EVALUATING THE STATE OF HEALTH OF LEAD-ACID BATTERY USED IN UPS

EVALUAREA STĂRII DE SĂNĂTATE A UNEI BATERII PB-ACID FOLOSITĂ ÎN UPS-URI

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Abstract: *The article presents the development of a system used to evaluate the State of Health (SoH) of lead-acid batteries that serve as the energy source for Uninterrupted Power Supplies (UPS). The aim is to make this system as unobtrusive as possible, particularly for UPS units without built-in monitoring features. The system's hardware framework relies on a compact electronic load applying two discharge pulses to the lead-acid battery. The system then computes the battery's State of Charge (SoC) and SoH using the measured values and the developed software logic.*

Keywords*: UPS, SoH, SoC, lead-acid battery*

Rezumat: *Lucrarea prezintă dezvoltarea unui sistem pentru evaluarea stării de sănătate (SoH) a bateriilor Pb-acid folosite ca sursă de energie în Uninterrupted Power Supplies (UPS-uri). Acest sistem este dezvoltat pentru a fi minim invaziv și este destinat UPS-urilor care nu sunt prevăzute cu funcție de monitorizare. Structura hardware a sistemului se bazează pe o sarcină electronică de mici dimensiuni care aplică două impulsuri de descărcare bateriei Pb-acid. Pe baza valorilor determinate și a logicii implementate sistemul evaluează starea de încărcare (SoC) și SoH.*

Cuvinte cheie: UPS, stare de sănătate, stare de încărcare, baterie plumb-acid

1. Introduction

In over 70% of cases, lead-acid batteries are still used as the energy source for UPS-es operating in data centres [1]. However, due to their much lower growth rate is expected that Li-Ion batteries will replace these

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batteries by 2030 [2]. Modern UPS-es, while employing a VRLA battery, have an internal system that monitors the SoH, SoC and other parameters to ensure the battery’s safe operation. Still, this system only exists in around 25% of all online UPS-es.

Regardless of the model, determining the optimal replacement time is an economic problem, but it always relies on estimating the battery's age. The SoH quantifies this value (age) and depends on the battery's nominal and actual capacity at a given time. Since the UPS must ensure an uninterrupted power supply, a battery is considered to have reached its end of life (EoL) when the SoH value drops below 80% [3].

From a different perspective, some researchers believe that due to the complex electrochemical processes occurring within the battery and mainly due to the corrosion that appears at the anode, determining the battery's age should also have a calendar component in addition to the one related to capacity fade [4].

In this context, the paper’s main goal is to present the development of a SoH evaluating system that all UPS-es can use. The premises for the developed system are:

- Is minimally invasive and does not disturb the UPS's operation;
- Is independent of historical information about the battery's evolution;
- Estimates the battery's SoH with a relative error below 5%;
- Has a low complexity and reduced dimensions.

A comprehensive literature review was performed conclusively with the chosen criteria to establish the best-suited evaluation method. Coulomb counting [5] is the most common SoC and SoH evaluation method. It has a low complexity requiring only a current sensor and usually produces errors under the 5% threshold if special algorithms to prevent error accumulation are used. The main drawback is that it should be applied from the beginning of the life of the battery, so in a way, it requires historical data. Model-based methods [6] also have relatively low complexity and produce errors under 5%, but they require historical data and are only designed for a specific battery chemistry. Impedance spectroscopy [7] does not depend on historical data, and has a very low error, usually under 2% but requires a very complex setup and a high testing time. It is generally used in laboratory conditions and is a reference for evaluating other methods. The two discharge pulses method [8] also does not depend on historical data and has low complexity but usually produces errors between 5 and 8%. Artificial Intelligence methods [9] have the lowest errors, under 1% but require complex architectures and large historical data sets for training.

Upon thorough examination, the two-discharge-pulse method aligns most effectively with the prescribed design data. While the error margin occasionally surpasses the set limit, a calibration process can be employed to rectify these deviations.

