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Fiber optic sensors for diagnosis and maintenance in lead-acid batteries

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This paper presents a fiber optic sensor for use in battery maintenance and also useful in determining the battery State of Health (SoH). The sensor was originally developed for electrolyte density measurements; the sensor comprises several plastic optical fiber sensors which measure the density of the electrolyte at different heights within the vessel of the battery. The sensor is based on light loss that occurs in the detection zone by means of the variation of the density of the electrolyte. This variation depends on the state of charge (SoC) of the battery at the height at which the sensor is placed and also depends on wear-out of battery. In summary, changes in the density of the electrolyte over time are an indicator of SoH. Strategic positioning of the measuring points of the sensor also allows measurements of other variables that facilitate maintenance: detection of low level of the electrolyte and the sediment of the active material that settles into space at the bottom of the cell.

Keywords: Reliability, Availability, Maintainability, Safety, Dependability, RAMS, Active learning, Cooperative learning

1. INTRODUCTION

There are many electrical and electronic systems that require batteries to operate. In the field of the electrochemical accumulators, the most widely used are lead acid batteries. Their applications comprise diverse fields: automotive, energy accumulation from solar panels, remote telecommunication systems, Uninterruptible Power Supply (UPS), industrial electric vehicles, submarines, etc. In order to make an adequate management of the battery as well as an efficient maintenance, it is necessary to know the State of Charge (SoC) and the State of Health (SoH) of the battery.

Lead-acid battery uses lead dioxide (PbO_2) as the active material of the positive electrode, and metallic lead (Pb),very porous structure, as the active material of the negative electrode. The electrolyte is formed by sulphuric acid (H_2SO_4) diluted in water (H_2O). Electrochemical reactions that occur during charge and discharge are those in Table I.

According to the chemical reactions of Table 1, during the discharge process both electrodes transform the active material in lead sulphate ($PbSO_4$) with the subsequent consumption of H_2SO_4 and the release of water to the electrolyte, causing a decrease in density. In the process of charging the opposite occurs, H_2SO_4 is released and water is consumed, thus causing an increase in density of the electrolyte. The change in the density of the electrolyte also carries an associated change in the refractive index (Linden et al., 2002; Rand, 2004) (Fig. 1). Consequently, one of the two parameters can be known through the measurement of the other. Moreover, the evolution of density with the time of use of the battery is a good indicator of SoH.

Table 1. Chemical reactions

Charge
Ánode (+): $PbSO_4 + 2H_2O \longrightarrow PbO_2 + H_2SO_4 + 2H^+ + 2e^-$
Cathode (-): $PbSO_4 + 2e^- \longrightarrow SO_4^{2-} + Pb$
Global reaction: $2\ PbSO_4 + 2H_2O \longrightarrow Pb + PbO_2 + 2H_2SO_4$
Discharge
Ánode (+): $Pb + SO_4^{2-} \longrightarrow PbSO_4 + 2e^-$
Cathode (-): $PbO_2 + H_2SO_4 + 2H^+ + 2e^- \longrightarrow PbSO_4 + 2H_2O$
Global reaction: $Pb + PbO_2 + H_2SO_4 \longrightarrow 2\ PbSO_4 + 2H_2O$

Fiber optic sensors have several advantages. Since the 1970s multiple configurations have been developed for measurements in the field of physical, chemical, environmental, mechanical, etc. (John, 1989). The characteristics of the plastic optical fiber have enabled the development of sensors more robust, economic and versatile (Harmer, 1983; Lomer et al., 2007; Zubía, 2001). Using this technique, fiber optic sensors have been developed for the measurement of the density at different heights within the vessel of the battery (Cao-Paz et al., 2010).

During the battery charge, the sulphuric acid generated in the plates is deposited at the bottom of the battery since it has greater density than the electrolyte; it produces the stratification of the electrolyte density (Rand, 2004). If the sensor is placed in the upper part of the battery, like commercial sensors, the curve of density variation is nonlinear with respect to the SoC, as shown in Fig 2. At the end of the charge process, especially with fast charge strategies, a slight bubbling occurs in the electrolyte. This causes density homogenization in the battery cell. On discharge process, the relationship between SoC and the electrolyte density is linear.

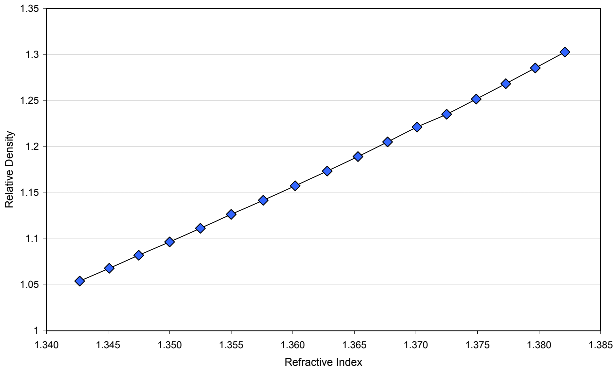

Fig. 1. Relation between density and refractive index of the electrolyte in lead acid batteries.

