Ultrasonic interrogation of AGM-VRLA batteries

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Abstract

This work propose a simple, non-destructive and non-intrusive characterization technique, applied to lead acid batteries for battery monitoring during operation. It consists in installing two piezoelectric transducers on the surface of a battery and studying the transport of ultrasonic acoustic waves through the battery. The acoustic signal transmitted through a commercial 6 V/195 Ah AGM-VRLA battery shows a significant and higly repeatable evolution with the state of charge over cycling, related to physical changes in the battery. From these observations, a light machine learning algorithme was applied to obtain an accurate and direct estimation of the state of charge from the characteristics of the waveform recorded, and could be used for a better management of this type of batteries.

Keywords**:** Lead-Acid, Ultrasound Acoustic Interrogation, Machine Learning, SoC Estimation, BMS

1. Introduction

Battery cells, modules and packs are oftentimes considered as black boxes that can store and deliver a determined amount of energy to an electrical device. In most cases, we don't care about what is happening inside the battery during operation, at least as long as the battery is able to meet the energy needs. This way of viewing a battery is probably not quite wrong if considering the lead-acid battery which is continuously maintained fully charged and doesn't require a battery management system to balance the charge of the cells or prevent safety issues. The lead-acid battery may basically be considered to present only three different status: 1- good ("does the job" such as supplying power to start up the combustion engine of a vehicle), 2- not good (can't do the job, but it is due to a low state of charge; the battery can be recharged), 3- battery is dead.

Up to now, advantages of lead-acid batteries outweighted the disadvantages for numerous applications (SLI, back up energy storage…) but progress on the development of Li-ion batteries (increase of both specific and volumic energy and power, sharp decrease of the costs) reduce the competitiveness of lead-acid batteries. Times have changed and even for lead-acid batteries, it is now important to have the possibility to monitor the performance, estimate accurately the state of charge and the state of health.

Battery management systems and Energy management systems use only few primary parameters for the battery monitoring and management: voltage (cell or module), current passing through the battery and a temperature measured somewhere in the battery module. It is clearly demonstrated that these few parameters are necessary but not sufficient for an accurate and efficient management of the batteries [1]–[5]. Development of BMS that allows a better understanding of the reactions occurring inside the batteries is required to increase the lifetime and the safety of the batteries, as well as their performance. An accurate monitoring of the battery could allow to adapt continuously the operation limits of the battery (cut-off voltage, max charge and discharge current, charge factor) to the specific conditions of operation. Such a management of the battery requires collecting relevant information from the battery behavior during operation. Electrochemical reactions that occur in batteries may lead to important structural changes of materials (electrode, electrolyte and current collectors): charging and discharging cycles are an important source of mechanical stress which is often at the origin of the performance decrease. Different characterization techniques can be used to detect the evolution of the physical properties of materials inside the battery. These characterization techniques have to be easy to put in place, incur a moderate cost and must not interfere with the usual operation of the battery.

We present here some example of the capabilities of the ultrasonic interrogation technique for an accurate monitoring of the lead acid batteries. This technique of characterization is recognized as a non-destructive test (NDT) method, widely used to detect and locate defects in materials and structures exposed to mechanical stress. It is an active characterization method in which acoustic waves of a defined wavelength are injected from a transducer within the battery material (see Figure 1). The acoustic waves interact with the materials and can be absorbed or reflected by defects. Comparison of the reflected and transmitted acoustic signals allows detecting changes in the acoustic impedance of the battery (e.g. change in density of electrolyte or due to the evolution of an interface between two materials).

