Implementation of “State of Charge Estimation” for Lithium-ion Battery Pack

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Abstract- **State of charge (SOC) estimation is an increasingly important issue in battery management system (BMS). In addition to offering the real time display of battery parameters to user, the accurate SOC information would exert some controls over the charging and discharging process that in turn reduces the risk of cell over voltage. This paper proposes a method to conduct real-time monitoring of the battery state accurately, such as the battery charge and discharge current, voltage, temperature and the state of charge. SOC estimation error is made less than 5%.It can also timely alarm and carry out protection action in the abnormal state of the battery. A new method named combination algorithm is proposed in this paper in accordance with the characteristics of lithium-ion power battery.**

Index Terms- combination algorithm; state of charge (SOC); open circuit voltage (OCV); extended Kalman filtering (EKF); ampere hour (Ah); battery management system (BMS).

I. INTRODUCTION

In recent years, with the gradual expansion of the integration of power supply applications in the power system, the demand for the battery packs have increased rapidly. However, the actual service life of the battery pack is not satisfactory due to the characteristics of the battery, the limitations of the current inspection and maintenance equipment. If the battery status and life cannot be guaranteed, it will be a great security system to the power grid system, while causing a large number of batteries in advance scrap, a serious waste of resources and funds, and increased environmental pressure. There are many reasons why the battery cannot achieve the expected service life, including manufacturing process, production quality, the use of materials. But the most important reason is the improper battery management program, resulting in overcharge, undercharge, over discharge and ambient temperature and other issues.

According to each cell’s SOC, performance differences among batteries in the pack can be identified, and equalization in charge and discharge could be carried out smoothly to prolong battery pack’s lifetime and optimize cell energy efficiency. Nowadays, lithium-ion battery gets the characteristics of high working voltage, large capacity, small internal resistance, long cycle life and no memory effect, so that it has become the hotspot in the field of power battery research and application. Nevertheless, from the perspective of production technology, there are nonlinearity, inconsistency and time variation existing in lithium-ion battery manufacture.

In an conclusion, some specially designed estimation methods need to be taken in the BMS to avoid over charging and over discharging that may cause permanent damage and result in battery lifetime reduced.

II. STATE OF CHARGE ESTIMATION

Above all, there are a list of definitions given to help us better understand the definition of SOC before we introduce the estimation methods in details.

A cell is fully charged when its voltage reaches U=UH after being charged at infinitesimal current levels approximate to 0.1A normally. Here, we take UH=3.8V at room temperature (25°C).

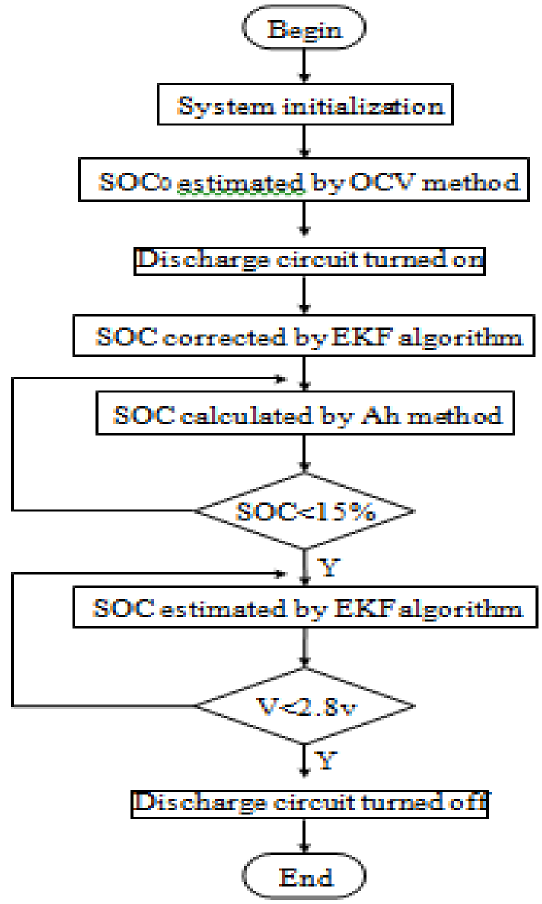
A cell is fully discharged when its voltage reaches U=UL after being drained at infinitesimal current levels which generally takes the value of 0.1A. Here, we take UL=3.0V at room temperature.

