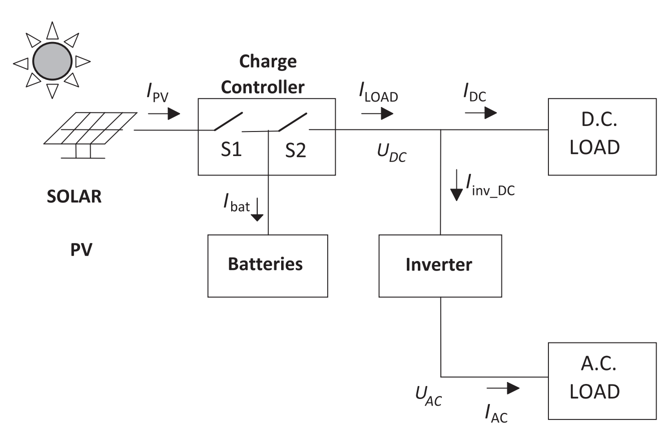

Fig. 1. PV system.