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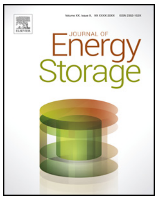

State-of-charge observers for lead-acid storage units used in autonomous solar applications

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ABSTRACT

The article provides practical means to monitor batteries that work in the so-called float cycling regime. The main interest of the case study is destined for autonomous solar applications. The problem of the state-of-charge estimation of lead-acid storage unit is studied. Two approaches are considered and compared: the sliding mode technique and the fuzzy logic modelling. Based on the grounds of observers design theory, it was shown that the sliding mode technique exhibits robustness properties in the face of parameters imprecision and unknown non-linear behaviour. The fuzzy logic modelling approach allows designing the monitoring scheme using the reduced number of available information. An evolutionary programming technique is applied to adjust the parameters of the fuzzy logic resolution scheme. The results are compared with reference state-of-charge measurements taken from an industrial battery charge regulator. The developed models are potentially extensible to other types of storage units.

1. Introduction

Electric energy storage is a crucial problem for autonomous systems powered by photovoltaic installations [1]. The excess of produced energy under favourable conditions is normally stored into batteries. For large scale applications, where more than one battery is used, the correct utilization of the storing bank plays an important role in order to extend the batteries' lifetime. The context of this work is related to the research on a solar assisted domestic heating application, which includes an autonomous photovoltaic installation and a software-driven resistance load which represents a dwelling heated by a heat pump. The load stands as a sink with time-varying energy consumption. The energy pattern resulting from the climate condition and the user driving behaviour implies a hard float cycling work of the storing bank. Moreover, in such applications, due to the tolerances on the internal parameters, the interactions between the batteries are unavoidable. As a result, some storage units work under constant discharge conditions whereas the others take on the overcharge current and imbalances occur. Therefore, a state-of-charge monitoring scheme of an individual unit can provide an essential information in order to improve energy management.

The notion of State-Of-Charge (SOC) can be explained in terms of the energy available to the user in given charge/discharge conditions. Knowing the amount of energy left in a battery compared with the energy it had when it was new gives the user an indication of how much longer a battery will continue to perform before it needs recharging. The SOC is a fictitious variable which embodies the physical phenomena that occur in the battery and it cannot be explicitly measured. Hence, many modelling approaches have been developed to determine the SOC [2–7]. Unfortunately, none of the existent model assures a reliable estimation of it and new approaches are under development. Typically, the procedure of SOC determination involves the modelling of the battery behaviour under operating conditions. Generally, several methods of SOC estimation are used [8,9]:

- SOC as a linear/non-linear function of the battery open circuit voltage
- Ampere-counting techniques such as current integration
- SOC as a function of the battery impedance

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Each technique has its disadvantages. Since the SOC is a nonlinear function depending on many parameters it is difficult to design an adequate model. The open circuit voltage represents the SOC function but is not though available under load. Thus, different observers based on the equivalent electric circuit have been designed to reconstruct this state in order to determine the SOC.

The current integration method stands as a better solution to determine the SOC and it takes into account all charging and discharging currents. But also ampere counting does not allow an adequate SOC processing due to the errors accumulated during integration.

The Electrochemical Impedance Spectroscopy (EIS) methods [4] are commonly used to determine the physical parameters of the equivalent electric circuit and therefore give the essential information about SOC. Nevertheless, the battery impedance does not altogether reflect the SOC but provides in turn knowledge about faults, battery age, corrosion of electrodes, and other active mass properties. Besides, its practical implementation with systems that constantly work under load is complicated too.

Since the battery exhibits a non-linear behaviour and its parameters may contain uncertainties, it appears interesting to study and compare two approaches of SOC calculation:

- Robust state estimation, based on the sliding mode technique
- Fuzzy logic observation, based on the black-box modelling

The sliding mode technique for SOC calculation is an important approach for robust observers design. It addresses the problem to improve the accuracy of information of incoming data containing errors or uncertainties [10–12]. The recent investigations in SOC estimation for lithium batteries [13] prove the interest of developing robust observers also for other types of electrochemical storage units. However, the gain of robustness properties pays its price for some speed performances.

