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Research Article

A Novel Method for SoC Estimation of Lithium-Ion Batteries Based on Kalman Filter in Electric Vehicle

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Abstract **–** In recent years, the energy crisis has become more and more serious. Li-ion batteries are used in grids because of their benefits such as contributing to the intermittent generation of renewable energy sources and stabilizing the grid. In addition, li-ion batteries are widely used in electric vehicles due to their long cycle life and high energy density. Li-ion battery state of charge (SoC) is an important indicator for safety. Therefore, the SoC estimation of li-ion batteries is important. Today, there are different methods to determine the state of the SoC in many applications. The traditional estimation method, the ampere-hour integration method and the coulomb counting method, has a cumulative error and cannot achieve good results in a working environment with Gaussian noise. For this purpose, in this study, firstly, the Thevenin equivalent model was created for battery SOC estimation, and then the Kalman filter algorithm was applied. Thus, the estimation error caused by Gaussian noise is eliminated. SoC estimation was simulated for the battery model created in the MATLAB/Simulink program using this method. Using these simulation results, the charge/discharge characteristics of the battery were obtained. However, the SoC estimation has been made for the charging and discharging processes of the battery. In the simulation, the charge value was recorded for 6 hours. The data recorded every 10 minutes gave results very close to the true value.

Keywords – Electric Vehicle, Estimation, Li-Ion Battery, Kalman Filter, SoC

I. INTRODUCTION

The world is threatened by the emission of greenhouse gases from the use of fossil fuels [1]. One of the main causes of these pollutants is the widespread use of automobiles with internal combustion engines. The use of electric vehicles is seen as a method to reduce these environmental impacts [2-3]. For this solution to be effectively implemented, electric vehicle prices must be competitive with conventional vehicle prices. The battery has the largest share in the costs of electric vehicles [4]. In addition to electric vehicles, batteries have recently been used worldwide to store electrical energy for reasons such as grid stability and energy crisis [5-7].

Since electrical energy cannot be stored directly, batteries store electrical energy by converting it into chemical energy. With the development of technology, interest in battery systems is increasing day by day [8]. Battery types have also started to be produced in different types to meet the needs of these sectors. However, lithium ion batteries have a wider range of applications due to their advantages such as high energy density, low variation in operating voltage levels, long cycle life and light weight [9]. In recent years, lithium ion batteries have gained a significant place as an energy storage technology for electric vehicles, mobile electronic devices and grid stability [10].

Lithium ion batteries need to be monitored and managed by battery management systems for reliable operation. The success of an efficient and effective battery management system depends on the accurate estimation of the battery state of charge [11-12]. Battery estimation methods have become a subject of academic study for the safe operation of batteries. SoC estimation is not only an important topic but also difficult and complex to estimate accurately [13]. This is due to the parametric uncertainties between batteries. In response to this, different SoC estimation methods are available today [14].

In the literature review, it is seen that the studies are categorized under three main headings. Experiment-based, state space model-based and smart algorithm-based methods were identified [15]. In this study, simulations were performed in MATLAB/Simulink environment with the Kalman filter, which is a subheading of the state space model method.

II. Technical Background

A. *Equivalent Circuit Model*

Due to the difficulty of the chemical structure of batteries, modelling them as equivalent circuits to make them more understandable gives very successful results [16]. Battery modeling can be mainly divided into four groups: physical, electrical, analytical, and statistical. In the electrical model, the battery is modeled using an equivalent circuit. In this type of modeling, unknown parameters can be easily estimated by using mathematical equations for circuit parameters on the model. Thus, it is possible to make mathematical calculations on the model. For this reason, the electrical equivalent circuit is modeled for the charge-discharge curves. Battery runtime and SoC estimation can be easily done using the battery circuit model. Fig.1 shows the Thevenin equivalent battery model.

