State of Health Estimation of VRLA Batteries Using Fuzzy Logic

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Abstract— **State of Health (SOH) is an important characteristic in determining the overall profile of a battery. SOH is a measure of the remaining full charge capacity of a battery with respect to its nominal capacity. As continuously charged and discharged and battery ages, the chemical composition starts to degrade. This paper describes a novel online method to determine the SOH of a battery. In the proposed method, the SOH of Valve-Regulated Lead-Acid (VRLA) batteries is estimated using the relation between the State of Charge (SOC) and the battery open-circuit terminal voltage (Voc). This estimation is performed using the least-square method and the fuzzy logic. Experimental results show good estimation of the SOH in relatively short time.**

Keywords- State of Health, VRLA batteries, Estimation.

I. INTRODUCTION

One of the important issues in using industrial and consumer batteries is to know how many times a battery can still be charged and discharged. In other words, how long of the battery life still remains. This question can be answered by a concept known as the State of Health (SOH). In technical terms, SOH is the capability of the battery to deliver a given power profile $P(t)$ or a current profile $I(t)$. In terms of the stored charge in battery, the SOH is defined as

$$SOH = \frac{Q_{\max}(\text{Aged})}{Q_{\max}(\text{New})}, \tag{1}$$

where $Q_{\max}$ is the maximum amount of charge that can be drawn from the battery. Since the electrolyte density of an aged battery is reduced and its resistance is increased, this definition of SOH indicates how much reactive material is still electrically active in an aged battery [1, 2].

Different methods have been proposed in literatures for the SOH estimation. It should be noted that this estimation is not the same for different battery types and/or applications. The proposed methods for the SOH determination in literatures can be divided into two categories:

Determining the SOH in laboratory by changing effective parameters, such as temperature, in a wide range.

Determining the SOH using the AC and DC impedances and conductance measurements.

The model of a battery is the key part for estimation of the SOH of a battery. Salkind et al. have shown that the model of a Valve-Regulated Lead-Acid (VRLA) battery is based on the electrochemical operation and variations of the voltage and current during the charging and discharging processes [5]. Pascoe and Anbuky have proposed a model for VRLA batteries based on the discharge rate, ambient temperature, charge rate, initial SOC, and SOH degradation [6]. This model has been further developed in different operating conditions by Jossen [7].

Two AC-measuring methods, the conductance and impedance testings, have been proposed for assessing the SOH of VRLA batteries. These methods can find the failed battery in a battery bank [8, 9]. The Coup de fouet and temperature-based techniques are other algorithms for the battery SOH determination. However, the problem with determining the SOH using the temperature is that the battery SOH is indirectly correlated with the temperature changes. Moreover, the temperature has a low to medium reliability in this regard [10]. The SOH of a lead acid battery can be estimated accurately by measuring the coup de fouet voltage, appearing in the early stages of the battery discharge [11, 12 and 13]. Krein and Balog have proposed a method to find a failed battery in a bank of batteries, containing combination of multiple cells, using the charge balancing or equalization; hence, extending the battery life and reducing costs [14]. Successful approaches based on the impedance measurements to assess the SOC and SOH of lead–acid batteries have been proposed in literatures [15, 16 and 17]. The Galvano-static non-destructive technique has been used to determine the SOH of a battery by analyzing its impedance parameters [18]. The fuzzy logic [19, 20 and 21], Kalman Filter (KL) and Extended Kalman Filter (EKF) [22] have also been used to estimate the battery SOH. Measuring the effective voltage noise and the number of peaks counted in the voltage graph has been employed for SOH determination [23]. An accurate two-pulse load test method has been proposed by Coleman et al. to determine the SOH of VRLA batteries using the battery terminal voltage measurement [24]. The SOH of VRLA batteries has also been studied using the partial SOC operation [25].

In this paper, a dynamic model, which is based on the electrochemical operation of the battery and the variations of the terminal voltage and current, is proposed for determining the SOC and SOH of VRLA batteries. The SOC is estimated using the EKF. For the SOH estimation, the relation between

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the battery open circuit voltage and the SOC is employed. One of the main advantages of the proposed method is that it can be used online to estimate the SOH of VRLA batteries. Experimental results show accurate estimation of the SOH of VRLA batteries.

This paper is organized as follows. Section 2 illustrates the model of VRLA batteries, employed in this paper, for the on-line SOH estimation. Section 3 provides the Q-V_{OC} graph, necessary for the on-line SOH estimation. Section 4 shows how to design a fuzzy system for estimating the SOH. Section 5 shows the experimental results. Section 6 gives brief description of the hardware setup. Section 7 concludes the paper.

