REFRACTOMETRIC FIBER OPTIC SENSOR FOR IN-SITU MONITORING THE STATE-OF-CHARGE OF LEAD ACID BATTERY

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In-situ monitoring of the state of charge (SOC) of lead acid battery is important to understand the residual electrical energy. Usage of battery reduces the charge content of the active electrolyte which in turn changes its refractive index. This paper reports refract metric fiber optic sensor developed for on-line monitoring of SOC. The sensor is designed in such a way that it can be easily fitted in any cell of lead acid battery. The SOC of battery is estimated from sensor output. The battery performance parameters of the battery such as terminal voltage, discharge current, ampere-hour, battery temperature, SOC and Depth of discharge using fiber optic sensor output of battery are monitored for given electric load. The data is recorded continuously by data acquisition card USB 6009 using Lab VIEW Platform. Concurrently specific gravity of active electrolyte is measured using suck type of acidic hydrometer. The set of experiments are carried out for different discharge current by varying electrical load and SOC of the battery is monitored. After comparing the results for SOC of the battery with the conventional methods such as coulomb counting, terminal voltage and acidic hydrometer, it is concluded that developed sensor output is direct measure of SOC of battery.

Key words: *fiber optic sensor, state of charge of battery, lead acid battery, refractometric sensor.*

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Introduction

Electric vehicles, robotic systems, wheel chairs and submarine devices are typical examples where knowing the SOC (state of charge) is critical in order to optimize energy management and increase battery life. The SOC represents the fuel gauge of battery. Various techniques used to determine SOC of battery either needs manual intervention or sophisticated equipments. Optical sensors are also used for monitoring SOC because of its numerous advantages such as small size, light weight, immunity to EMI and RFI and ease of installation at the sight. There are few approaches of monitoring SOC based on optical sensors. Among those techniques some of them are measurement of specific gravity based on the principle of variation of the critical angle of reflection due to change in the density of the surrounding sensor electrolyte [1–3] and monitoring the change of absorption of electrolyte due to variation of its chemical properties [4]. These optical sensors need special arrangements and are not convenient for in-situ monitoring.

This paper proposes refractometric fiber optic sensor probe for in-situ monitoring of SOC of the lead acid battery. Various battery parameters such as terminal voltage, discharge current, ampere-hour (AH), battery temperature, SOC and Depth of discharge (DOD) are also measured using designed hardware and data acquisition system USB 6009 for different electric loads. The measured battery performance parameters are continuously monitored using Lab VIEW tool. The recorded value of SOC using fiber optic sensor is compared with SOC value calculated using conventional terminal voltage and coulomb counting method.

Theory

The Lorentz–Lorenz equation gives the relationship among density, refractive index and polarizability for a classical, one component fluid consisting of isotropic and non interacting molecules –

$$R \equiv \frac{1}{\rho}\frac{n^2-1}{n^2+2} = \frac{4\pi A\alpha}{3M}. \qquad (1)$$

In the equation (1), R is defined as specific refraction, ρ is the mass density, n is the refractive index, A is Avogadro's number, α is the molecular polarizability, and M is the molecular weight. If the wavelength of the light is far from any resonances in the molecules comprising the fluid, the polarizability and hence the refractive index depend only weakly on the wavelength. The important point is that the polarizability is presumed independent of the fluid density due to the assumptions molecules do not interact. It is further assumed that internal degrees of freedom do not influence the polarizability; hence α is independent of temperature. Thus under the assumptions implicit in Lorentz-Lorenz equation, at a given wavelength, the specific refraction is a constant, and a measure of refractive index gives the density directly, regardless of the temperature or pressure. The Lorentz-Lorenz equation may be generalized to non interacting molecules by the use of molar refraction $R_{\text{mix}} \equiv MR$

$$R_{\text{mix}} \equiv \frac{M_{\text{mix}}}{\rho_{\text{mix}}}\frac{n_{\text{mix}}^2-1}{n_{\text{mix}}^2+2}. \qquad (2)$$

The equation (2) states that if the molar refractions of the pure components of a mixture are known, then the molar refraction of the mixture may be calculated. Once R_{mix} is known a measurement of refractive index can be used to determine the density. Given the large number of assumptions the Lorentz-Lorenz equation is good approximation for highly associated fluids like water and for concentrated electrolyte solutions in water. That is these fluids exhibit a specific refraction that remains nearly constant over a wide range of temperature and density. Thus the specific refraction of a solution may be determined by measuring the refractive index and density [1].