The fuzzy logic approach stands as a very promising technique to estimate the SOC based on the least knowledge about the battery behaviour. Fuzzy logic allows complex systems to be modelled using a higher level of abstraction originating from knowledge and experience. In terms of SOC monitoring, recent studies have produced notable results. Numerous papers describe fuzzy logic observers which use the impedance knowledge database to determine the SOC [14,15]. However, the implementation of such observers is rather complicated because of the impedance measuring scheme. In practice only two parameters are available − voltage and current. Since the current-based SOC estimation method provides higher accuracy but still needs compensation for the operating conditions, it can be combined with the voltage-based method.

2. Material and methods

The experimental data have been collected from a flooded-vented lead-acid battery with declared 125 Ah of capacity for 20 h and 12 V of nominal operating voltage. The battery (VARTA) is designed to work in float cycling regime. The battery has been integrated into an experimental installation that consisted of a constant-voltage power supply (Agilent 6268B) connected to a battery charge regulator (STECA TAROM 2140) equipped with a data logger (TARCOM). A programmable electronic load (KIKUSUI PLZ-4W) has been either used to determine the energy consumption profile. The charge regulator has a built-in SOC meter and the manufacturer states its high reliability.

Two kinds of experiments have been carried out:

a) Impulse current discharge test. It allowed obtaining explicitly the analytical dependency of the open circuit voltage to the SOC. The applied procedure comprised the alternating short discharging tests with a 12.5A current and 10-min rest periods. Both the open circuit voltage and the SOC then have been recorded in the data logger at the end of every rest period.
b) Sequential charge and discharge test. It has aimed to investigate the battery behaviour in different discharging and charging conditions. The initially fully charged battery has been subjected to discharging and charging cycles of 1A-, 3A-, 5A-, 7A-, 9A- and 11A-constant rate current. The measurements of voltage, current and SOC have been stored in the data logger during 333 h of total work.

All the experiments have been carried out in a protected ambiance at about 20 °C without significant temperature variations – less than 1 °C.

3. Theory of the state-of-charge observers design

3.1. Robust sliding-mode observer

A robust observer faces the state estimation problem out of very inaccurate information. In real operating conditions, the battery is influenced by unknown disturbances and the model parameters vary with time [16]. The sliding mode technique guarantees the robustness of the observer as it allows rejecting any parameter variation and any unpredictable disturbance.

3.1.1. System modelling

The structure of the sliding mode observer is based on the RC-equivalent electric circuit presented on the Fig. 1, which many researchers have used to model the behaviour of an electrochemical storage unit [16,17]. The source $V_{oc}(Z)$ depends on the SOC, denoted as Z. R_t is the internal resistance of the battery, R_p is the charge transfer resistance which is due to limitations in the chemical reaction rates at the electrode/electrolyte side, C_p is the polarization capacitance. Both R_p and C_p are used to model the diffusion phenomena and the repartition of the cumulated charge in the active mass.

The numerical values of parameters R_t, R_p ad a C_p are usually identified by the EIS method with some adequate equipment. Distinctive results of the EIS identification for lead-acid batteries can be found in [18,19]. Since the systems designed on the ground of the sliding mode theory exhibit robustness properties in the face of internal parameters variations, we suggest using as numerical values of parameters those which are cited in the literature [18,19].

In accordance with the impulse current discharge test *(a)* results, the open circuit voltage $V_{oc}(Z)$ has been modelled by using a nonlinear function:

$$V_{oc}(Z) = kZ + d - \mu_1 e^{-\mu_2 Z} \tag{1}$$

The comparison of the measured and approximated open circuit voltages is shown in Fig. 2. The time derivative of the SOC is

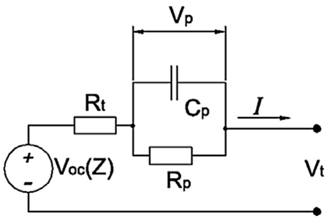

Fig. 1. RC-equivalent electric circuit of a lead-acid battery.