II. Model of VRLA Batteries

Fig 1 shows a simplified equivalent model of VRLA batteries [22]. This model has been employed before to simulate the response of VRLA cells to constant current and dynamic power cycles. In this figure, R_i is the lumped resistance due to the cell interconnections. A double layer capacitance $C_{surface}$ shows the result of charge separation at the electrolyte/electrode interface and R_t in parallel shows the impedance property of $C_{surface}$. The capacitance C_{bulk} models the battery's charge storability. When the battery is in rest, the charge stored in the small capacitance $C_{surface}$ will quickly discharge in R_t. Hence, after a short time, the circuit comes to the steady state and the battery's open circuit voltage is equivalent to the voltage across the C_{bulk}.

The open circuit voltage of a battery has the following linear relation with the SOC [26]:

$$V_{OC}(t) = a_1 SOC(t) + a_0 . \quad (2)$$

Moreover, the SOC is related to the stored charge Q as

$$SOC(t) = SOC(t_0) + \frac{\int_{t_0}^{t} I_b(\tau)d\tau}{Q_0} \times 100 , \quad (3)$$

where $SOC(t_0)$ is the initial SOC of the battery, η is the battery efficiency: [0,1] for charging and 1 for discharging, I is the battery's transient current: positive for charging and negative for discharging, Q_0 is the nominal power content of the battery based on the Ampere–hour or the maximum content of the stored power in a new and healthy battery.

Hence, it can be concluded that when terminals of the battery are open, the value of Q is proportional to the voltage across the C_{bulk}. During the charging and discharging, this value is proportional to the voltages across the bulk and surface capacitors.

The capacitance $C_{surface}$ shows the power storability of the battery; hence it can be a measure of the battery ages.

Consider two batteries, one new and completely healthy and the other one used with less charging capacity. Assume that the same amount of Q is stored in both batteries. Therefore, based on $Q = CV$ it can be concluded that the aged battery must have higher open-circuit voltage than the new one. This idea can also be observed from Figs. 2(a) and 3(a). These figures show the experimental measurements of the relation between the open-circuit voltage and the power stored in four batteries with different ages during charging and discharging processes, respectively. The stored power Q is estimated using the EKF [22]. Moreover, the SOH of these batteries are determined using Eq. (1). The data from three of these batteries with SOH=100% (blue), SOH=64% (green) and SOH=46% (black), are used off-line for constructing a fuzzy system to estimate on-line the SOH of the fourth battery.

