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State-of-Charge Estimation of Lead-Acid Batteries by using Multi-Frequency AC tests

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ABSTRACT*:* This work is devoted to battery AC impedance measurements in the frequency band. A computerized monitoring system have been developed to assess the battery behavior in long time periods. The paper focuses on the estimation of the battery State-of-Charge (SOC) via Nyquist and Bode characteristics. The minimum phase in the battery kinetic domain was proposed as the single integral parameter of the battery SOC estimation. A statistical analysis was performed using standard Toolbox ONE-WAY ANOVA of MatLab to confirm the measurement reliability.

KEYWORDS*:* Valve-Regulated Lead-Acid (VRLA) battery, Battery Management System (BMS), Impedance diagrams, Battery State-of-Charge (SOC), Depth-of-Discharge (DOD).

I.INTRODUCTION

Assessment of State-of-Charge (SOC) and State-of-Health (SOH) in Valve-Regulated Lead-Acid (VRLA) batteries is important to detect battery deterioration and capacity loss in various applications, especially when it is impossible to apply completely discharge test, such as the backup battery in Uninterruptible Power Supply (UPS) [1], [2], [3]. Non destructive impedance tests with small level of multi-frequency AC signals are widely used as an alternative to charge/discharge tests [4], [5]. These indirect methods are applied to test and estimate the status of the battery in laboratory conditions and known as Electrochemical Impedance Spectroscopy (EIS) [6]. The reliability of the indirect tests depends on battery constructive and electrochemical parameters and operating conditions, especially on temperature [4], [7], [8]. It was proved that SOC and SOH are individual parameters for each battery of the same type [4], [5]. A high accuracy of the battery measurements may be achieved only in laboratory conditions with special equipment. However, due to the development of microelectronics, nowadays the laboratory methods of multi-frequency impedance measuring of batteries and data processing algorithms can be implemented for the sealed battery state estimation in field applications.

The typical Nyquist diagram of the EIS battery test is shown in Figure 1. It is possible distinguish three areas in this diagram: the resistive region, the active mass transfer region, and the diffusion region [9]. As it was shown in [10], the most important region for battery SOC estimation and its decrease due to battery deterioration is the kinetically controlled region that corresponds to the frequency range of 1 - 100 Hz. In the low frequency (below 1 Hz), the diffusion process in the VRLA battery has a relatively few influence for a battery deterioration. Above 100 Hz, the Faradaic process is predominant. Various Battery Monitoring Systems (BMS) make use of different models and parameters to estimate battery SOC and SOH [11], [12]. To evaluate SOC in practice, the Randles linear model of the first order is widely used as a lumped model of electrochemical battery cell [1], [13], [14], [15].

The mass transfer region of the Nyquist diagram in such models is approximated by semi-circumference, and the battery status is usually estimated by three lumped parameters [10], [15]: *Rs* is used for modeling of all conductive effects in the battery, *Rct* and *Cdl* represent the plate charge transfer resistance and the electrochemical double layer capacitance between the parallel conducting plates in the electrolyte respectively. However, the real behavior of the VRLA battery does not correspond to the linear Randles model, and the Nyquist curves are not semi-circumferences, and flattened significantly in the active mass transfer region. This requires more complex distributed battery models with much more electrical parameters to assess the battery status [16]. Nevertheless, this approach with multiple

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parameters is not acceptable in practical conditions. It is necessary to use other techniques. The present paper is devoted to the Battery Monitoring Systems (BMS) based on the multi-frequency impedance tests and permits to estimate the battery SOC by one integral parameter. This BMS controls operational characteristics, such as the battery temperature, nominal voltage, charge and discharge currents, during a long observation time with a high level of reliability.