In lead acid battery the SOC or energy content is linearly related to the concentration of the electrolyte i.e. sulfuric acid solution. As the battery is charged or discharged the concentration of the sulfuric acid changes depending upon the type of battery. In the sulfuric acid solution the refractive index of the solution varies linearly with the concentration of acid in the solution. Therefore the battery charge level or discharge level is proportional to the acid concentration in the solution and this can be directly derived from the relative change in refractive index of the battery electrolyte.

Operating Principle

The proposed fiber optic based sensor works on the principle of refractometry. It is useful in detection of change in the refractive index of liquids [5]. The developed fiber optic sensor consists of two parallel fibers with a reflector at a distance. The light is launched into one of the fibers called transmitting fiber. The cone of emission from this fiber depends on numerical aperture (NA) of the fiber given by equation

$$\theta_{\text{NA}} = \sin^{-1}\frac{\text{NA}}{n_1}. \qquad (3)$$

Where θ_{NA} is a cone of emission, NA is the numerical aperture, n_1 is the refractive index of the medium. For a fixed distance z between the fiber end face and the reflector, amount of light reflected from the reflector depends on the refractive index of the medium between the fiber sensor probe and the reflector. The reflected light is collected by the receiving fiber. The output of the receiving fiber varies in accordance with the refractive index n_1 of the medium.

Operating principle of refractometric fiber optic sensor is as shown in Fig 1. The region between the fiber end faces and the reflector is filled with liquid having refractive indices n_1 and n_2 where $n_1 > n_2$. Using equation (1), $\theta_{\text{NA}\,(n_1)} < \theta_{\text{NA}\,(n_2)}$. With medium having refractive index n_1, emitted light energy density is more than that for the medium having refractive index n_2. Thus received light intensity after reflection is more with medium having refractive index n_1 than for the medium having refractive index n_2. Hence received light intensity is directly proportional to the change in refractive index of medium.

Sensor Structure

FOS-SOC sensor is developed for on line detection of State-of-Charge of lead acid battery. It consists of two parallel fibers having

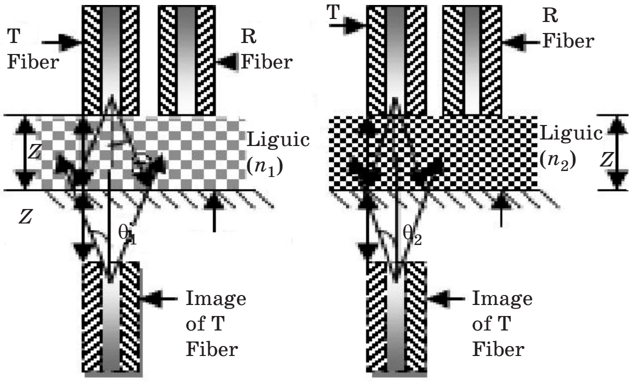

Figure 1. Basic Principle of Refractometric Fiber optic sensor.

Figure 3. Photograph of FOS-SOC sensor.

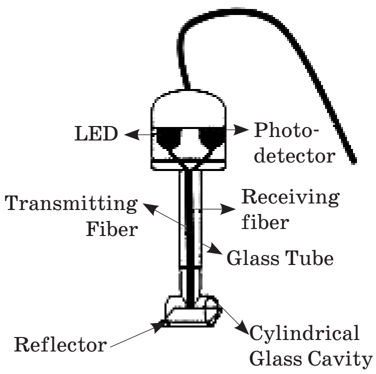

Figure 2. Schematic of FOS-SOC sensor.

specifications viz. fiber diameter (fd) – 2.2 mm, NA = 0.47, core diameter – 1 mm and cladding thickness – 0.612 mm. Fibers are encapsulated in the T-shaped glass tube as shown in Fig 2. In the T-shape structure the vertical part encapsulates two parallel fibers while the lower cylindrical part has reflector fitted at the base. Sensor is fabricated in glass to avoid the corrosive effect of the sulphuric acid, the electrolyte inside the battery. Cylindrical glass cavity is fused with the glass tube for placing reflector at a fixed distance of 6mm. The structure is immersed in the lead acid battery consisting of electrolyte which is the mixture of sulphuric acid and water. Light is launched in one of fibers called transmitting fiber using high bright RED LED with wavelength 673 nm.

Cone of light emitted by transmitting fiber depends on the refractive index of electrolyte of lead acid battery. Light reflected from mirror is collected by the receiving fiber. The received light is converted in electrical signal using photo detector L14G3. The amount of light received is a function of refractive index of electrolyte. As discussed earlier refractive index is linear with specific gravity which is in turn related to the state of charge of lead acid battery. Figure 3 shows photograph of the developed fiber optic sensor for measuring state of charge of lead acid battery.