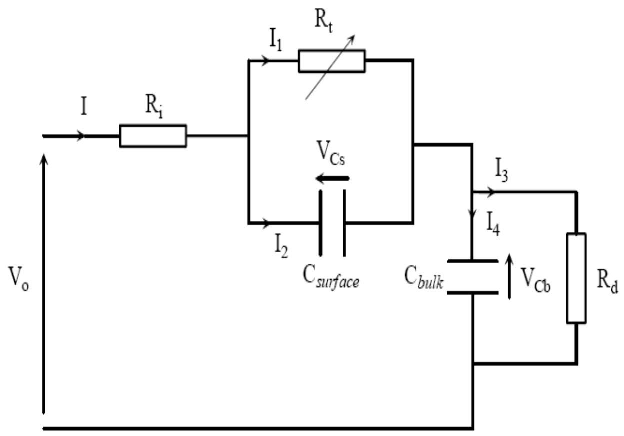

Fig.1. equivalent circuit of a VRLA battery

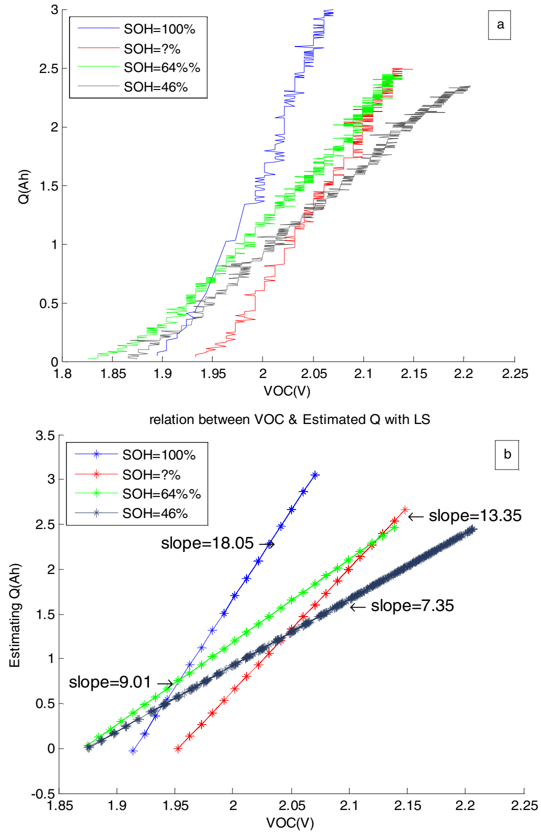

Fig.2. The graph of V_{oc} vs. Q of 4 batteries with different *SOH* during charging process (a) experimental result (b) estimation line by LS method.

III. SOH Estimation Using Fuzzy Logic

A. Slope of Q-V_{OC} Graph

Figs. 2(a) and 3(a) show the graph of Q vs. V_{OC} during the charging and discharging processes, respectively. By ignoring the first part of these graphs (circled in Fig. 3(a)), which corresponds to the very low charge volume and low voltages of the battery (i.e. when the device cannot be used as a power source), the remaining part of the graph shows an almost linear relation between the Q and V_{OC}. Eq. (2) also confirms this fact. It should be noted that the SOH of three batteries (marked with blue, green and black colors) have been determined using Eq. (1) by data collected from experiments.

The slopes of these three graphs are determined using the familiar Least-Square (LS) method [27, 28]. Fig. 2(b) and 3(b) show the calculated slopes for the charging and discharging processes, respectively. These values are also summarized in Tables I and II, respectively. It should be noted that 46% is the lowest value of SOH that a battery can have. I.e., any battery with $SOH < 46\%$ is considered as a dead battery.

In the next subsection, the slopes of these three lines along with their corresponding SOH are used to build a fuzzy system. Then, the fuzzy system is employed for online estimation of the SOH of an unknown battery during charging and discharging processes. The Recursive LS (RLS) is employed for online estimation of the unknown SOH [27, 28]. In this method, instead of using all data off line to estimate the slope the Q-V_{oc} graph, it is estimated in on-line fashion using the current and previous samples of data. Hence, for the first few samples, the slope changes drastically, especially because noise and uncertainties in systems parameters are present in measurements. However, after several sampling data, the slope will converge to a certain value; after this point almost no noticeable change in the slope can be observed. The RLS algorithm can be found in most text books related to parameter identification, e.g. [27].

B. Designing Fuzzy System

Two fuzzy systems are designed in this paper for the SOH estimation, one for charging and the other one for discharging. The input to the fuzzy systems is the slope of the Q-V_{oc} graph. The output is the SOH. Figs. 4, 5, and 6 show the membership functions of the linguistic variables defined for the input and output, respectively. The fuzzy IF-THEN rules are shown in Table III. As this table shows, the fuzzy system is comprised of only four rules, which make the fuzzy system very simple with little calculations. Therefore, the proposed method can be applied with inexpensive processors.

The inference engine is of Mamdani product type. The singleton fuzzifier and the center of average defuzzifier are selected for designing two fuzzy systems.

TABLE. I. Slope of Q-V_{OC} graphs and their corresponding *SOH* of three batteries during charging

Slope of Q-V_{OC} graph	**SOH**
18.05	100%
12.01	64%
7.36	46%

TABLE. II. Slope of Q-V_{OC} graphs and their corresponding *SOH* of three batteries during discharging