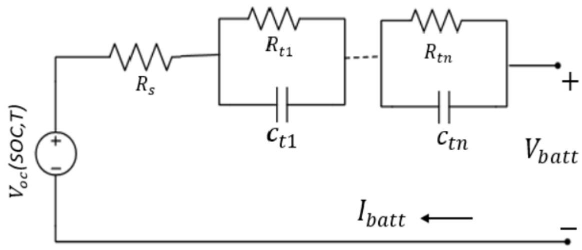

Fig 1. The common Thevenin's equivalent circuit of batteries [17]

Although in some of the electrical equivalent circuit models the circuit parameters are assumed to be constant, in reality these values are not constant but depend on the internal dynamics of the battery such as battery state of charge, temperature, battery current, capacity and battery life. Eqs.1 and 2 show how to calculate these dynamics-dependent values.

$$V_{oc} = \left(\frac{1}{R_{tn}} + \frac{1}{C_{tn}} \right) \cdot I_B \tag{1}$$

$$V_B = V_{OC} - \left(R_s \cdot I_B + V_{OC} \right) \tag{2}$$

B. *Kalman Filter*

The Kalman Filter tries to predict the next state of a dynamic system based on its previous states. To do this, a mathematical model of the system is created. When estimating the battery state of charge with filtering algorithms, the state-space model of the system is used. The battery state of charge is estimated by appropriate filtering or observer algorithms [18]. The state-space model is usually obtained from the equivalent circuit model of the battery. Since the accuracy of the equivalent circuit model directly affects the state space model, it directly affects the accuracy of the charge state estimation [19]. Therefore, it is important to improve the equivalent circuit model to realize high accuracy predictions. Figure 2 shows the state of charge estimation diagram for the state space model.

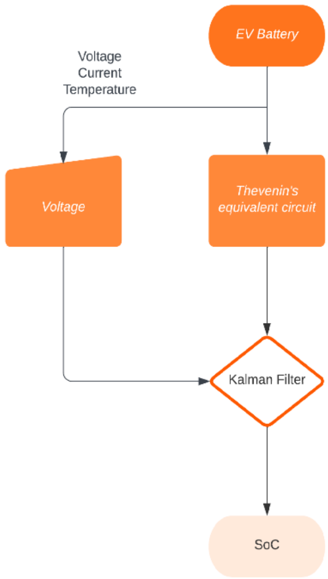

Fig 2. The state of charge estimation diagram for the state space model

The real system cannot be fully reflected as a mathematical model. We try to create a mathematical model that is closest to the real system. Because the data obtained consists of noisy and imprecise data. In real life, there may be many factors affecting our system. Modeling all of these factors will bring difficulty and complexity. In this context, many experts and scientists have used various filtering methods based on the Kalman filter to estimate the battery load status and various models are still being developed to reduce the computational burden. Figure 3 shows the algorithm of the Kalman filter.

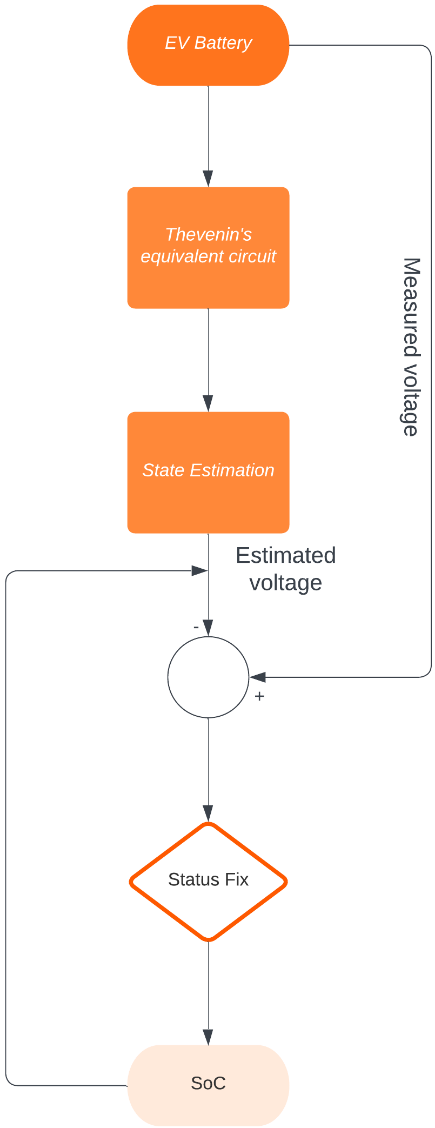

Fig 3. Kalman filter diagram

The Kalman filter is used in dynamic systems when you have uncertain and imprecise information [20]. Thus, it is preferred in forecasting applications. By evaluating the inputs and outputs of your system, the Kalman filter helps you understand what is actually happening in the system. By obtaining data that you cannot directly measure or whose accuracy is not accurate, it tries to make a prediction close to the actual state of the system [21]. If the data you obtain contains various noises, the Kalman filter allows you to estimate the value closest to reality.

