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Estimation of the state-of-charge of gel lead-acid batteries and application to the control of a stand-alone wind-solar test-bed with hydrogen support

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ABSTRACT

In hybrid renewable energy systems, batteries act as a DC bus to provide constant voltage and to smooth out commutations between the generating devices. These batteries are usually of a lead-acid type and operate under harsh variable conditions due to fluctuations of both solar radiation and wind speed. Precise knowledge of the state-of-charge of the batteries, and hence of their available energy, play a key role in effecting efficient control and energy management of the installation. The present study had a twofold aim. One objective was to adjust and validate a method based on coulomb counting to estimate the state-of-charge (SOC) of a gelled lead-acid battery which is the DC bus of a hybrid wind-solar system with hydrogen storage. Other works evaluate SOC models based on several parameters, however, the present proposal based on experimental measurements involves only a few parameters. The second objective was to modify the installation's control algorithm to use the battery's calculated SOC as control parameter instead of its voltage. The results of a test-bed system, showing how the system evolved under real operating conditions, constitute a proof-of-concept of the validity of the method.

1. Introduction

In recent years, the combination of renewable energy sources has contributed to minimize atmospheric degradation and climate change by substituting fossil fuel energy. The major advantage of combining these energy sources in a hybrid system is that it enhances the reliability of the system [1]. Renewable energy (RE) based power systems offer off-grid energy supply for various applications, such as the electrification of rural and remote areas with problematic grid connections, the powering of telecommunication stations, and others. These systems usually combine photovoltaic (PV) systems, wind generators, and diesel generators [2].

Storage and transport are among the problems which need to be solved when using renewable energies, since they are diluted and diffuse forms of energy, and so their supply can be extremely intermittent and unreliable [3]. There is therefore a need for storage systems that can accumulate the energy produced in periods of low demand to be utilized when the demand is high, ensuring full utilization of the intermittent sources that are available. Hydrogen is an attractive energy carrier since it is one of the cleanest, lightest, and most efficient fuels. However, it is not found naturally and, like

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Nomenclature

AGM	absortive glass mat
C	available capacity
C_{nom}	nominal capacity
CSGE	colloidal silica gel electrolytes
DC	direct current
EMF	electromotive force
G	global irradiance, (W/m^2)
I	electrical current, (A)
LHV	lower heating value, (J/kg)
VOC	open-circuit voltage
PLC	programmable logic control
PMS	power management strategy
PV	photovoltaic
RE	renewable energy
RES	renewable energy sources
SOC	state-of-charge
T	temperature, (°C or K)
TP	touch panel
UPS	uninterruptible power supply
V	voltage, (V)
VRLA	valve-regulated-lead-acid

Greek letters

δ_C	temperature coefficient
η_{bat}	battery efficiency (dimensionless)
σ	self-discharge coefficient (dimensionless)

electricity, must be produced from primary energy sources. Unlike electricity however, after production it can be stored. For short-term applications, batteries, compressed air, flywheels, and capacitors appear to be the most feasible and attractive, but for long-term application the use of certain chemicals is preferred [4].

Batteries currently constitute the main solution to energy storage needs in a wide variety of autonomous applications, from vehicles and portable devices to isolated renewable energy systems, including many industrial uses mainly related to ensuring energy supply in case of mains failure (for example, UPS or telecommunications) [5].

Batteries are not appropriate for long-term storage because of their low energy density and self-discharge. The combination of a battery bank with long-term energy storage in the form of H_2 can significantly improve the performance of stand-alone RE systems. In such an RE system, the electrolyzer generates H_2 during times when excess solar and wind energy is available, and the fuel cell utilizes this H_2 to produce electricity when there is insufficient solar and wind energy [6–12]. The battery bank smooths out the electrical power flow between the components and provides electricity for the daily operation of the control unit and auxiliary devices [13,14].

In practice, two different immobile electrolyte battery technologies have commonly been used. One is the valve-regulated lead-acid (VRLA) battery with an AGM (absorptive glass mat) separator and starved electrolyte [15–18]. The other is the VRLA battery with gelled electrolyte [19,20]. Tang et al. [21] enumerate the advantages of gel VRLA batteries in comparison with conventional flooded or AGM batteries: (i) they have a long service life and high reliability under deep discharge cycles; (ii) there is no acid stratification and they can be installed in any orientation; (iii) there is no leakage of acid mist, charge stability is good, and operation is maintenance-free. The most commonly used gelled electrolyte consists of fumed silica, although colloidal silica gelled electrolytes (CSGE) are receiving increasing attention because of their good stability and low cost.

With gelled electrolyte, the corrosion rate of the positive grids is lower than with AGM technology, and the evolution of the hydrogen overpotential on the negative plate is also higher. For these reasons VRLA batteries have a considerably improved performance [20].

The higher cost of VRLA batteries as compared to flooded ones has restricted their use in installations such as automotive or PV systems, despite their excellent performance, which has been patent for decades, in deep cycling applications [22]. In hybrid systems with hydrogen support, a battery bank is used for short-term energy storage due to its high charging-discharging efficiency, and also because of its ability to deal with the effects caused by instantaneous load, electrolyzer transients, and wind energy peaks.

A complete analysis of the battery's charge and discharge requirements is required in order to size the battery bank in this kind of application. Two properties of the battery are usually related to the hybrid system's performance: state-of-charge (SOC) and open-circuit voltage (VOC) [23].

The present work proposes a method for determining the SOC of a gel VRLA battery installed in a test-bed hybrid wind-solar system with hydrogen storage support. The resulting value is used to control the test-bed system. Prior to this work, hydrogen generation and consumption devices were controlled using as control variable the DC bus voltage, i.e., the voltage across the battery terminals. However, this voltage is not representative of the energy in the battery because it depends on the current intensity being supplied or withdrawn, the ripple introduced by the electrolyzer and the fuel cell, variations in load demand, and the intrinsic intermittent nature of RES. As indicated by Agbossou [24], the DC bus voltage alone cannot be considered an appropriate variable with which to control the operation of an RE plant.

The contribution of this work to estimating the SOC of a gel battery is the adaptation and validation of an Ah counting method based on current integration using the actual values of the variables involved. The battery is the DC bus of a hybrid wind-solar installation with hydrogen storage. The estimated SOC value will be used as the system's control parameter. Unlike other work on hybrid power systems which use a computer to estimate the battery's SOC [25–27], in our case the calculation procedure is implemented in the PLC that controls and monitors the system. This procedure for estimating the battery's SOC is particularly innovative, and endows the system with robustness, reliability, and dependability. The paper is organized as follows. Section 2 describes the hybrid system, and Sec. 3 defines the SOC level of a battery. Different methods for estimating the SOC are