The rest of the paper is organised as follows; Chapter Two presents the materials and the evaluation method, followed by the calibration setup described in Chapter Three. In the last part, the experimental results for determining the SoH of three lead-acid batteries with known histories are presented, and the Conclusions are drawn.

2. Materials and Method

As established in [10], the two-discharge-pulse method is grounded in experimental findings and electrochemistry principles. However, it can only be employed on Valve-Regulated Lead-Acid (VRLA) batteries, which respect a simple reaction-diffusion model for acid concentration [11]. This method produces inconsistent results for more complex batteries involving Butler-Volmer kinetics or more complex diffusion processes [12].

The test sequence is presented in Figure 1.

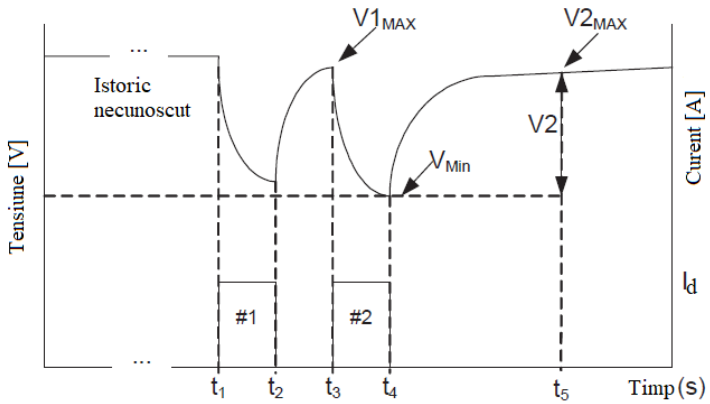


Figure 1. The test sequence [10]

The test procedure was developed in accordance with the PNGV – Hybrid Pulse Power Characterization Test [13] and employs a discharge pulse of 18 seconds ($t_2 - t_1$), followed by a resting period of 32 seconds ($t_3 - t_2$) and a final discharge pulse of 18 seconds ($t_4 - t_3$).

The method boasts a significant advantage in that it does not rely on historical data, a benefit derived from using two discharge pulses, wherein only the voltage drop produced by the second pulse is considered. The voltage drop of the first pulse isn't reliable due to the incorporation of unknown variables, such as the kinetic effects of charge carriers from a preceding charge or discharge process. The discharge procedure is applied as follows:

1) Disconnect the battery from the load/charging system for at least 2 minutes.

2) Post this period, the battery terminal voltage is viewed as the open circuit voltage (OCV).

3) Implement the test sequence depicted in Figure 1.

4) Measure the voltage drop value (ΔV_2) following the second discharge pulse.

5) The nominal discharge current coefficient (Cr) is computed as

$$C_r = \delta \cdot (\Delta V_2) + \gamma \tag{1}$$

where δ and γ are determined based on Table 1.

6) Determine the battery's (SoC) using the equation:

$$C = \frac{V_{max} + \beta - EMF_{min}}{\alpha} \tag{2}$$

where V_{max}, EMF_{min}, β and α are established based on discharge data provided by the battery manufacturer.

7) Predict the maximum effective capacity remaining in the battery using the equation:

$$C_{ef} = \frac{1}{C_r} \tag{3}$$

8) Ascertain the battery's SoH using the equation:

$$SoH = \frac{C_{ef}}{C} \tag{4}$$

where C is the battery's nominal capacity.

Table 1. **Values for the C_r coefficient [8]**

ID	Discharge current [A]	C_r [Ah^{-1}]
1	10	1,093
2	25	2,732
3	35	3,825
4	50	5,464
5	65	7,104
6	80	8,743

The hardware implementation of the test method was done with readily available "off-the-shelf" components, resulting in a minimal footprint and high efficiency. The components were chosen based on criteria that ensured high measurement accuracy and precision under 1%.

The block diagram of the designed system is presented in Figure 2.