The capacity Q of a cell is the maximum number of ampere-hours that can be drawn from the cell at the practical rate before it is fully discharged, starting with the cell fully charged.

The nominal capacity on of the cell is the number of ampere hours that can be drawn from the cell at the C/30 rate, starting with the cell fully charged at room temperature.
The remaining capacity Qt is the number of ampere hours that can be drawn from the cell at room temperature at the C/30 rate before it is fully discharged. Therefore, SOC is referred to the ratio of the remaining capacity to the nominal capacity. But this definition is only aiming at one cell, while the battery pack is usually made up of many unbalanced cells. Hence, in order to avoid over charge and over discharge, it is necessary to estimate each cell's SOC respectively and select the minimum value as the battery pack's SOC.

A. Combination Algorithm for State of Charge Estimation

On account of these two methods' limitation and the particular working conditions, an efficient estimation method called combination algorithm is proposed in the paper. Fig. 1 shows a simple flowchart, and a short description is given below.
Firstly, the system is initialized and the algorithm calculates the original value of SOC (SOC0) by the OCV method.. In this section, every cell's SOC0 needs to be estimated and the minimum value is considered as the battery pack's SOC0.
Secondly, the extended Kalman filtering (EKF) algorithm is taken to correct the value of SOC that is based on SOC0 immediately when batteries start to work. In general case, this procedure requires at least 200 sampling data to get a more accurate SOC. Subsequently, the Ah counting method takes the task of SOC calculation when battery voltages are changed slowly. Hence, this discharge part is not suitable for EKF algorithm where voltage is the EKF's input parameter and the SOC is computed by the value and change degree of battery voltage. When SOC is reduced to 15%, the EKF algorithm is taken again to estimate SOC until the discharge process is finished.
Actually, combination algorithm is made up of three methods: Ah counting method, OCV method and EKF algorithm.



The Open Circuit Voltage Method:
During the beginning and ending stages of discharge, this method has a good performance when there is a distinct corresponding relation between the open circuit voltage (OCV) and SOC. However, this method does not meet the requirements for online detection. Because of the self-recovery effect, battery needs a long time to get into the stable state when open circuit voltage changed little as time goes on. Besides, it is very hard to determine whether the battery is in stable state or not. What's more, measuring the open circuit voltage precisely is not an easy task.

The Ampere Hour Counting Method
The ampere hour (Ah) counting method mainly makes use of the Peukert equation to change actual current into standard current, and takes integration of time to estimate SOC. We define the initial state as SOC_0, so the present value SOC can be calculated:
$SOC = SOC_0 - Q^{1n} \int_0^t \eta_i i dt$. (1)

Here, η_i is the current efficiency coefficient computed and deduced by the Peukert equation. The ampere hour counting method is one of the simplest and most universal methods for SOC estimation. Nevertheless, SOC estimation error, as time goes on, becomes increasingly greater because deviation caused by inaccurate current sensor measurement would be gradually accumulated.

The Extended Kalman Filtering Algorithm:

EKF algorithm, an elegant and powerful solution, is the optimum state estimator for a linear system. It is an established technology for dynamic system state estimation. We will apply Kalman filtering theory by viewing each cell in the battery pack to be a dynamic system whose inputs include the current and temperature experienced by the cell and whose output is the battery terminal voltage. If the system is nonlinear, we may use a linearization process at every time step to approximate the nonlinear system with a linear time varying (LTV) system. In the course of recursive filtering, this method makes use of test data to correct state estimated values with the minimum variance to reduce the estimation error. We get the discretetime linear model as following:

state equation: $x_k+_1 = A_k x_k + B_k u_k + w_k$, (2)

output equation: $y_k = C_k x_k + D_k u_k + v_k$. (3)

Here, x_k is the system state vector SOC at time index k. The known or deterministic input to the system is u_k. The output of the system is y_k which represents the battery terminal voltage. w_k is the stochastic "process noise" that models some unmeasured input which affects the system state. v_k models the "sensor noise" that sways the measurement of system output in a memoryless way, but does not change the system state. A_k, B_k, Ck and D_k describe the system dynamics, and are possibly time varying.

EKF algorithm has a strong ability of correction to SOC initial value, so this method is suitable for the hybrid power battery application. Nevertheless, because of high demands on both software and hardware, plus many vector operations existing in the recursion-iteration equations, it is difficult to make SOC online estimation on common processing chips.