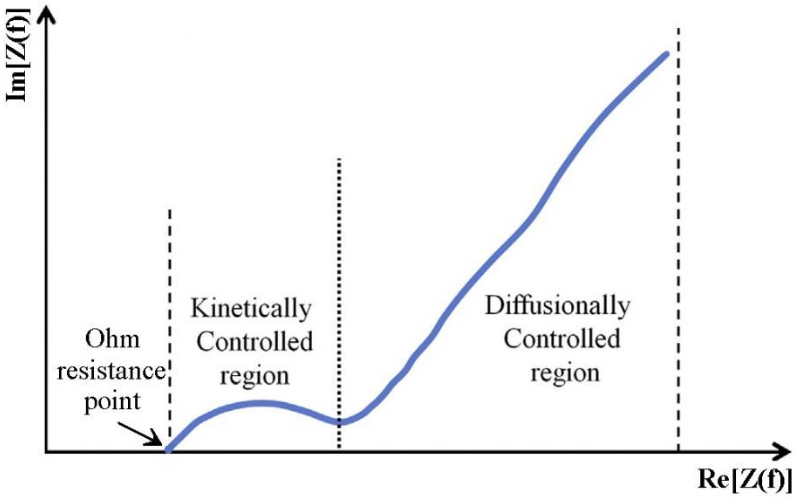

Fig. 1 Typical Nyquist diagram of the battery impedance analysis

II.BATTERY MONITORING SYSTEM

A. TEST BENCH SETUP AND HUMAN MACHINE INTERFACE.

To acquire experimental data from VRLA battery, a prototype of the Battery Monitoring System (BMS) was developed based on using the host PC (notebook) with the National Instruments 6062A DAQ card interfaced to the external custom designed circuit. The block diagram and the prototype system setup were presented in [15]. BMS should be capable of being employed in two ways: firstly, to perform the programmable tests, and, secondly, to control and measure various monitoring parameters such as the charging and discharging current, the battery voltage, the rest period, the battery temperature and others for a long time. It is known that a battery behavior depends very strongly on temperature. Therefore, the testing battery is put inside the cabinet wth a controlled temperature in the range of ±0,5°C. To avoid the influence of the external circuit on the measurement precision, the custom designed circuit was placed in another cabinet within the controlled limits of ±1°C. The Human Machine Interface (HMI) was developed to control the test process and to analyze the recorded data over time. HMI consists of the graphical user interface that is programmed in LabView environment and by MatLab software. This graphic interface consists of working areas whereby a user defines the battery operating mode, configures the monitoring parameters and outputs the measuring values. The main user window is comprised of the eight screens as it is shown in Figure 2.

This main graphical interface represents the battery measurement parameters during last 14 hours of the test. The nominal battery voltage falls and the temperature of the test circuit increases during the test as it is visible in the Screens 6 and 8. Two peaks correspond to the two tests between the rest period. The battery temperature continues to be in the range of ±0,5°C (the Screen 7).

The windows may be configured to display other parameters, for example, the established battery current. To keep the battery in the stable state in long time periods, a small charging current of some milliamperes was applied to compensate the internal self-discharge as was recommended in [17]. Thus, by means of described measurement system, it is possible to carry out the multi-frequency testing of the battery in several operating modes.

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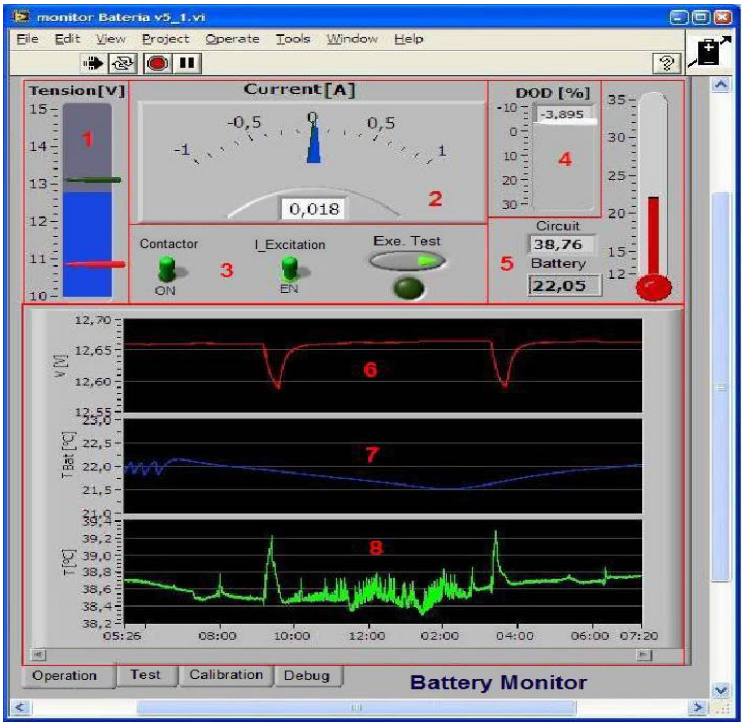

