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Hysteresis effect influence on electrochemical battery modeling

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ABSTRACT

This paper studies the influence on the voltage estimation accuracy of a novel hysteresis effect model. The model is applied to six different battery technologies: Lead–acid AGM, Lead–acid gel, Nickel–cadmium, Nickel–metal hydride, Lithium-ion, Lithium-ion polymer. The proposed hysteresis electrical model estimates the variation of the parameters in a classical model when considering hysteresis effects. A general model is proposed and the characterization process is optimized so that it can be applied to all studied cells. The model is composed of three circuits: voltage–current circuit, Ah counting circuit and hysteresis electrical model circuit. All the parameters for all six technologies are calculated and compared. The model evaluation is carried out through 18 case studies. The results are compared in terms of increment of voltage estimation accuracy when considering hysteresis and influence of hysteresis on a certain technology. The model average voltage estimation error of all technologies is 0.48%. When hysteresis effect is included the average error reduces in 0.71%.

1. Introduction

As the use of electrochemical batteries becomes a standard practice in applications like transportation, electronics or renewable energies [1], due basically to its wide range of power and energy densities and competitive costs, accurate battery information becomes a relevant issue in order to efficiently use them [2]. A great variety of electrochemical battery technologies have been presented, being the ones based on lead, nickel and lithium the most used nowadays [1,3,4].

Accurate battery information is crucial to ensure the most efficient working conditions and therefore, having a good battery model is critical [2]. There exist a great number of types of battery models although electrochemical and electrical approaches are the most important at present [5]. In this paper, only electrical models are considered, because of their simplicity and low computational requirements.

Among electrical models we find Thevenin models, which are designed for time domain, and Impedance models [6,7], which are designed for frequency domain.

Thevenin circuits use simple elements, such as capacitors or resistors, resulting in a simple model with low computational burden and are therefore very suitable for the paper interests. The accuracy of these models is very high for the majority of applications even though they do not model all battery frequency range.

The value of certain internal and external variables greatly affects the response of the models depending on the battery state. The most significant internal and external variables that affect the battery behavior are state of charge (SOC) [8,9], hysteresis [9], state of health (SOH) [2,10] cell temperature [7,10] and current [8].

A model composed of a second order Thevenin circuit, an Ah counting circuit and a novel hysteresis-dependent parameter model was presented in Ref. [11]. This model was verified for a single Ni–Cd cell. In this paper, the accuracy of the model for Lead–acid AGM, Lead–acid Gel, Nickel–cadmium, Nickel–metal hydride, Lithium-ion, Lithium-ion polymer cells is studied. An evaluation of the significance of the hysteresis on the different technologies is also presented. This study has not been showed in other papers before.

The main three contributions of the paper can be summarized as:

- Introduction of a comprehensive battery model able to include hysteresis effects. Optimized characterization processes for each circuit of the model are also included.
- Study and estimation of each model parameter for Lead–acid AGM, Lead–acid Gel, Nickel–metal hydride, Lithium-ion and Lithium-ion polymer. Previous results obtained for NiCd are also included in the comparison.

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- Validation of the proposed model for each cell type. Comparison of the contribution of considering the hysteresis in the battery model to increase the accuracy of the voltage response of the model.

2. Overview of the battery technologies used in the paper

Despite the fact that they exist for more than one hundred years already, electrochemical batteries development has only taken place in the past decades, when the number of applications with batteries has notably increased. Improvements like higher efficiency are theoretically limited due to physical properties of the materials. Polarizations have a very high influence on battery efficiency and are therefore a key factor for increasing battery efficiency. Each technology has its particular energy density and power density properties [12–14].

Only a few of the thousands of battery systems proposed throughout history were commercialized [13]. There are a set of characteristics that define their commercial adequacy. Very few combinations comply with these criteria. A proof of this is the fact that two of the oldest battery systems, introduced more than one hundred years ago, are still among the most used, as is the case with lead–acid batteries (rechargeable) and zinc dioxide–manganese batteries (primary) [13].

The most important secondary electrochemical batteries are, following actual and traditional applications, those based on lead, nickel and lithium, with a high market penetration percentage [12,13]. This paper is focused on six different commercial cells: lead–acid AGM, lead–acid gel, nickel–cadmium, nickel–metal hydride, lithium-ion and lithium-ion polymer.

Main cell characteristics are presented in what follows. Table 1 shows main manufacturing parameters.

2.1. Lead

First lead–acid cell was introduced by Gaston Plante in 1859. With a few design modifications, lead–acid batteries are still one of the most common technologies and widely used as rechargeable batteries. Lead and lead oxide electrodes are submerged into a water diluted sulfuric acid electrolyte. Heavy electrodes and electrolyte components result in low energy density. Sulfation is likely to occur for non-standard charging or discharging processes, such as deep discharges or high current charges or discharges, leading to a reduced lifespan. Moreover, efficiency decreases with high temperatures. Despite these drawbacks, lead–acid technology has been widely used in stationary applications, in vehicle applications as starting, lightning, ignition systems (SLI), for forklift and similar vehicles traction and in uninterruptible power supply systems (UPS).