The Kalman filter is used in SoC estimation applications because it can detect even the smallest variations. The equations used in the battery mathematical models are given in Eq. 3 and Eq. 4.

$$x_{k+1} = f\left(x_k, u_k\right) + w_k \tag{3}$$

$$y_{k+1} = g\left(x_k, u_k\right) + v_k \tag{4}$$

In Eq.3 and Eq.4, u_k contains the inputs of the system such as current, temperature and internal resistance and y_{k+1} contains the output of the system such as open circuit voltage. The state variable x_k defines the estimated SoC value. The functions *f* and *g* represent the nonlinear equations in the battery model. These values need to be linearized in the calculation process [22].

The Kalman filter algorithm should be expressed by an electrical equivalent model. In this study, the PNGV model and the Kalman filter algorithm are used to extract the battery state equations. Eq.5 and Eq.6 give the state equations of the battery.

$$\begin{bmatrix} \dot{u}_b \\ \dot{u}_2 \end{bmatrix} = \begin{bmatrix} 0 & 0 \\ 0 & -\dfrac{1}{R_2 C_2} \end{bmatrix} \begin{bmatrix} u_b \\ u_2 \end{bmatrix} + \begin{bmatrix} \dfrac{1}{C_b} \\ \dfrac{1}{C_2} \end{bmatrix} I \tag{5}$$

$$u_{oc} = \begin{bmatrix} -1 & -1 \end{bmatrix} \begin{bmatrix} u_b \\ u_2 \end{bmatrix} + \left(-R_1 I\right) + u_{oc} \tag{6}$$

In the equations, u_b is the voltage at capacity c_b; u_2 is the voltage across the *RC* tank; *R1* is the internal resistance and u_{oc} is the open circuit voltage.

III. MATERIAL METHOD

Battery health State of Health (SoH) is the term used to describe the battery's ability to energize the load. The capacity of the battery gradually decreases as the battery is used (aged). For this reason, a battery that has been used for a long time can store approximately 70%-80% of the energy stored at full capacity when new, although the charge status shows 100% when fully charged. This operating range may vary depending on the place of use of the battery and the frequency of charging/discharging. However, in many applications, this operating range is defined as 20≤SoC≤80.

This study shows how to estimate the SoC of the battery using a Kalman filter. The initial SoC of the battery is equal to 20%. The estimator uses an initial condition for the SoC equal to 50%. The battery is charged and discharged for 6 hours in MATLAB/Simulink. The Kalman filter estimator converges to the actual value of SoC in less than 10 minutes and then follows the actual SoC value. At these values, the accuracy is estimated by comparing battery data that has been previously charged and discharged with similar parameters. This study was simulated on an Intel® 3.2 GHz i7 multi-core CPU computer using MATLAB/Simulink software. The model of the study is given in Fig. 4.