Fig. 2 HMI main window

B. TEST SIGNAL GENERATION

The assignment of the test consists of the two scripts in MatLab. The pre-processing script generates the excitation digital vector which corresponds to the sum of testing harmonics in the frequency range from 1 to 500 Hz. Each harmonic has an adjustable amplitude. All amplitudes and phases of excitation current harmonics should be adjusted to provide the amplitude voltage response in the range of ±10mV to maintain the linearity of the battery [18]. To minimize the impact of the test signal, the Hanning window was applied to the excitation vector. The excitation vector via the DAQCard and the dedicated electronic circuit generates the test current harmonics that are applied to the battery terminals. The test current signal and the voltage response are shown in Figure 3.

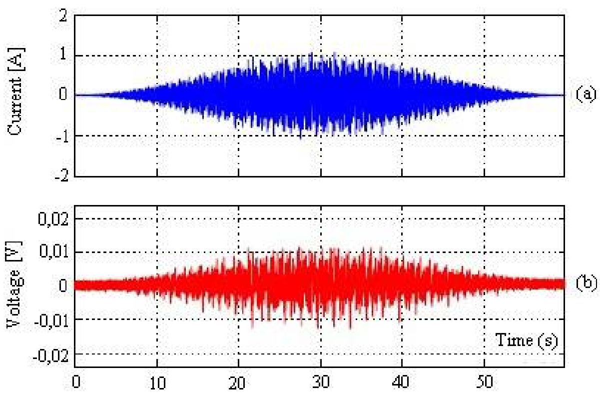

Fig. 3 Excitation (a) and response (b) signals with the Hanning window

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A rectangular window has been applied to eliminate cycles with low signal/noise ratio in the post-processing, and the Fast Fourier Transform (FFT) was used to filter the corresponding current and voltage harmonics for calculating the battery impedance in the frequency domain.

C. DATA MONITORING AND POST-PROCESSING

BMS allows to create pre-processing and post-processing data. The pre-processing file contains the excitation signal parameters. The monitoring data have been collected in real time in the post-processing file of the *Datalog*. One example of the *Datalog* file post-processed by MatLab software is shown in Figure 4.

