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Lifetime estimation tool of lead–acid batteries for hybrid power sources design

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ABSTRACT

Generally, battery lifespan depends on the number of cycles and depth of discharge (DOD). Nevertheless, in a renewable hybrid power system, charge and discharge cycles are random and not regular. Therefore, it is important to develop an aging model suitable to this case. Thus, in this paper, a pertinent way for aging lead–acid batteries connected to a stand-alone multi-source renewable system has been developed. It is based on the Rain Flow method for counting cycles and considers instantaneous DOD and average temperature. In fact, for each functioning year, a classification of the number of cycles according to the DOD is done. Then, based on these data, the battery degradation rate is estimated so that it is possible to draw conclusions about battery lifespan.

The method has been successfully applied to a multi-source power system simulated dynamically under Matlab/Simulink. This last takes into account with good accuracy several inputs and elements such as sun irradiation, wind speed, load profile, photovoltaic generator, wind turbine, and diesel generator. Results show the influence of the DOD and the batteries nominal capacity on their lifespan. A mean of eight years' life is detected. Finally, a reasonable over-sizing may favor battery longevity.

1. Introduction

During this last decade, renewable energy power sources coupled to a diesel generator (DG) and batteries [1] have been widely used for isolated electrification sites. Indeed, in many cases, autonomous renewable systems may be insufficient to completely satisfy the load without diesel generators; hence the importance of such multi-source configurations. For this reason, several authors have adopted autonomous hybrid configurations combining solar, wind and diesel generators, gas turbines, and various storage systems. In [2–5], authors have been interested in hybrid installation design considering different architectures and optimizing the economic cost. In [6,7], authors have proposed to integrate the ecological cost in addition to the economic one on the design optimization of a stand-alone hybrid wind–photovoltaic (WT–PV) power system with battery storage. They have considered embodied energy expressed on MJ as a relevant objective function taking into account the components' life cycle just based on manufacturers' mean values. For example, they consider 5-year lifespan for VRLA lead–acid batteries. Thus, to continue and improve such a kind of study, we propose to thoroughly evaluate battery lifespan for better cost and replacement evaluation and consequently better optimization results.

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In [8], several approaches for lifespan assessment have been presented and applied to lead–acid batteries. The first approach uses an aging physicochemical model; it is based on a study of chemical and electrochemical reactions. The second approach is called "Ah Weighted aging model". Its principle is founded on the assumption that battery degradation affects its initial nominal capacity. The third approach is based on the "Event-oriented aging model". Its principle consists on the use of a Wöhler curve which models the aging rate according to the number of cycles. For electrochemical systems, this approach is valid when several conditions are met. An event corresponds to a rate of life, generally identified in an experimental way or by using knowledge bases.

A comparative study between aging models has been presented in [9]. They are applied to estimate the longevity of lead–acid batteries integrated in an autonomous photovoltaic system. The influence of a charge controller has been investigated. A behavioral study of the lead–acid battery in a PV system was presented by [10]. The Authors have used mathematical models to follow battery capacitance and internal resistance variations, depending on the charge–discharge current and temperature.

In [11], the Event-oriented aging approach is applied to the analysis of lead–acid battery lifespan connected to a hybrid solar–wind power system.

In [12], a methodology to evaluate lithium battery life under well-defined operating conditions has been proposed. It allows for determining the number of battery cycles from the following variables: operating temperature *T*, depth of discharge (DOD) and the current rate of battery charge–discharge.

After aging tests, several mathematical models have been determined. A first model represents the variation of the number of cycles according to temperature; four operation points have been considered: $-18\,°C$, $0\,°C$, $25\,°C$ and $40\,°C$.

A second model represents variation of the number of cycles according to various depths of discharge DOD: 20%, 40%, 60%, 80% and 100%. A third model translates the variation of the number of cycles with the current rate of charge and discharge.

The aim of our work was to propose a new modeling approach to evaluate the lifetime of a lead–acid battery integrated within a multi-source system (PV/WT/GD + Battery). The objective is to minimize the cost of the installation and then the cost of energy [1,13]. Storage systems based on a lead–acid technology are largely used in electrification powers systems [14–16] and especially in renewable energy applications (Uninterruptable Power Source (UPS), multi-source system) [17,18]. Lead–acid technology presents different advantages such as good performance and low cost. Also, in power grid applications the lead–acid technology allows the provision of power up to 10 MW compared to lithium technology which is limited to 1 MW [17,18]. However, lithium battery technology is used in stationary applications and more largely in embedded systems such as hybrid vehicle [12]. This is due to its high performance and low weight. In addition, to improve the performance of hybrid electrification systems both battery technologies are used simultaneously [18].

In our study the cost of the installation represents an important parameter of the sizing optimization of the multi-source system. That is why the choice of the lead–acid technology has been considered.

The proposed methodology is based on mathematical aging models depending on the DOD and the temperature. A new model has been developed by using experimental data from the lead–acid battery manufacturer and the exploitation of the interpolation technique. This model is able to describe the aging behavior of the battery for every operating DOD and\or temperature.

The battery aging model takes into consideration the sizing parameters of the different energy sources of multisource system (PV/wind/DG) and the load profile for one year of operation (17.520 points). The load profile test is generated by the dynamic simulator using real data which represent the consumption of a residential habitat [19]. This profile is characterized by a dynamic behavior and random cycles including a lot of micro-cycles of charge–discharge of the battery bank.

The paper is thus organized as follows:

In the section two, the lead–acid battery aging model is presented for different technologies and taking into account the DOD and temperature. Then, in section three the proposed aging model is applied to evaluate the lifetime of a battery bank integrated in a multi-source system. Sensitivity studies for different depths of discharges and storage capacities are performed. Satisfactory results obtained by the proposed methodology will be discussed in section four. Finally, conclusions and perspectives of our work are deduced.

2. Battery lifetime modeling

Battery lifespan assessment in multi-source power systems is very important for better design optimization and management. In this section, two models are presented. The first gives a maximum number of cycles depending on the DOD. The second reflects the temperature influence on battery cycling and performances.

2.1. Battery aging model depending on DOD

The first model is based on manufacturer's data [20,21]. It characterizes the lifetime in terms of a maximum number of cycles *Nc* for different depths of discharge *DOD*. To illustrate this model, various types of lead–acid batteries are considered as summarized in Table 1.