Experimental Setup

The light from high bright red light emitting diode was launched into one of the optical fiber i.e. transmitting fiber. The light reflected from the mirror is collected by another optical fiber i.e. receiving fiber. Collected light is converted to electrical form by using the photo detector (L14G3). The assembly is enclosed in the glass structure so that there will be no corrosion effects on the optical fibers. The local made lead acid battery having specifications as 12V/35Ah is used for experimentation. First battery is fully charged using charger 12V with 5A charging current for period of 7 hours. After the rest period of 1 hour, battery is connected to different electrical load for discharging. Considering the specific case for the load of 50Watt (halogen lamp) measurements are taken. During this, FOS-SOC sensor is immersed into one of the cells of the battery. Temperature sensor LM 35 is used to sense the battery temperature during discharging of the battery. The discharging current is also measured using the developed hardware for coulomb counting to display ampere-hour consumption of the battery. The battery data i.e. current, temperature, sensor output and terminal voltage are acquired using data acquisition card of National Instrument USB 6009 of having sampling rate of 20 k samples/s. The Lead acid

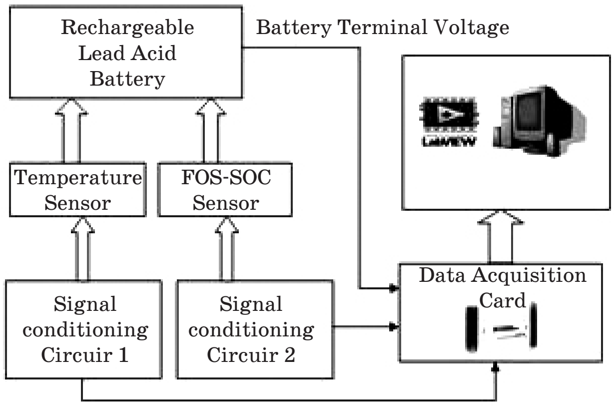

Figure 4. Block Diagram of DAS with FOS-SOC.

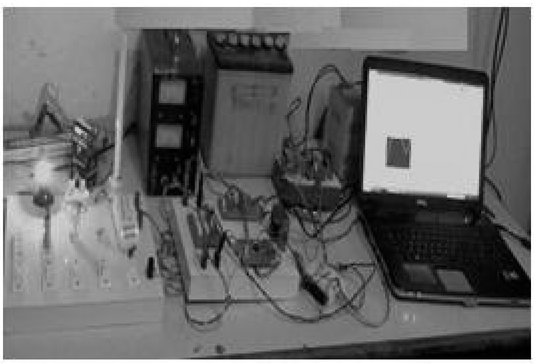

Figure 5. Experimental Setup with DAS.

Figure 6. Sensor Mounting.

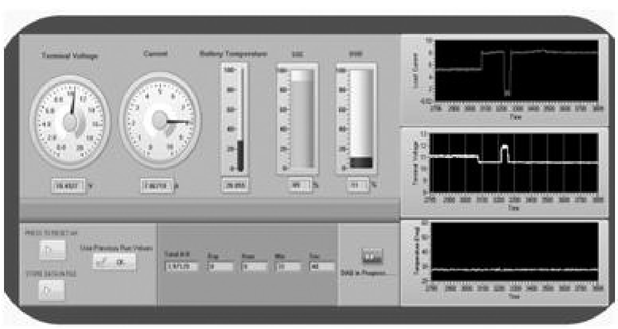

Figure 7. Screen shot for monitoring the SOC of battery.

battery 12v/35AH battery (Murphy Company) is used for experimentation purpose. Figure 4 shows experimental setup for on line monitoring of the SOC of lead acid battery. Figures 5 and 6 show actual photographs of DAS system and sensor mounting on the battery for on line monitoring.

The data acquisition module of NI USB 6009 card is used to read sensor output, terminal voltage, discharging current and temperature of the battery. The acquired data is processed and analyzed. Front panel developed in LABVIEW shows performance parameters of lead acid battery viz. terminal voltage, current, temperature, Ampere/hour, backup time, SOC and DOD. Current up to 50 A can be measured using the developed hardware. This current is integrated over the fixed period of time and ampere hours are calculated and displayed. Backup time of battery is calculated from the ampere hour and displayed.

State of charge (SOC) and depth of discharge (DOD) is estimated from the output of FOS-SOC sensor. Other parameters such as temperature, discharge current, DOD, battery terminal voltage are also monitored by using the LABVIEW as shown in Fig. 7.