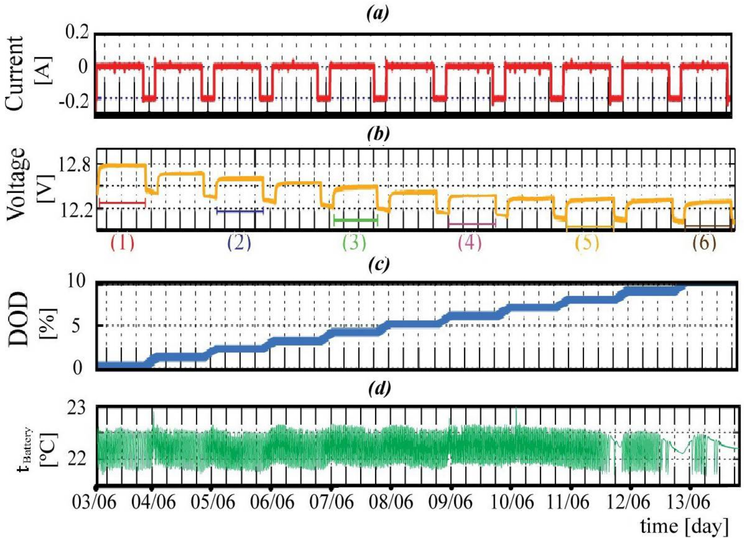

Fig. 4 Post-processing of the monitoring data

The data for the post-processing have been collected within 11 days automatically and continuously during the discharging of the completely charged battery up to 10% of DOD. Depth-of-Discharge (DOD) is usually used to measure how deeply depleted the battery is, and represents the percentage of battery capacity that has been discharged expressed as a percentage of maximum capacity: DOD = (1 – SOC) [16]. As the sharp boundary between operation of battery in "open circuit" and "floating mode" does not exist, the battery was considered completely charged (bit overcharged), provided that the Nyquist diagram appears legible during the impedance test, i.e. the gas emission process is over. Figure 4 shows the discharge current of 200 mA within 5 hours and following 19 hours of the rest (a), the change of DOD and the battery voltage during the test (b, c), and the temperature in the battery cabinet (d). A long rest time of 19 hours was used to wait the end of the electrochemical transient during the battery discharge, and to consider the battery temperature equal to the controlled cabinet temperature. The small glitches in the "on-off" temperature control at the end of Day 11, 12 and 13 days had no impact on the temperature stability in the battery cabinet remaining within the range of ±0,5°C. The impedance tests were applied after 5 hours of the battery discharge, and were repeated every 5 minutes (1 min of the test and 4 min of the rest).

III. SOC ESTIMATION OF THE VRLA BATTERY

A. VRLA MULTI-FREQUENCY BATTERY TESTS

The battery used in the test is the sealed Valve-Regulated-Lead-Acid (VRLA) battery, MI100HE, produced by "MOURA Batteries" Brazilian Corporation. The nominal voltage of the battery is 12V and the nominal capacity is 100Ah. All the measurements were carried out at temperature of 22 ±0,5°C. The Nyquist curves of the studied battery in the frequency range from 1 to 200 Hz are shown in Figure 5 for the medium measuring values.

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Every average curve was constructed on the basis of 100-200 individual tests at the same battery state. The tests during the first 3-hours of the rest period after the battery discharge were excluded from the calculations for greater confidence in the battery SOC estimation.

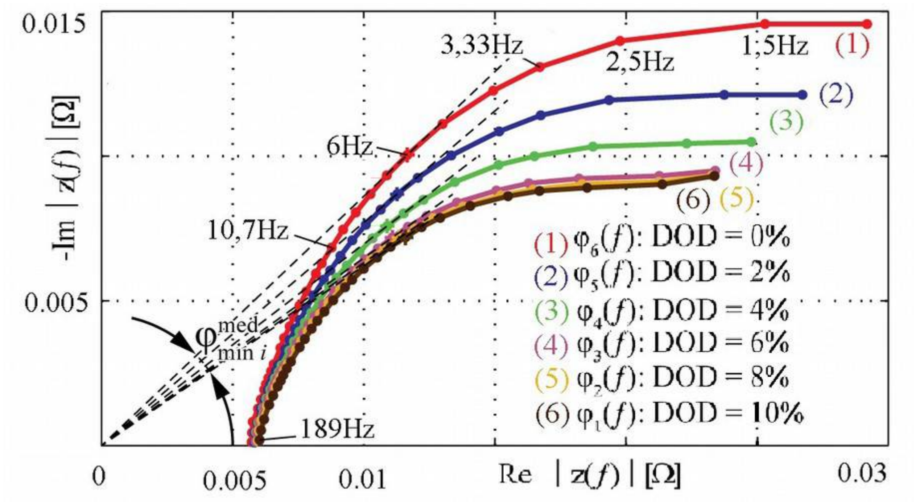

Fig. 5 Experimental Nyquist curves of the VRLA battery for different DOD

All impedance curves are flattened significantly comparing with the theoretical Randles model. In [15] the impedance curves were approximate by circumferences in accordance with the battery Randles model of the first order, and the three parameters *Rs*, *Rct*and *Cdl* were used to determine the level of battery SOC. However, these parameters vary slightly for small quantities of DOD. It is the assessment of the small SOC change of the completely charged reserve batteries is very important in UPS applications. Therefore, a special attention should be paid to the means of the Bode phasecurves with a dispersion of 95% that are shown in Figure 6.

