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Methods of SoC determination of lead acid battery

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ABSTRACT

Lead acid batteries are typically used in the automotive industry, where they provide a high current pulse to start the vehicle, in traction applications, where they undergo periodic deep discharge and charge, and in stationary applications, where they remain in charged state most of their life. They are used also in hybrid electric vehicles (HEVs) and in remote area power supply systems (RAPS), where they remain in a state of about 50% of charge during their operation. In this state, these batteries can be charged or discharged with high effectivity. In all these applications, it is necessary to monitor and report the battery state of charge (SoC) instead of simply monitoring the battery voltage.

1. Introduction

The paper explores SoC determination methods for lead acid battery systems. This topic gives a systematic overview of battery capacity monitoring. It gives definitions for battery state of charge at different rates of discharge and temperature. Three common SoC monitoring methods – voltage correlation, current integration, and Impedance Track are discussed.

State of charge of lead acid battery is the ratio of the remaining capacity RC to the battery capacity FCC [1]. The FCC (Q) is the usable capacity at the current discharge rate and temperature. The FCC is derived from the maximum chemical capacity of the fully charged battery Q_{MAX} and the battery impedance R_{DC} (see Fig. 1) [2].

$$SoC = \frac{RC}{FCC} \tag{1}$$

Measurement and monitoring voltage of the battery is not the correct SoC indicator due to the effects of the charging/discharging current and temperature. The reason is in chemical kinetics when charging and discharging battery. In order to obtain a qualified SoC estimation from voltage measurement, it is necessary to keep the battery in the current off state for at least several hours (for example, four hours) to reach the equilibrium state before the OCV voltage can be measured.

Battery SoC can be monitored with accurate measurements of battery voltage, temperature and current. When the battery is in idle mode, the SoC is determined by the battery voltage and the predefined table of the OCV/SoC relationship, which is temperature-compensated. Instead of a table, it is possible to use a suitable mathematical function describing this dependence obtained by regression analysis. If the battery is in charged or discharged state, the current integration begins.

The OCV measurement method with current integration can also be used to update the capacity of a fully charged battery [3]. If SoC before current load is known and added or removed capacity is measured, SoC can be determined after end of current load as shown in Fig. 2 [4]. This method can be used whenever the initial SoC is known and the added or removed capacity is measured. Battery capacity Q_{MAX} is given by [3]:

$$Q_{MAX} = \frac{\Delta Q}{|SoC1 - SoC2|} = \frac{\Delta Q}{|DoD2 - DoD1|}, \tag{2}$$

where ΔQ is the difference between the capacity Q before and after charging or before and after discharging, DoD is the depth of discharge: DoD = 1 − SoC. Once Q_{MAX} is calculated, the same value is used to calculate the SoC during charging/discharging until the next Q_{MAX} update.

The total capacity determined by the OCV voltage measurement method corresponds to the current off conditions – i.e. the maximum possible capacity that can be obtained from the battery. With non-zero load, the capacity will be lower due to the IR drop.

The SoC is determined by the current integration [5]:

$$SoC = SoC_{t=0} - \frac{1}{FCC(\bar{I}, \vartheta)} \int_0^t I(\tau) d\tau, \tag{3}$$

where FCC is the capacity of the cell for discharge current I and temperature ϑ.

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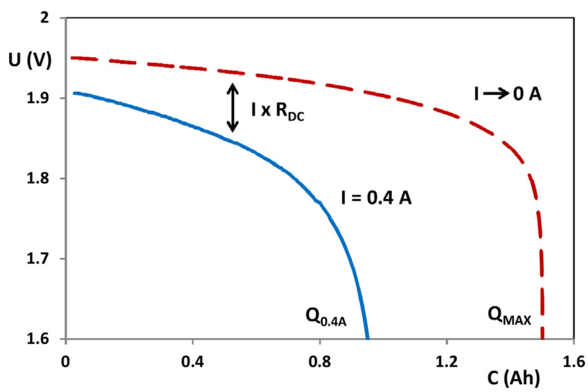

Fig. 1. The cell voltage as a function of capacity during discharging with current load 0.4 A and with no current load. The usable capacity Q is reduced due to impedance of cell (R_{DC}).

In current off conditions the SoC is calculated [6]:

$$SoC = 1 - \frac{Q_{PASS}}{Q_{MAX}} = 1 - DoD, \tag{4}$$

where Q_{PASS} is passed charge.