Their cost is low and, by means of a good recycling process, they are considered to have a low environmental impact. According to the *Battery Council International Incorporation*, 98% of lead–acid batteries in USA are recycled [13,15].

All lead–acid batteries follow the same chemical reaction, as in Plante's original cell, which can be expressed as

$$PbO_2 + Pb + 2H_2SO_4 \underset{\text{charge}}{\overset{\text{discharge}}{\rightleftarrows}} 2PbSO_4 + 2H_2O \quad (1)$$

Valve-regulated lead–acid batteries (VRLA) were commercially presented in 1960. They are also known as sealed or maintenance-free batteries. They include a valve to avoid electrolyte spilling and leaks caused by electrolyte vaporization or gasification, which increases their lifespan and reduces maintenance. These valves can release gas when overpressure exists, avoiding recipient break.

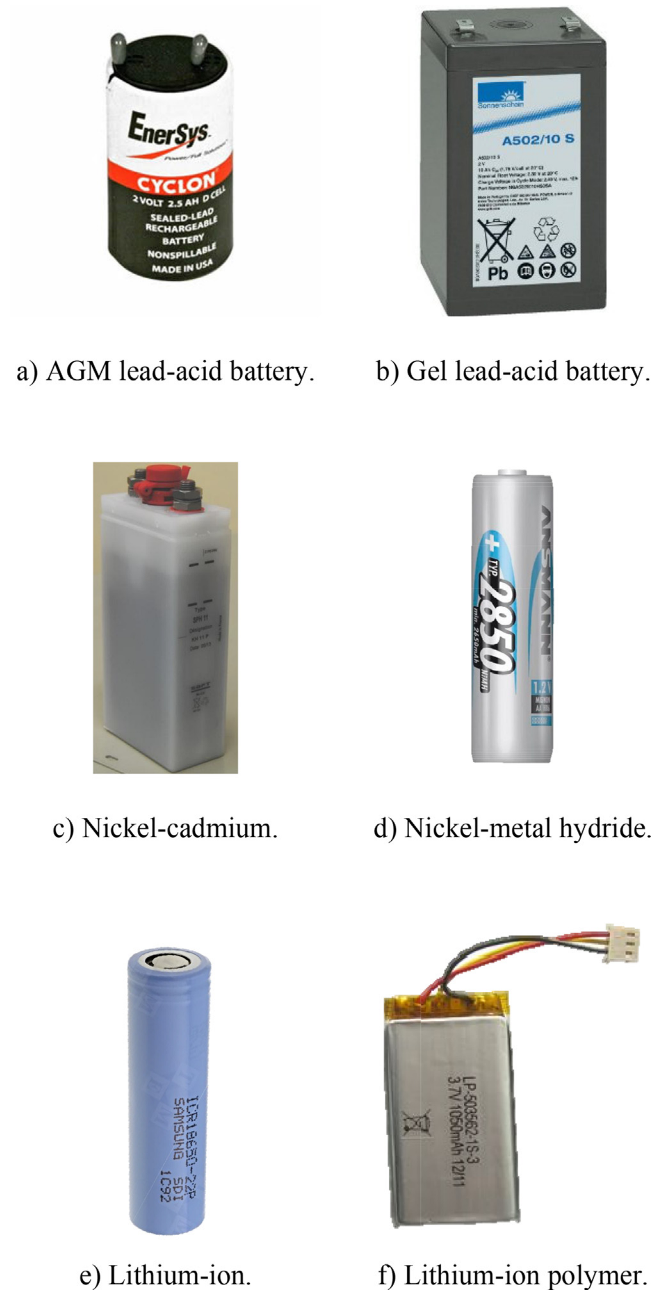

Fig. 1. Lead–acid, nickel and lithium batteries.

Their main advantage is the possibility of oxygen recombination in controlled overcharge processes [16].

There exist two main VRLA batteries: those having a fiber glass separator in the electrolyte, named *Absorbed Glass Mat* (AGM) and those with a silica-thickened electrolyte, resulting in a structure similar to gel. Gel batteries show less evaporation, greater lifespan and better voltage stability. They also tolerate deeper discharges, vibrations and high temperatures, but are in general more expensive.

In this paper, the following lead–acid batteries were used:

- AGM lead–acid battery, manufacturer EnerSys, model Cyclon D, shown in Fig. 1a.
- Gel lead–acid battery, manufacturer Sonnenschein, model A502/10 S, shown in Fig. 1b.