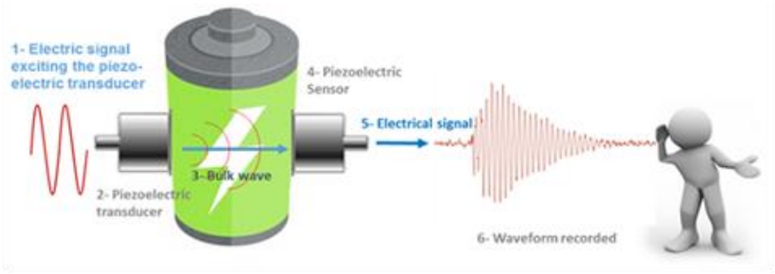

Figure 1 : working principle of the acoustic interrogation characterization technique

Attributes of the waveforms recorded by the sensor (e.g. time of flight, amplitude, frequency, presence of any echoes, etc…) can be analyzed to identify physical changes in the battery. It allows monitoring of material fatigue or/and aging through non-intrusive, non-destructive and in-operando. Even though this technique has been developed and evaluated on lead–acid batteries long ago [6], [7], there has been significant progress over the last few years and it was recently demonstrated that significant variations of the acoustic impedance could be observed on different types of batteries, both during aging [8]–[11] and battery cycling [12]–[15].

2. Materials and Methods

In practice, at least two piezoelectric transducers sensitive to ultrasonic wave or vibration (frequency range between 20 kHz and 1 MHz) are directly placed in contact with the outer surface of the battery (see Figure 1). One transducer is used to generate a short acoustic signal that flows through the battery whereas the others are used too detect the signal transmitted and record the waveform. Two types of acoustic transducers have been used: - Acoustic transducers R15α provided by MISTRAS Group, Inc. with an operating frequency ranging between 50 and 400 kHz and the resonant frequency of 150 kHz; - and another type of transducers “low cost”, with a very small footprint: flat tranducers EPZ-20MS64W, having a resonant frequency of 6.4 kHz and an impedance of 400 ohm. In both cases, the electric signal sent to the emission transducer was generated using the Wave-Gen software and a ARB-1410 arbitrary waveform generator from Mistras Group. Signal acquisition and digital signal processing were obtained via a PCI-2 AE system board also manufactured by Mistras group. Two different AGM-type lead-acid batteries were considered: a 12 V / 7 Ah Yuasa NP7-12 battery, and a 6 V / 195 Ah GNB Sprinter XP6V2800.

3.

Figure 2: top – pictures of the two different types of AGM –type lead acid batteries studied. Bottom: drawing that shows the location of the transducers (Emission – Reception); example on the Yuasa NP7-12 battery.

Results and Discussion

The acoustic signals transmitted by the battery materials provide a wealth of information on the dynamic structural changes inside the batteries. It was observed that attributes of the waveforms recorded (time of flight, amplitude and energy of the signal transmitted, shape of the waveform, frequency…) show a significant and higly repeatable evolution with the state of charge over cycling and can be analyzed to identify physical changes in the battery. An example of results is proposed on figure 3. Each dot is an acoutic measurement and a specific color has been atttibuted to the dots, from the waveform characteristics (amplitude, energy, durantion, power spectral density…).

