SOC 추정을 위한 밀폐형 Flooded 연축전지의 히스테리시스 모델링

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Hysteresis Modeling of the Sealed Flooded Lead Acid Battery for SOC Estimation

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ABSTRACT

Sealed flooded lead acid batteries are becoming popular in the industry because of their low cost as compared to their counterparts. State of Charge (SOC) estimation has always been an important factor in battery management systems. For the accurate SOC estimation, open circuit voltage (OCV) hysteresis should be modelled accurately. The hysteresis phenomenon of the sealed flooded lead acid battery is discussed in detail and its ultimate modeling is proposed based on the conventional parallelogram method. The SOC estimation is performed by using Unscented Kalman Filter (UKF) while the parameters of the battery are estimated using Auto Regressive with external input (ARX) method. The validity of the proposed method is verified by the experimental results. The SOC estimation error by the proposed method is less than 3 % all during the 125hr test.

Index Terms – Hysteresis Modeling, Flooded Battery, State of Charge Estimation, Unscented Kalman Filter.

1. Introduction

There are different types of batteries available in the market such as Li-Ion, Lead-Acid and Nickel-Cadmium etc. Among the lead acid batteries, flooded batteries are also widely used due to their low cost and long life[1]. The flooded batteries are available in both serviceable and maintenance free styles. The state of charge (SOC) estimation of a battery is one of the fundamental requirements of the battery management system. The SOC-OCV relationship is very important in the modeling of the battery by using an equivalent circuit. However, the relation between SOC and OCV is not simply a one-to-one mapping but it exhibits hysteresis effect and diffusion effect[2]. Normally hysteresis effect is not taken into account for most of the Li-ion batteries because the gap between the SOC-OCV charge and discharge curves is very small in most of the region. Hysteresis effect is very prominent in lead acid batteries[3]. Therefore modeling the hysteresis phenomenon is an important aspect for SOC estimation. Since the hysteresis phenomenon in maintenance free (sealed) flooded lead acid battery has not been investigated clearly, the behavior of OCV requires both proper investigation and modeling accordingly. The paper is unique in a sense that it has fully investigated the OCV behavior and proposed a suitable hysteresis model for the Sealed Flooded Lead Acid (SFLA) Batteries. The model is then validated by experimentation.

2. Hysteresis Phenomenon and its Modeling

In electrochemical systems, the potential depends upon the history of charge and discharge of the electrodes instead of just depending upon the state of charge[4]. This phenomenon is known as hysteresis effect. The hysteresis effect is very prominent in SFLA batteries as shown in Fig. 1. It has been observed by different hysteresis tests that the behavior of OCV in SFLA is totally different as compared to other lead acid (LA) batteries. During a hysteresis test, OCV always touch the SOC-OCV charge curve in all other LA batteries while this is not true for SFLA in which OCV not even touch but becomes parallel to the SOC-OCV charge curve as shown in Fig. 1. Furthermore it is observed that rate of change of OCV w r.t. the SOC is different in different regions of SOC. This is shown in Fig. 2 in which three hysteresis curves at different SOC regions are shifted and plotted together.

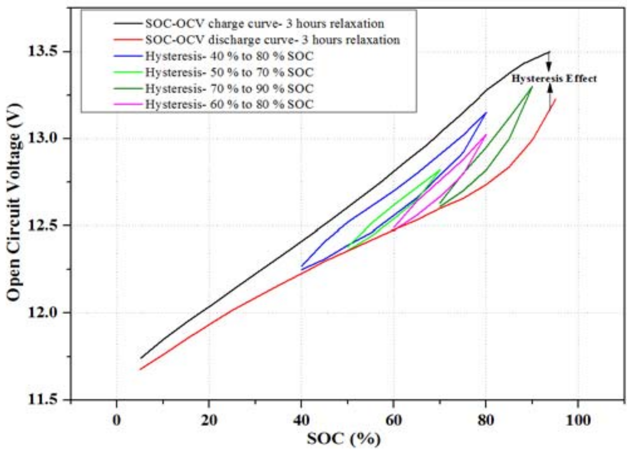

Fig. 1. Different hysteresis curves with SOC-OCV 3hr curves

It can be noticed that the rate of increase in OCV is higher in higher region of SOC. To model the mentioned facts about OCV behavior during hysteresis, a parallelogram modeling is used as shown in Fig. 3.