III. EKF-AH METHOD ESTIMATION STATE OF CHARGE

In view of comparison among performances of abovementioned methods, a new algorithm called EKF-Ah is proposed, which combines the EKF algorithm with the Ah counting method and the open circuit voltage method. The main operation procedure is given below:

Firstly, measure the open circuit voltage and use the mathematic expressions concerning SOC and OCV to calculate the SOC initial value (SOC0) at time t0 when battery is at resting state.

Secondly, SOC0 is corrected by the EKF algorithm during the time of t0 to t1, and SOC at time t1 (SOC1) is obtained.

Thirdly, SOC at time t2 (SOC2) is estimated by the Ah counting method based on SOC1 during the time of t1to t2.

Subsequently, SOC2 is corrected by the EKF algorithm during the time of t2 to t3, so we get the estimation value at time t3 (SOC3).

Finally, the step 3 and 4 are executed repeatedly until the process of battery discharge is over.

The EKF-Ah algorithm primarily uses the EKF's correction characteristic to improve the result accuracy which is inferred by the open circuit voltage method and the Ah counting method.

EKF-Ah not only overcomes the shortcoming of the initial SOC estimation imprecision calculated by the open circuit voltage method, but also solves the problem of SOC accumulative error caused by the long-time current inaccurate measurement. Meanwhile, compared with the single use of EKF algorithm, the EKF-Ah method depends less on the performances of software and hardware, and reduces the system's cost.

IV. SYSTEM STRUCTURE DESIGN

In view of combination algorithm, a corresponding system is designed and the block diagram is shown in Fig. 1. A simple description is given as follows:

This SOC estimation system is mainly divided into four sections: parameters measurement module, sampling computation module, algorithm processing unit, diagnose and display module. In the measurement module, hall sensor and thermal resistor are used to measure the battery's current and surface temperature.

Meanwhile, an optical coupler array circuit is chose to sample cell voltages and solves the problem of battery common mode voltage, instead of conventional voltage dividing circuit using precision resistors. Fig. 2 shows the schematic diagram of this circuit as follows.

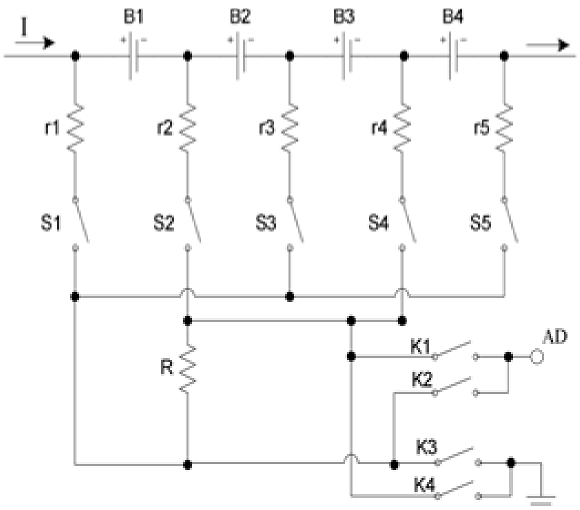


Figure 2. Cell voltages measuring circuit

Because the cells in battery pack have some differences in battery parameters among them, a two stages structure is adopted in the system. Besides, a analog to digital converter with high precision and speed is used to sample every cell's. terminal voltage, battery pack's voltage, charge or discharge current and battery surface temperature. Afterward, the sampling results are firstly sent to the micro controller for prestage processing, such as data restore, digital filtering and state judgment, then taken to the central controller for the combination algorithm calculation. Finally, according to the SOC, the central controller makes a diagnosis of the battery pack and some state messages are displayed in curves. If the battery pack is in abnormal states, the central or micro controller would send order to the power MOS transistors to cut off the battery circuit immediately.