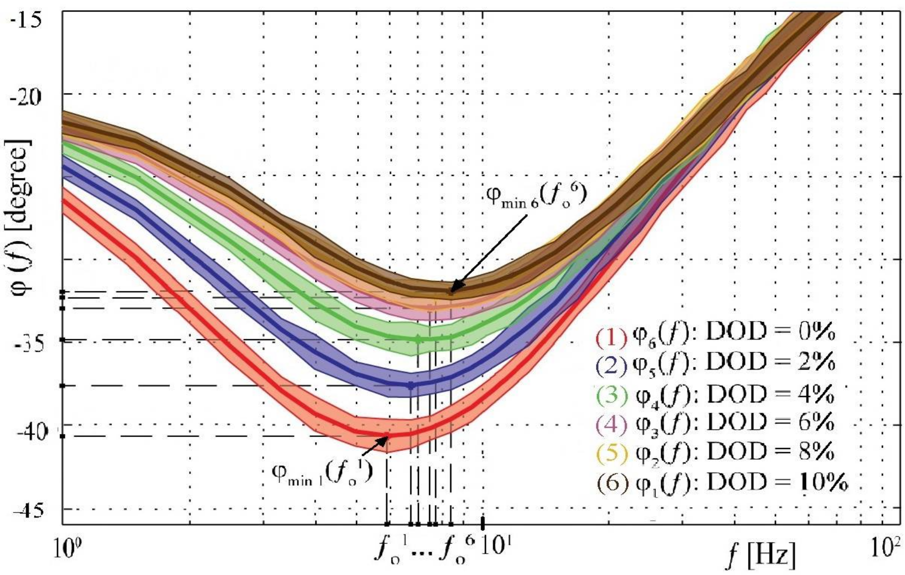

Fig. 6 Bode phase diagrams of the tested VRLA battery for differentvalues of DOD

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The phase curves have clearly distinguishable minimum points. And these minimums tend to move in both axes, depending on the level of DOD. In [19] was determined the frequency shift of the minimum point to the right during the battery discharging, i.e. alone the abscissa axis. However, the vertical shift along the phase axis is more accented. That is, the phase value in the minimum point characterizes very well the level of the battery SOC. Thus, the minimum angle $\varphi_{min}(f_0^i)$ in the Bode phase diagram may be used as the integral parameter of the battery SOC estimation independently of the battery model. The integral parameter $\varphi_{min}(f_0^i)$ is shown in Figure 5 too as the angle between the abscissa axis and tangent line to the Nyquist curve. The measurement of $\varphi_{min}(f_0^i)$ is better to estimate in the Bode phase diagram at the frequency point (f_0^i) that was approximated by quadratic curve drawn through the three minimum adjacent points. The measurement accuracy is worsening on the other frequencies. For example, the phases are indistinguishable in the frequency of tens of Hz as shown in Figure 6.

B. STATISTICAL ANALYSIS OF THE MEASUREMENT RESULTS

For the statistical analysis of the measurement results the Toolbox ONE-WAY ANOVA of MatLab was used [20]. This Toolbox is designed to perform the variance analysis of the random observations that depend on one factor. The factor that influences the impedance phase change is DOD. The variances of the phase means in some frequency points were researched by MatLab functions one-way *anova1* and *multcompare*. For greater clarity, a step of the DOD change was chosen at 0.25%. Figure 7 shows the difference between the random phases for 16 levels of DOD in the three frequency points, produced by the function plotbox of ANOVA