Remaining capacity RC [6]:

$$RC = Q_{MAX} - Q_{PASS} \tag{5}$$

During discharge [6]:

$$SoC = 1 - \frac{Q_{PASS}}{FCC(I, \vartheta)} \tag{6}$$

$$RC = FCC(I, \vartheta) - Q_{PASS} \tag{7}$$

Time to end of discharge t [6]:

$$t = \frac{RC}{I}, \tag{8}$$

where I is discharge current.

The battery impedance R_{DC} is calculated according to the equation [6]:

$$R_{DC} = \frac{|U_{OC} - U|}{I}, \tag{9}$$

where U is the battery voltage, U_{OC} is open circuit voltage and I is the charging/discharging current.

Impedance of the battery R_{DC} consists of ohmic polarization (IR) including resistance of the electrolyte, active masses, collector, contact resistance between the collector and the active mass and resistance of the cell interconnection. Activation polarization (describing the charge transfer at the positive and negative electrodes) and concentration polarization (describing the diffusion processes at the positive and negative electrodes) (Fig. 3) [7].

In case of ohmic polarization (internal resistance) determination, an alternating current I_{AC} of about 1 kHz applied to the battery terminals can be used. In the 1 kHz range, the imaginary component of the battery impedance is close to zero and the real component is minimal. This current is superimposed on a DC charging/discharging current passing through the battery or it may pass through the battery circuit in a current off condition. An alternating voltage U_{AC} response is measured and the battery impedance R_{AC} is calculated according to the equation:

$$R_{AC} = \frac{U_{AC}}{I_{AC}} \tag{10}$$

SoC can be determined from the measured voltage, current integration or from the DC impedance:

From the measured voltage:

Suitable at the end of the discharge when there is a significant change in voltage. In the first phase of discharge there is low accuracy due to a small voltage change, the first voltage measurement must be done approx. 5 min after start of discharge to avoid distortion due to transients [6]. Voltage must be compensated for a discharge current and temperature.

From current integration:

Low precision at end of discharge due to change of FCC during cycling – necessity of SoH determination. FCC must be compensated for a discharge current and temperature.

From the DC impedance:

The R_{DC} is calculated from the measured voltage – the same advantages and disadvantages as the voltage measurement. R_{DC} must be compensated for a discharge current and temperature.

Texas Instruments uses the Impedance Track method to determine SoC of lead acid batteries [6]. While current off, the OCV is measured, which is used to determine the SoC and to update Q_{MAX}. When discharging, both discharge current and voltage are measured. Charge passed is determined from the current integration and the DC impedance R_{DC} is determined from the measured voltage. Voltage and current are used to determine actual SoC.

The measured impedance R_{DC} is temperature compensated and the measured values R_{DC} during discharge are compared with the values from the tables R_{DC} on DoD dependence. However, compensation for the discharge current is not considered here. Experiments presented in this paper show that impedance R_{DC} depends on the discharge current.

2. Experimental section

For the experiment investigating impedance changes in the lead acid battery in a flooded state during discharging a test cell was prepared with a capacity of about $C_{2.5}$ = 1 Ah. The cell was composed of one positive and one negative electrode (with

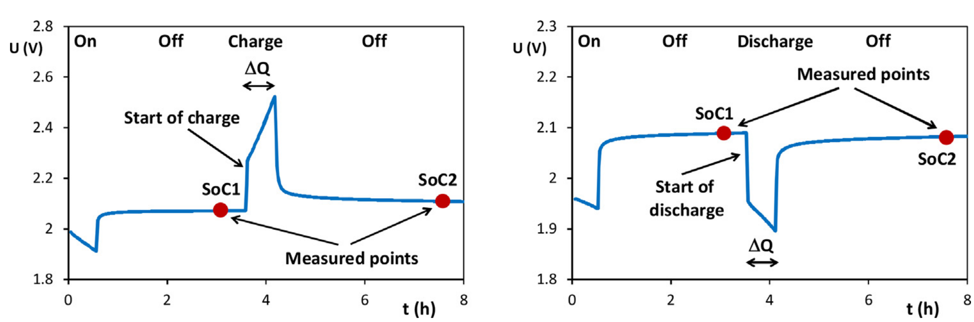

Fig. 2. Determination of total capacity based on charge (left) and discharge (right).