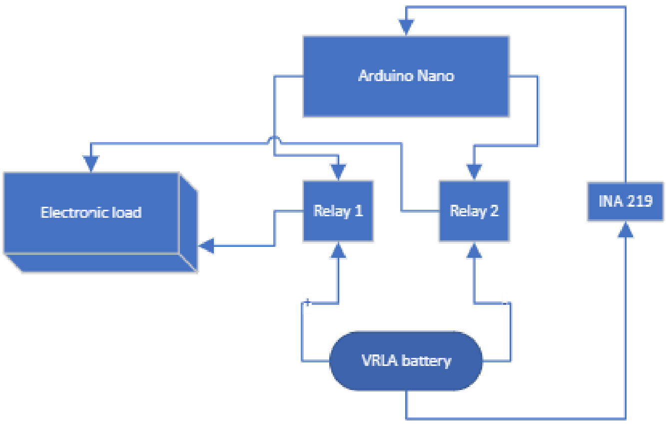


Figure 2. The block diagram of the designed system

The electronic load, which applies the necessary two current pulses to the VRLA battery to determine the voltages ΔV_2 and V_{max}, forms the core element of the system. This electronic load is connected through the two relays' normally open (NO) contacts. The command sequence is issued by an Arduino Nano unit based on the current and voltage data from the integrated sensor INA219. This sequence involves applying two current pulses, each with a value of 1A for 18 seconds, and recording the voltages at the start and end of each pulse.

The system also includes an isolated power supply that connects to the mains and provides a steady 5 VDC for the operation of the prototype while ensuring galvanic isolation.

Data on the recorded and estimated parameters, including SoC and SoH, are displayed on an OLED screen.

The software architecture was designed in alignment with both the test methodology and the developed hardware structure. It is based on several libraries available online and custom-designed functions to measure, estimate and display the computed values. The main libraries are:

• <Wire.h> - the I2C communication library used by the INA219 integrated sensor

• <Adafruit_INA219.h> - library for processing information from the INA219 sensor

• <SPI.h> - the SPI communication library used by the OLED screen

• <Adafruit_GFX.h> - library used to display messages on the screen

• <Adafruit_SSD1306.h> - the library used as a device driver

A snippet from the estimating function is presented below.

```
{
  delay(5000);
  SOC=(maxim1+b-EMFMIN)/a;
  DV=maxim2-minim1;
  Cr=abs(Cr1*DV-Cr2);
  AhC=(curent/1000)/Cr;
  SOH=(AhC/Ah)*100;
  afiseaza();
  delay(100000);
}
```

3. System calibration

The system was calibrated using the test structure shown in Figure 3 and the experimental data from [10]. Rather than using a VRLA battery, the chosen structure employs a programmable voltage source. This source can mimic, during the span of the two 18-second pulses, the voltage drop from the terminals of a battery under test.

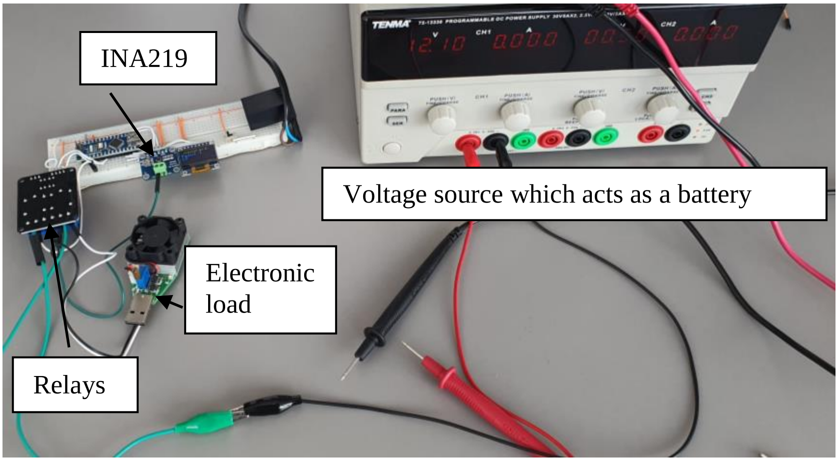


Figure 3. The calibration setup

In the tests conducted in reference [10], a discharge current of 10 A was utilised, a level that the developed system cannot attain. Thus, using the data from Table 1, the value for C_{rate}, corresponding to a discharge current of 1A, was extrapolated – Figure 4, resulting in C_{rate} = 0.1093 Ah.