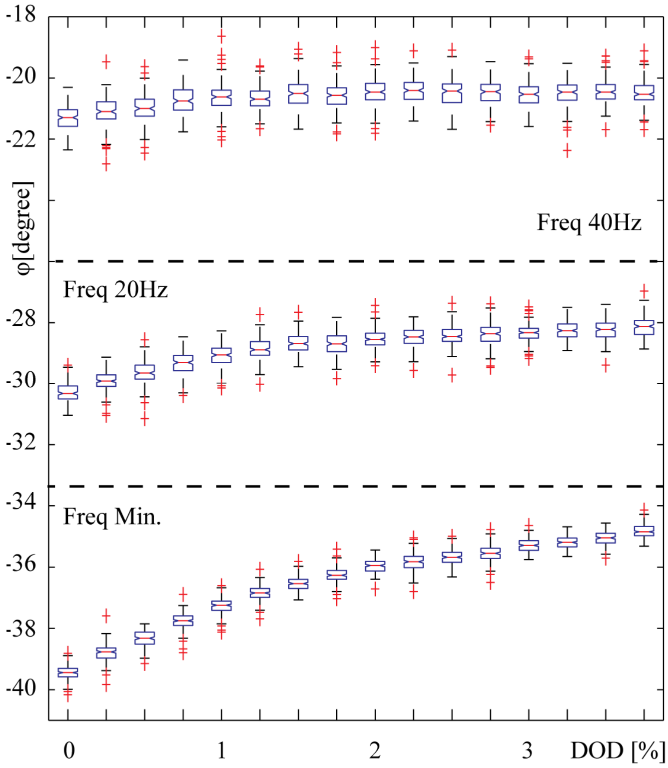

Fig. 7 Box-Plot of the function *anova1*

On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers extend to the most extreme data points. It is seen from this analysis that the minimum phases are the best points for reliable estimation of the battery SOC. Moreover, the sensitivity of the phase characteristics falls as the battery discharging.

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IV. DISCUSSION AND CONCLUSIONS

The use of multi-frequency AC methods for battery SOC and SOH estimation in practical measurements has been possible due to data processing by microcontrollers. However, the measuring parameters are individual for every battery and strongly depend on temperature. Therefore, it is possible to estimate individual battery status by impedance test only in temperature stable conditions that is performed in UPS applications.

This paper presents a prototype of Battery Monitoring Systems to control and supervise the measuring parameters of the reserve battery in UPS during long time periods. The proposed BMS permits to carry out impedance tests in a frequency range of 1 to 500 Hz that is sufficient for practical applications. EIS methods to estimate the battery status in laboratory conditions produce multiple electrochemical parameters for scientific research of battery cells that is not suitable for industrial use. The Randles model of the first order is used sometimes to approximately estimate the battery SOC and SOH by three linear parameters *Rs*, *Rct* and *Cdl* [4], [5], [15]. Nevertheless, the accuracy of such approximation is valid only in small capacity changes of a completely charged battery. In practice, the battery characteristics are not linear and it is necessary more accurate SOC estimation. The minimum point of the battery Bode phase curve $\varphi_{min}(f_0)$ was proposed as the single integral parameter for the battery SOC assess. As it is shown in Section 3.1, the integral parameter permits to estimate the battery SOC by more than 10% of DOD. This level of battery discharge is sufficient for the UPS application where the industrial standard limits SOC up to 80% [2]. The statistical analysis in Section 3.2 confirms that the measuring phase values in the minimum frequency pointsf_0^iprovide the best accuracy of the SOC estimation. This approach may be extended to other kinds of batteries used in industry: Ni-MH, Ni-Cd, and Li-ion batteries with the similar impedance behavior[16].

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BIOGRAPHY

Stanislav Tairov (IEEE member), he received B.S. and M. Sc. degrees in Electrical Engineering from Moscow State Technical University n.a. N.E. Bauman (MSTU), USSR, on 1971 and 1972, respectively, and in 1981 the PhD degree from National Research University Moscow Institute of Electronic Technology (MIET), USSR which research project was in embedded controllers and machine drives. Currently, he is a professor and researcher in Exact Science and Technology Center, University of Caxias do Sul, Brazil. His research fields include machine drive control, signal processing and measurement.

Luiz Carlos Stevanatto was born in 1975. He received degree on Electrical Engineering (1998) from Engineering School inMauá, Brazil and M.Sc. degree on Electrical Engineering (2008) from University Federal of Rio Grande do Sul, where research subject was multivariable system identification through decentralized relays. In 2003, he joined Universityof Caxias do Sul, with current work at Engineering Lab Position. His research interests include system identification and robust control.