It can be seen from the above that it is interesting to measure the density of the electrolyte at different heights inside the battery cell and also its variation in time (dρ / dt). Because the fiber sensor is small in size, it is possible to place it inside the vessel of the battery at different heights, as will be discussed later. With this configuration it is possible to take multipoint measurements. This setup eliminates the disadvantage of commercial sensors that measure only at the top of the battery: they are not able to measure changes in density until the battery is around 70-80% SoC.

2. OPTICAL FIBER SENSOR

The sensor consists of a plastic optical fiber bended in a U shape without the protective jacket on the bended zone, so that, the fiber cladding is in direct contact with the liquid (electrolyte). At one end of the fiber is placed a light source (LED) and at the opposite end is placed a photodetector. The propagation of light through an optical fiber has been studied by several authors (Snyder et al., 1983). The light rays are guided through the core by total internal reflection due to the difference in the refractive indexes of the core and the layer surrounding it (the cladding).

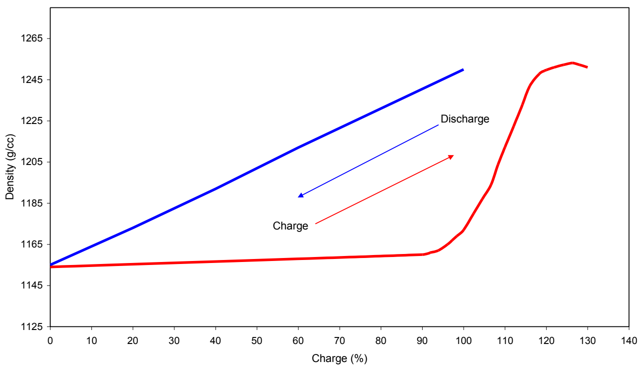

Fig. 2. Variation of density at the top of the battery during the charge-discharge process.

In the zone of curvature (Figure 3), the angle of incidence changes in the core-cladding interface and a part of the light is refracted to the cladding. When this light is in the cladding and strikes the cladding - external medium interface, there is a refraction of light to the external medium, electrolyte in this case. These losses of light can be calculated by the Fresnel coefficient (Equation 1) (Ghatak et al., 1988; Gloge, 1972; Love et al., 1978; Marcuse, 1975; Snyder et al., 1975), using the values of the angle $\theta_{z'}$ and the complementary of the critical angle $\theta_{c'}$ (Equation 2). It can be seen that the light losses in the curvature of the fiber depends on the refractive index of the electrolyte of the battery. As mentioned in the introduction, the changes in refractive index are linked to density changes; consequently, by measuring light losses in the optical fiber, it is possible to measure the density of the electrolyte.

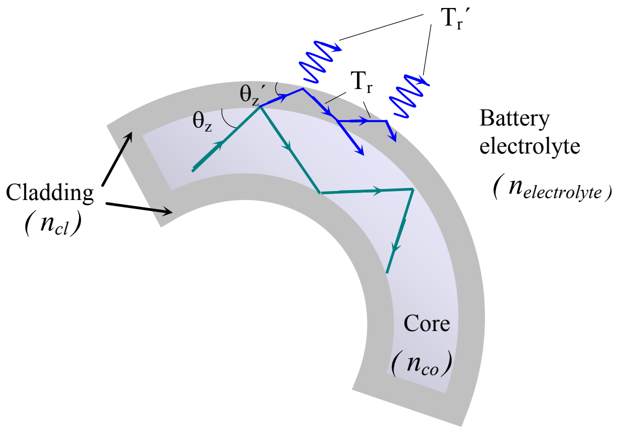

Fig. 3. Optical power losses in the bended zone of the fiber (sensitive zone).

$$T_r' = \frac{4 \sin \theta_z' (\sin^2 \theta_z' - \sin^2 \theta_c')^{1/2}}{\{\sin \theta_z' + (\sin^2 \theta_z' - \sin^2 \theta_c')^{1/2}\}^2} \qquad (1)$$

$$\theta_c' = \cos^{-1}\left[\frac{n_{electrolyte}}{n_{cl}}\right] \qquad (2)$$

2.1 Single point sensor

The simplest version of the sensor consists of a fiber bended in a U shape, with a light emitter (LED) in one end and a photodetector on the other. The configuration is similar to the one described above and it can be seen in Figure 4.

In order to compensate undesirable interferences, a second fiber is added. This fiber is bended in U shape too, but it maintains the protective jacket and it is not in contact with the electrolyte. The function of this fiber is to compensate common mode interferences that could affect the density measurement of the sensitive fiber. In Figure 5 it can be seen an outline with the configuration of the sensor and the block diagram of the associated electronics.

A large number of trials were conducted in batteries with the developed sensor. The tests were performed on the test bench in our laboratory which has an automated system for charge and discharge batteries with different strategies of charge (Marcos et al., 2005; Marcos et al., 2006). During the experiments, the single point optical fiber sensor was introduced inside the battery cell and it was placed at the top