Slope of Q-V_{OC} graph	**SOH**
8.78	100%
4.03	64%
2.79	46%

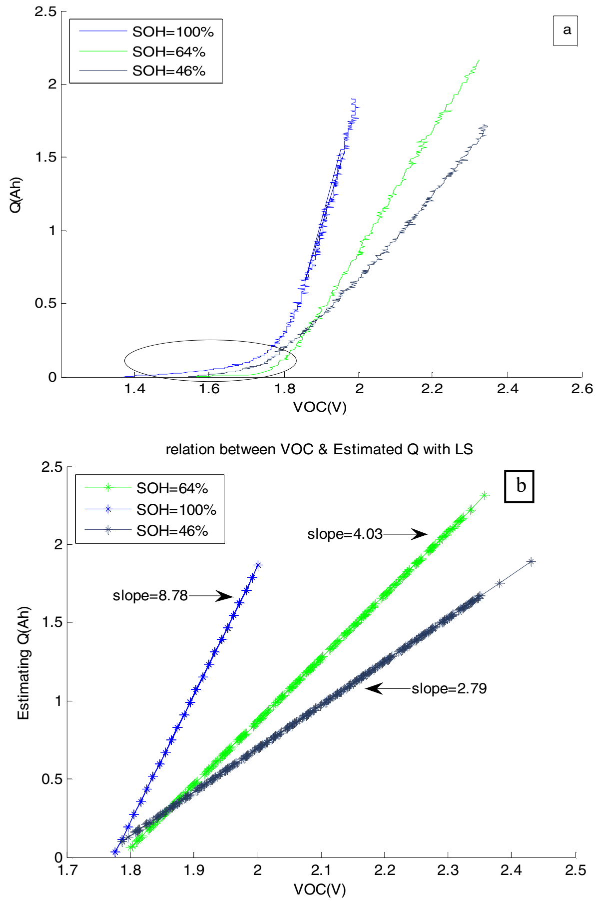

Fig.3. Same as Fig. 2 but for discharging process.

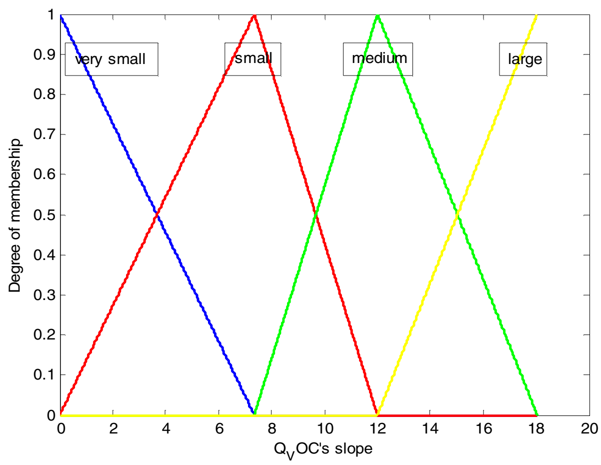

Fig. 4. Membership functions of the input variable (slope of the Q-V_{OC} graph) for the charging process.

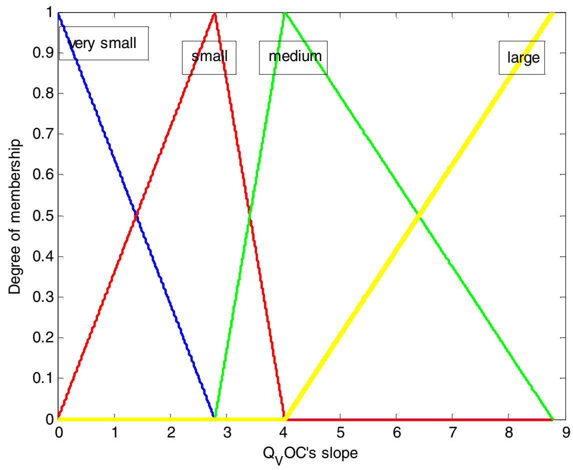

Fig. 5. Membership functions of the input variable (slope of the Q-V_{OC} graph) for the discharging process.

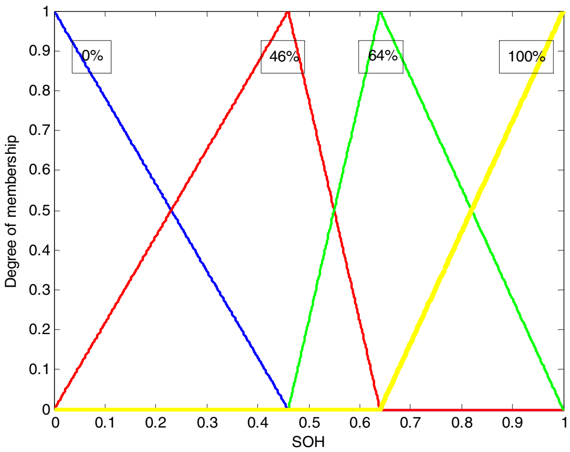

Fig. 6. output (*SOH*) membership function

TABLE. III. FUZZY IF-THEN RULES FOR ESTIMATING *SOH*

	RULES
1	**IF** *slope* is very small, **THEN** *SOH* is 0%
2	**IF** *slope* is small, **THEN** *SOH* is 46%
3	**IF** *slope* is medium, **THEN** *SOH* is 64%
4	**IF** *slope* is large, **TEHN** *SOH* is 100%