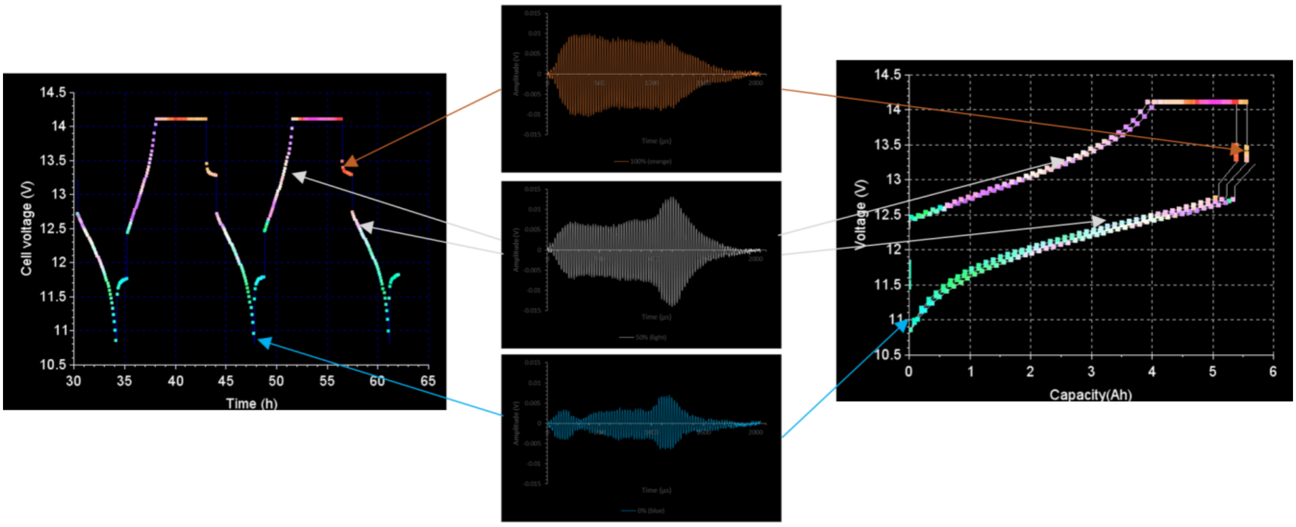

Figure 3 : Example of results obtained on the Yuasa NP7-12 battery during cycling. Left : evolution of cell voltage with time during cycling. Middle: waveforms of the acoustic signal transmitted by the battery at different state of charge (0 % blue, 50 % white, and 100 % orange). Right: battery voltage vs. stored capacity over several cycles; colors of dots has been attributed from the acoustic waveform characteristics.

As a results, the acoustic signal transmitted can be used to estimate the state of charge of the battery. A very simple machine learning algorithme was developed in order to make an estimation of the state of charge from the characteristics of the waveform recorded. An example that illustrates the accuracy of estimation obtainted with this technique on the GNB Sprinter XP6V2800 battery is porposed on the figure 4.

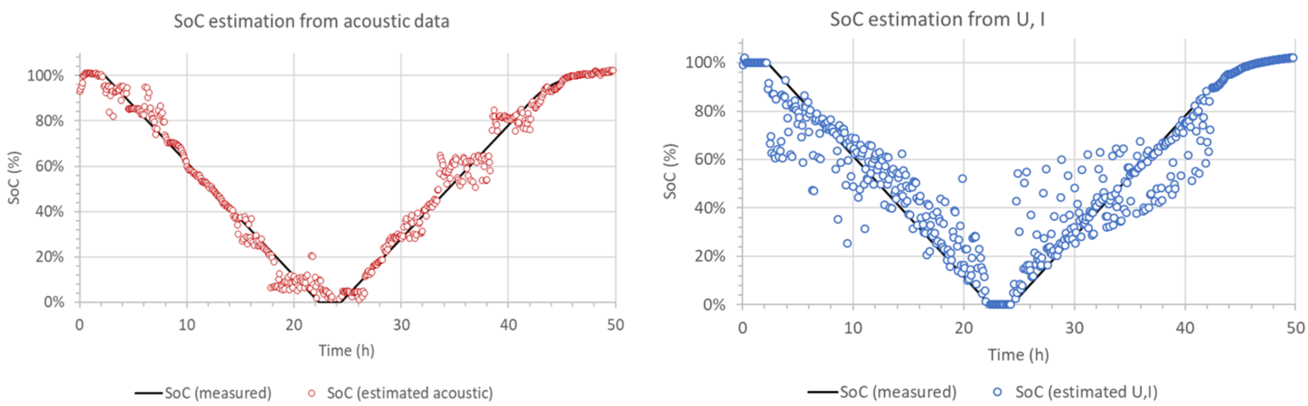

Figure 4 : Estimation of the state of charge of a GNB Sprinter XP6V2800 battery during cycling at ~C/20, using a simple machine learning algorithm. Left : estimation from acoustic datas. Right : estimation from the battery voltage and the current passing through the battery.

Table 1: error on the estimation of the state of charge of the GNB Sprinter XP6V2800 battery during cycling at ~C/20 when using acoustic datas or the battery voltage and the current.

	Acoustic datas	**Voltage and current**
Mean error on full cycle (%)	3.2	7.3
Max error on full cycle (%)	18.1	51.4

It can be observed that the estimation of the state of charge of the batery from acoustic datas is able to give a better accuracy than the same estimation from the battery voltage and the current that goes through. However, the objective is to use all the input parameters available (acoustic data but also cell voltage and current) to further improve the accuracy of the estimation.