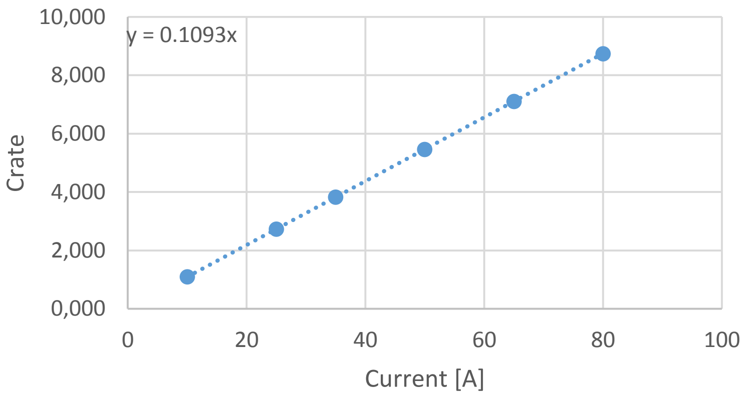


Figure 4. The extrapolation of the C_{rate} coefficient

For a ΔV_2 variation of 0.07 V, the VRLA battery tested in [8] possessed a nominal capacity of 183 Ah and exhibited a SoC and a SoH at 80%. These values were used as input for the calibration setup – Figure 5.

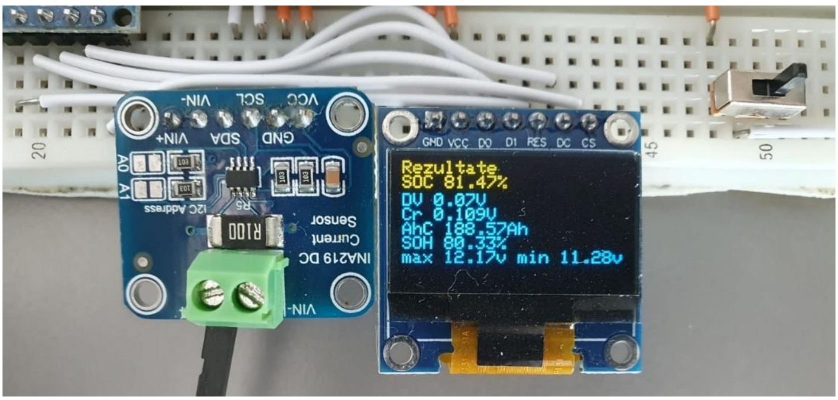


Figure 5. The calibration results

The experimentally derived values fall within a maximum relative error of 2% for SoC and 0.5% for SoH. This confirms the extrapolated value for C_{rate} and makes the system suitable for VRLA battery testing.

4. Results and discussions

The developed system was used to test three VRLA batteries of varying capacities sourced from UPS-es equipped with SoH monitoring functions. The final recorded values for SoH were assumed to represent the actual SoH. The data for these three batteries are presented in Table 2.

Table 2. **The tested batteries SoH**

ID	Nominal capacity [Ah]	SoH [%]
1	9	92
2	12	86
3	14	81

Following their extraction from the UPS-es, the batteries were allowed to rest for an hour. Then, the batteries were discharged at a constant current until they reached the following SoCs: SoC_1 = 60%, SoC_2 = 75%, and SoC_3 = 90%. Upon completion of the discharge process, each battery was given another hour of rest, after which the test sequence embedded in the developed prototype was applied.

The results obtained for the three batteries are presented in Figures 6 a, b and c.