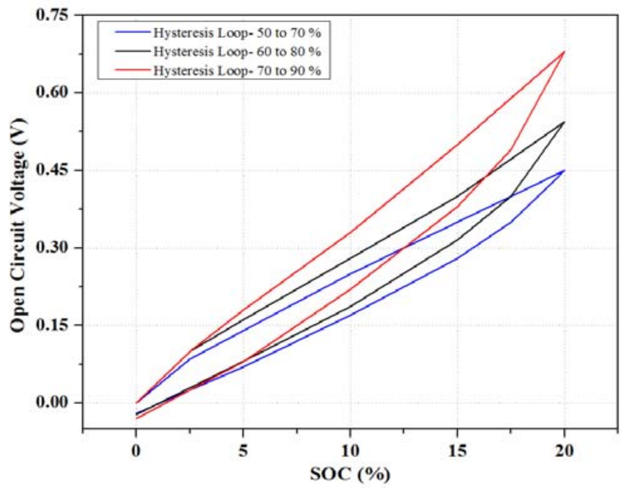

Fig. 2. Shifted Hysteresis Loops

During the hysteresis, OCV will follow 'k_1' slope for about 5 % SOC and after that it will start following 'k_2' slope until SOC becomes equal to 100 %. The slope is calculated by the following formula in (1).

$$Slope = \frac{Difference\,in\,OCV\;value}{Difference\,in\,Ah\,value} \tag{1}$$

The final OCV due to the hysteresis can be calculated as

$$OCV_{hys} = k_1 * SOC_1 + k_2 * SOC_2 \tag{2}$$

$$SOC_1 = SOC_2 = \int \frac{I}{Cn} dt \quad (3)$$

$$0 \le SOC_1 \le 0.05 \text{ and } 0 \le SOC_2 \le 0.95 \quad (4)$$

where, C_n represents the capacity of the battery.

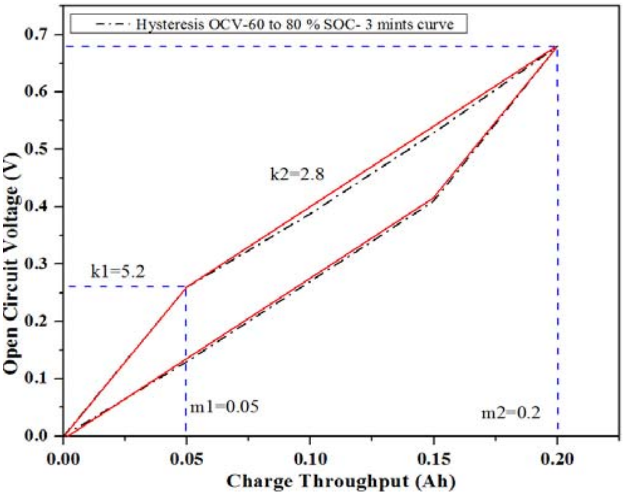

Fig. 3. Parallelogram Hysteresis Modeling

Fig. 4 shows the relationship between the starting SOC and their corresponding calculated slopes values. Whenever the OCV changes from SOC-OCV discharge curve then depending upon the SOC at that point, the slopes are different for hysteresis calculation.