Results and Discussion

The SOC of battery can be determined by measuring optical property of the electrolyte. When the load is connected to the charges in the battery get consumed. This changes the concentration of electrolyte which in turn changes the refractive index of it. Thus number of charges remained in a battery i.e. SOC is determined by concentration of charges left in the battery electrolyte. Equation (4) shows direct proportionality of concentration of charges with the refractive index. Therefore SOC can be determined by change in the refractive index of the electrolyte.

The lead acid battery uses lead dioxide (PbO_2) as the active material in the positive electrode, and metallic lead (Pb) of a very porous structure, as the active material in the negative electrode. The electrolyte is formed by sulphuric acid (H_2SO_4) diluted in water (H_2O), with concentrations between 8% and 40% depending upon state of charge and the type of the battery. The electrochemical reactions which occur during the process of charging and discharging are described in equations (4) to (9) [6].

During the charge:

Anode (+):

$$PbSO_4 + 2H_2O \rightarrow PbO_2 + H_2SO_4 + 2H^+ + 2e^-, \quad (4)$$

Cathode (−):

$$PbSO_4 + 2e^- \rightarrow SO_4^{2-} + Pb, \quad (5)$$

Global reaction:

$$2\,PbSO_4 + 2H_2O \rightarrow Pb + PbO_2 + 2H_2SO_4. \quad (6)$$

During the discharge:

$$\text{Anode (+): } Pb + SO_4^{2-} \rightarrow PbSO_4 + 2e^-, \quad (7)$$

Cathode (−):

$$PbO_2 + H_2SO_4 + 2H^+ + 2e^- \rightarrow PbSO_4 + 2H_2O, \quad (8)$$

Global reaction:

$$Pb + PbO_2 + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O. \quad (9)$$

According to equation (7) to (9) during the discharging process both electrodes transform the active material into lead sulphate ($PbSO_4$), with consequent consumption of H_2SO_4 and the release of water to electrolyte. As a result the concentration of $2e^-$ in the electrolyte is decreased. This in turn reduces the refractive index of the electrolyte. In the charging process, equations (4) to (6), the opposite reaction occurs since H_2SO_4 is released and water is consumed thereby increasing the refractive index of the electrolyte.

Developed FOS-SOC sensor is refractometric retro-reflective fiber optic sensor. It is immersed into one of the cell of the battery for measuring the refractive index of the active electrolyte which changes during the charge and discharge process of battery. SOC of the battery should be monitored when battery is connected to the load i.e. during the discharge. Figure 8 shows that FOS-SOC sensor output is direct measure of SOC of battery as when battery is connected to the load of 100 Watt for the period of 5 hours with discharging current of 5 A/hour.

Similar readings are taken by connecting different loads to the battery viz. 50 Watt, 86 Watt, 100 Watt. Figure 9 shows the variation in the sensor output voltage during discharge for different loads taken over the time period of 1hour. It is observed that as the load value is decreased from 100 Watt to 50 Watt the sensor output voltage more for the same time interval. This is because for smaller values of load, the charge remained in the electrolyte is more

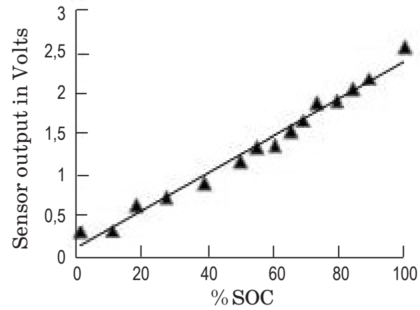

Figure 8. Sensor output with SOC.

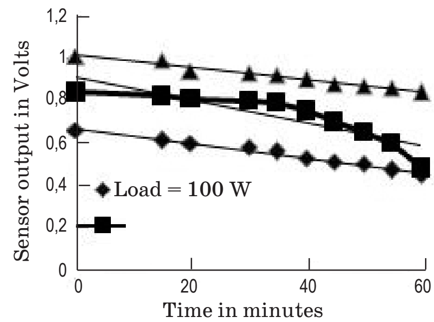

Figure 9. Sensor output voltage during discharge of battery.

compared to that for the larger values of load. Thus this sensor is used to directly measure the battery SOC.

Conclusion

This paper mainly describes a sensor based on the refractometry principle for measuring the SOC of the lead acid battery. Most of the present day methods available for measuring the SOC of battery are either offline or indirect. Few on line measurement methods are reported but it requires modification in the structure of battery itself. Such modification in the battery structure is not required by the FOS-SOC sensor. It is a direct and online method of measurement of SOC of lead acid battery. Experiments are carried out with FOS-SOC sensor by discharging battery with different loads. The sensor shows good sensitivity for this. Thus the sensor is useful for online determination of the SOC of the lead acid battery.

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