C. *SOH Estimation and Experimental Results*

The designed system, explained in previous sections, is tested in the next step as an estimator. At this stage, the SOC is estimated online using EKF [29] during charging and discharging processes [22]. The charging method is of the reflecting type in this paper [26]. Hence, the open-circuit voltage V_{oc} is measured during the zero current (i.e. when the battery's states are stabilized). Using the estimated SOC and the measured V_{oc}, the slope of the Q–V_{oc} is calculated using the RLS method. After about one hour, the estimated slope will converge to its final value. Then, using the estimated slope as the input to the fuzzy system, the estimated SOH of the battery is the output of the fuzzy system.

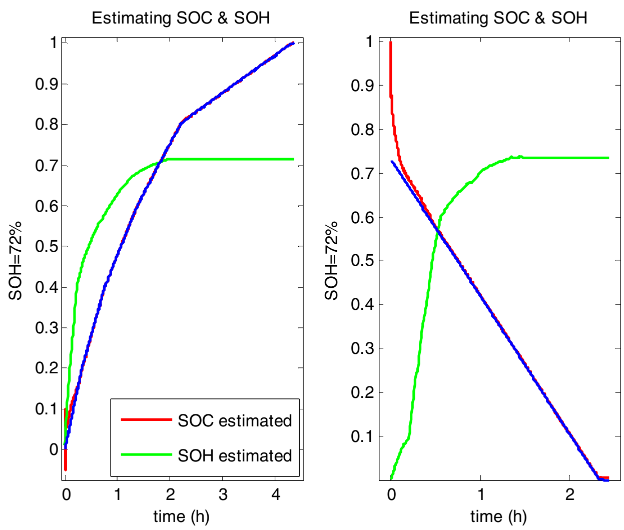

Fig. 8. Estimation of SOH and SOC of an unknown battery during charging and discharging processes.

First, the SOC and the SOH of the same three batteries, whose data were used for constructing the fuzzy system, is estimated to show the accuracy of the proposed method (Fig. 7). As this figure shows, the estimated SOC converges to the actual SOC (measured by the Ampere-Hour technique) very quickly during charging and discharging processes. The estimated SOH also converges to the actual SOH (calculated by Eq. (2)) in about one hour. The final estimation of SOH (the green lines in Fig. 7) shows that the proposed method has an estimation error of 3% or less.

Next, the SOC and SOH of an unknown battery (i.e. a battery, whose data were not used to construct the fuzzy estimator) will be investigated. The actual SOH of this battery, calculated by Eq. (1), is 72%. Fig. 7 shows that the estimated SOH during the charging and discharging processes is 71% and 73%, respectively. That is, the estimated error of the SOH of the battery (with unknown SOC and SOH) is almost 1%, which shows the accuracy of the proposed method.

IV. HARDWARE SETUP

All experimental results presented in this paper are obtained from tests carried out on VRLA batteries with the nominal capacity of 2.5 Ah and the nominal voltage of 2 V [30]. Appropriate voltage and current sources are designed to provide accurate charging process, which is of reflecting type [26]. The sampling rate in the hardware design procedure is equal to 27 msec., which has been defined based on the battery time constant provided by the manufacturer equal to 100 msec. The *SOC* is estimated during every sampling time using the EKF. The AVR-ATmega128 processor [31] can perform the required calculations in less than 10 milliseconds. Figure 9 shows the hardware setup. The hardware is comprised of the voltage and current sensing circuits, the current supply, the voltage limiter (driver), and the interface circuit.