4. Conclusions and perspectives

Ultrasonic interrogation technique is a non-intrusive and non destructive technique that can be readily implemented to monitor various battery types. We presented here an example of the capability of this technique to estimate the state of charge. It could be interesting to use acoustic datas in order to develop battery management system (BMS) that could allow a more accurate estimation of parameters such as the state of charge (SoC) and the state of health (SoH), ensure a longer service life and prevent safety issues.

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References:

[1] S. Jiao *et al.*, "Behavior of Lithium Metal Anodes under Various Capacity Utilization and High Current Density in Lithium Metal Batteries Behavior of Lithium Metal Anodes under Various Capacity Utilization and High Current Density in Lithium Metal Batteries," pp. 110–124, 2018.

[2] J. P. Rivera-Barrera, N. Muñoz-Galeano, and H. O. Sarmiento-Maldonado, *Soc estimation for lithium-ion batteries: Review and future challenges*, vol. 6, no. 4. 2017.

[3] M. Danko, J. Adamec, M. Taraba, and P. Drgona, "Overview of batteries State of Charge estimation methods," *Transp. Res. Procedia*, vol. 40, pp. 186–192, 2019.

[4] R. Xiong, *Battery SOC and SOH Estimation*. Springer, Singapore, 2020.

[5] C. Lin, A. Tang, and W. Wang, "A Review of SOH Estimation Methods in Lithium-ion Batteries for Electric Vehicle Applications," *Energy Procedia*, vol. 75, pp. 1920–1925, 2015.

[6] C. A. C. A. Swoboda *et al.*, "Development of an Ultrasonic Technique to Measure Specific Gravity in Lead-Acid Battery Electrolyte," *IEEE Trans. sonics Ultrason.*, vol. 30, no. 2, pp. 69–77, 1983.

[7] J. X. Liu, G. F. Li, W. Q. Xiong, H. J. Xiao, and L. Wang, "An ultrasonic approach to measure the density of battery electrolyte," *Proc. - Int. Conf. Electr. Control Eng. ICECE 2010*, no. 1, pp. 414–418, 2010.

[8] B. Sood *et al.*, "Health Monitoring of Lithium-ion Batteries," in *Proc. 2013 IEEE Symposium on Product Compliance Engineering (ISPCE)*, 2013, pp. 3–8.

[9] A. G. Hsieh *et al.*, "Electrochemical-Acoustic Time of Flight: In Operando Correlation of Physical Dynamics with Battery Charge and Health," *Energy Environ. Sci.*, vol. 8, no. 5, pp. 1569–1577, 2015.

[10] P. Ladpli, F. Kopsaftopoulos, R. Nardari, and F.-K. Chang, "Battery charge and health state monitoring via ultrasonic guided-wave-based methods using built-in piezoelectric transducers," *Proc. SPIE*, vol. 10171, pp. 1017108–1017112, 2017.

[11] J. Smulko, K. Józwiak, M. Olesz, and L. Hasse, "Acoustic emission for detecting deterioration of capacitors under aging," *Microelectron. Reliab.*, vol. 51, no. 3, pp. 621–627, 2011.

[12] S. Bhadra, D. A. Steingart, B. J. Hertzberg, A. Hsieh, and P. J. Gjeltema, "Interrogation of Alkaline AA Batteries Using in Operando Electrochemical Acoustic Time - of - Flight Analysis and in Operando energy Dispersive X - Ray Diffraction," *ECS Meet.*, p. 2017, 2017.

[13] L. Gold *et al.*, "Probing lithium-ion batteries' state-of-charge using ultrasonic transmission – Concept and laboratory testing," *J. Power Sources*, vol. 343, pp. 536–544, 2017.

[14] Y.-S. Chou, N.-Y. Hsu, K.-T. Jeng, K.-H. Chen, and S.-C. Yen, "A novel ultrasonic velocity sensing approach to monitoring state of charge of vanadium redox flow battery," *Appl. Energy*, vol. 182, pp. 253–259, 2016.

[15] P. Ladpli, F. Kopsaftopoulos, and F. K. Chang, "Estimating state of charge and health of lithium-ion batteries with guided waves using built-in piezoelectric sensors/actuators," *J. Power Sources*, vol. 384, no. October 2017, pp. 342–354, 2018.