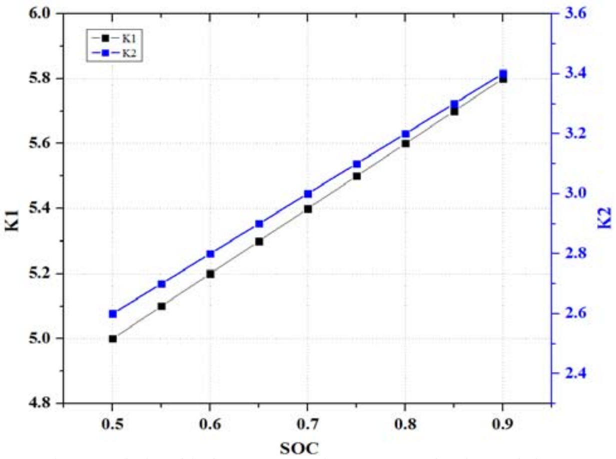

Fig. 4. Relationship between starting SOCs and values of slopes

3. SOC Estimation

A Thevenin-based electrical circuit model is used for the battery's SOC estimation. Both hysteresis and diffusion are included in the OCV[3]. The state equations for the battery model can be shown as:

$$\begin{pmatrix} SOC_{k+1} \\ V_{Cdl\,k+1} \end{pmatrix} = \begin{pmatrix} 1 & 0 \\ 0 & 1 - \dfrac{\Delta t}{R_{ct} C_{dl}} \end{pmatrix} \begin{pmatrix} SOC_k \\ V_{Cdl\,k} \end{pmatrix} + \begin{pmatrix} -\dfrac{\Delta t}{C_n} & \dfrac{\Delta t}{C_{dl}} \end{pmatrix}^T I_k + w_k \quad (5)$$

$$V_k = \text{OCV} - V_{Cdl,k} - R_i I_k + v_k \quad (6)$$

V_k, V_{cdl} , w_k and v_k represent terminal voltage, polarization voltage, process noise and measurement noise respectively. The parameters (R_i, R_{ct} and C_{dl}) of the battery are estimated online by using ARX method and finally SOC is estimated by using UKF algorithm.

4. Experimental Results

For experimentation, a 90Ah, 12V sealed flooded battery from Sebang Company is used. The battery is placed in a temperature controlled chamber to maintain its temperature. To verify the hysteresis modeling at different SOC regions a special profile is made in which SOC goes to a certain value and then charged up to a certain value and then goes back again. The coulomb counting method is used as reference for comparison of SOC estimation. Fig.5 shows the SOC estimation results by the proposed method and by using fixed slopes during hysteresis. In the proposed method the slopes always changes depending upon the SOC value whenever the battery changes its state from discharge to charge while in fixed slope method , slopes remains constant during all of the SOC region.

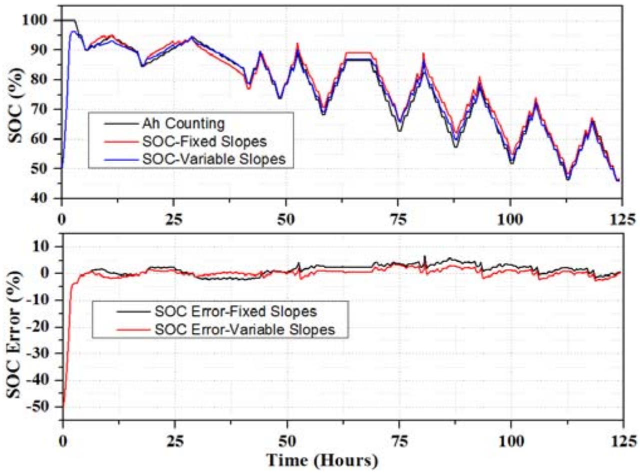

Fig. 5. Comparison of SOC estimation by proposed method.

The SOC estimation result clearly shows that the proposed method of hysteresis modeling is very accurate as the error is just about 3 %. When fixed slopes are used then as the hysteresis voltage increases, the SOC estimation error also starts increasing which clearly shows that the fixed hysteresis model is not suitable for a sealed flooded lead acid battery. The SOC error with fixed slope method is about 6 %.

5. Conclusion

The OCV behavior of a sealed flooded lead acid battery is investigated for the first time. It is observed that the hysteresis behavior of the battery under consideration is totally different from the other types of batteries due to which it also requires different hysteresis modeling. Finally the hysteresis modeling is proposed based on the observations of the hysteresis behavior. The Unscented Kalman filter is used for state of charge estimation of the battery and results are presented, which show an error of 3 % with the proposed model.

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