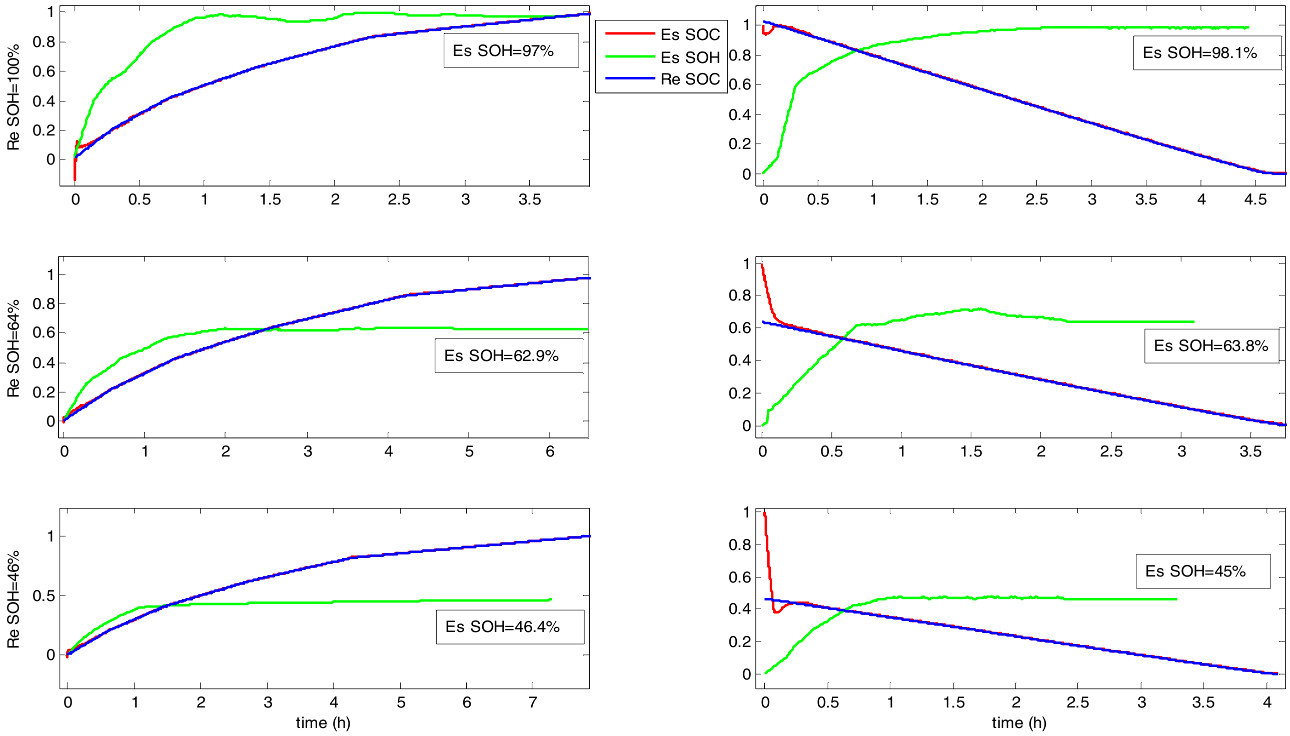

Fig. 7. Estimation of *SOH* and *SOC* of three batteries for known *SOH*=100%, 64%, and 46% during charging (left) and discharging (right).

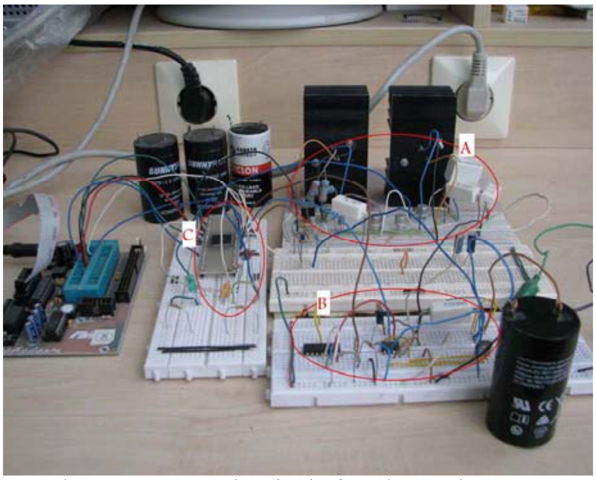

Fig.9. Hardware setup, A: sensing circuits for voltage and current, B: current supply and voltage limiter, C: interface circuit.

V. Conclusions

In this paper, a novel method was proposed for on-line estimation of State-of-Health (SOH) of Valve-regulated Lead-Acid (VRLA) batteries. The proposed method is based on estimation of the slope of the linear relationship between the available power in the battery versus the open-circuit voltage of the battery. For this reason, three batteries with known SOC and SOH were used to construct a fuzzy system. These three batteries provide information form a completely healthy battery, an almost dead battery, and a half-used battery. Then, the proposed method was used to estimate the SOH of an unknown battery. Experimental results show accurate estimation of the SOH as well as the SOC during the charging and discharging processes. Moreover, due to the very simple structure of the fuzzy system, the proposed method can be applied with low costs to industrial devices as well as household appliances. Although the results shown in this paper were obtained by connecting the circuits to a PC, for practical applications just an LCD suffices to show the predicted SOH after about one hour.

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