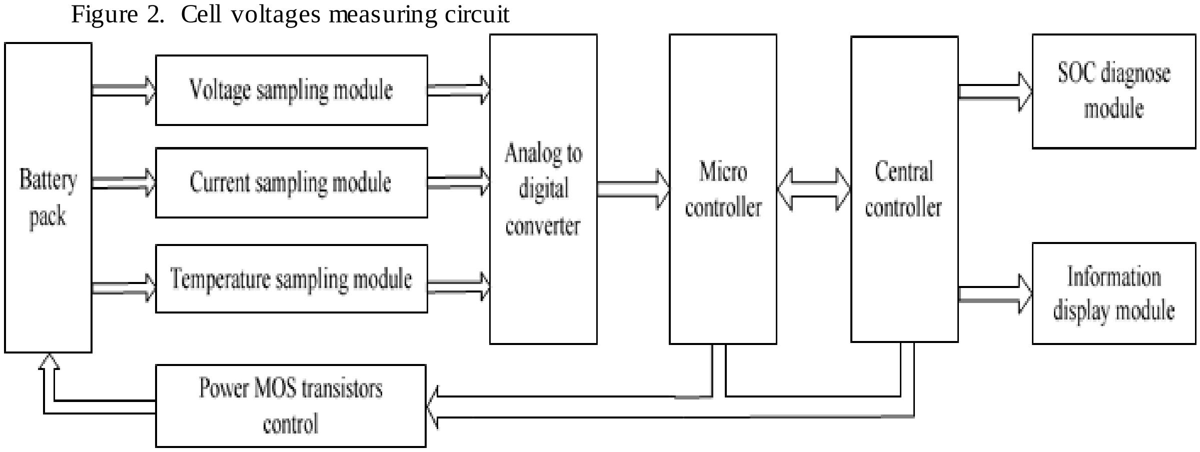


Figure 1. System block diagram in state of charge estimation

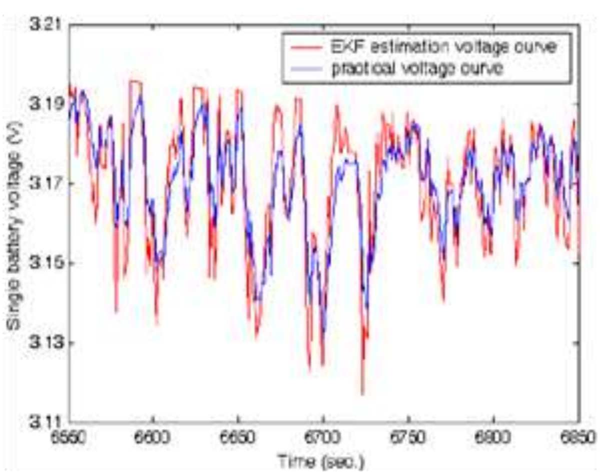


Figure 3. Cell voltages measuring circuit

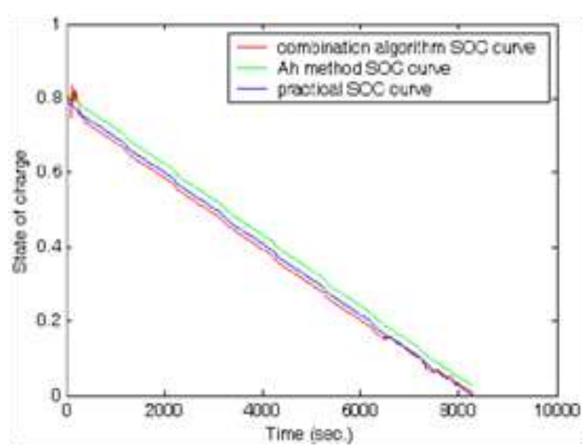


Figure 4. Comparison of SOC estimation methods for the battery

V. CONCLUSIONS

From the Fig.3, we get to know that the combined model in EKF algorithm has a good performance on SOC estimation where the estimated voltage is similar to the practical voltage and has the same voltage variation tendency. Besides, in the Fig. 4, it is seen clearly that the SOC estimation curve using combination algorithm is very closed to the practical SOC curve, especially in the terminating stage, while the SOC only estimated by Ah counting method is departing from the actual SOC more and more seriously and the estimation error is biggest when the pack discharge comes to the end. The maximal error of combination algorithm is less than 5% in the UDDS test, which completely conforms to the SOC estimation accuracy requirement of lithium-ion power battery.

The combination algorithm gives full play to the advantages of OCV method, Ah counting method and EKF algorithm. According to the pack's working state, it takes suitable estimation method in different discharge sections and prevents big error appearing at the end of discharge. In conclusion, this method is a good approach to fulfilling the algorithmic requirements of SOC estimation.

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