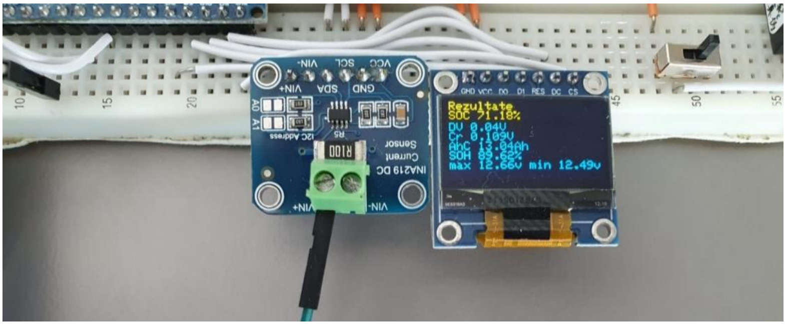
For each battery and each state, the absolute and relative errors were computed and summarised in Table 3.

Table 3. **The tested batteries SoH**

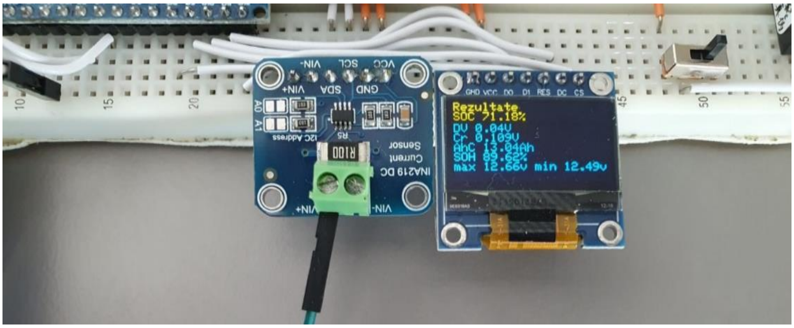
ID	Real SoC[%]	Estimated SoC [%]	Abs. Error [%]	Relative error [%]	Real SoH[%]	Estimated SoH [%]	Abs. Error [%]	Relative error [%]
1	60	52,22	7,78	**12,96**	92	95,12	-3,12	3,39
2	75	71,18	3,82	5,09	86	89,62	-3,62	4,20
3	90	91,44	-1,44	1,60	81	84,96	-3,96	**4,88**

The relative errors in estimating the SoC ranged between 1.60 - 12.96%. Battery 1 exceeded the generally accepted field standard of 5%. It should be noted that the SoC estimation method, based on two discharge pulses, is primarily utilised within the 40 - 100% range. This places the SoC of battery 1 in the initial third of the measurement range, where larger errors up to about 10% are expected.

a) Battery 1 – 9Ah, SoC = 60%, SoH = 92%



b) Battery 2 – 12Ah, SoC = 75%, SoH = 86%



c) Battery 3 – 14Ah, SoC = 90%, SoH = 81%

Figure 6. The experimental results

In estimating the SoH, the error range was much narrower, between 3.39 - 4.88%, falling under the 5% limit. The maximum error was observed for the lowest SoH value. It's worth noting that VRLA batteries used in UPS-es are typically considered to have reached their EoL around an SoH of

80% [14] (the reason why these batteries were selected for the study). This permits the developed device to impose a measurement limit of 83%, beneath which the VRLA batteries should be replaced. This limit was chosen because measurements taken with the prototype generally tended to overestimate the SoH compared to the actual SoH.

5. Conclusions

The paper presents the development of an SoH estimating system that can be used to evaluate the state of health of a VRLA battery from a UPS that is not equipped with a monitoring system. The proposed system uses a two-pulses discharge method to evaluate the SoC and SoH and can be used only for VRLA batteries with or without a known discharge history. The system's accuracy was evaluated by direct comparison with measured data and was found to be at 4.88% under the 5% threshold. Considering that the system usually produces larger estimates than the real age of the battery an 83% limit was considered to be a good trade-off between technical and economic aspects in replacing the battery.

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