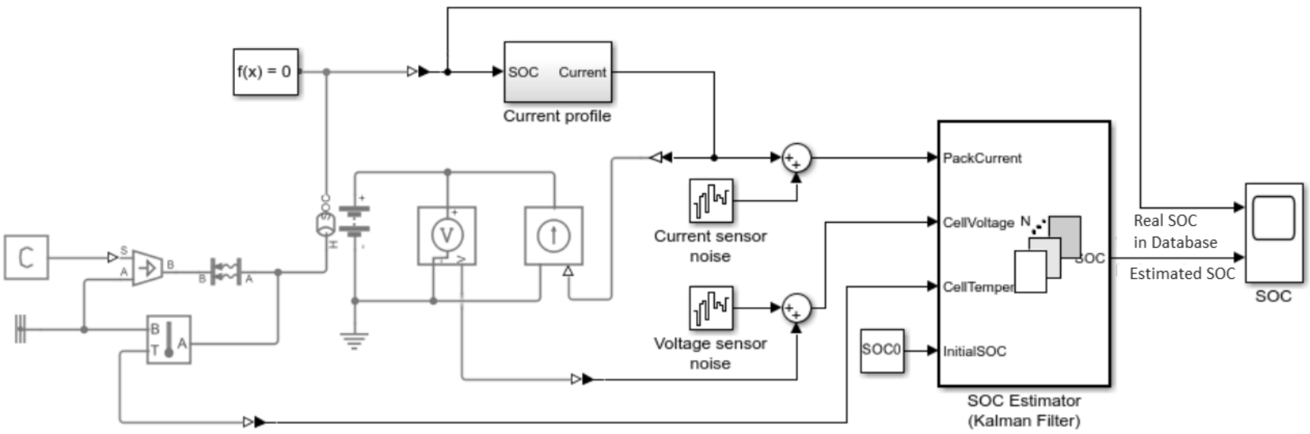

Fig 4. Kalman filter MATLAB/Simulink model

A comparison of the performance of the different proposed methods used to estimate the SOC is performed through experimental data. For this purpose, the comparison is based on the 18650 cylindrical battery model used in electric vehicles. In this study, real driving conditions were simulated such that the battery has a charge between 20% and 80%. These batteries contain LiFePO 4 cathodes and provide a nominal voltage of 3.8 V.

IV. Result And Discussion

Battery charge/discharge graphs were obtained using MATLAB/Simulink software for the battery SoC value taken into the computer. The variation of the battery with respect to time while charging is given in Figures 5 and 6. It was observed that the actual values of the battery charge/discharge status obtained from the database were very close to the data obtained by applying the Kalman filter.

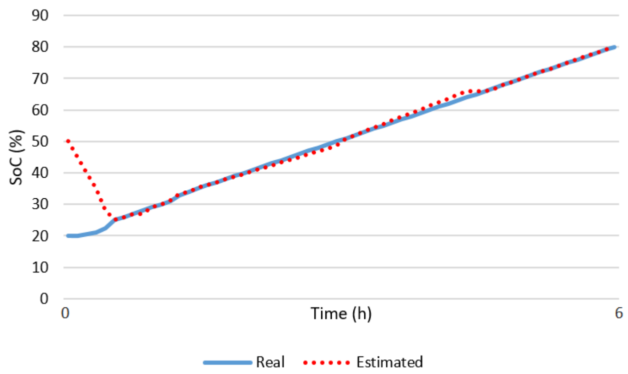

Fig 5. SoC for a charging stage

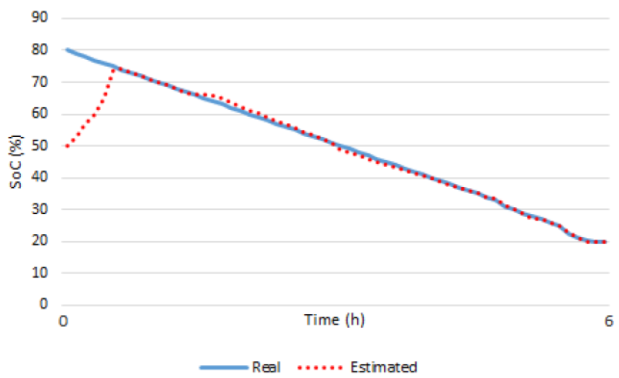

Fig 6. SoC for a discharging stage

We tested the implemented Kalman filter algorithm in charge mode, discharge mode and both modes together using MATLAB simulation tool. In Figures 5 and 6, the blue curves represent the actual SoC values and the red curves represent the estimated SOC obtained with the Kalman filter algorithm.

The estimation accuracy of the Kalman filter is quite high even with noisy signals. The initial state of charge is not important for estimation. However, the estimation accuracy varies according to the electrical model selected. Not suitable for nonlinear systems. Battery SoC values are nonlinear, so the extended Kalman filter could have been used instead of the Kalman filter. In this study, the extended Kalman filter was not preferred because estimation errors may occur due to the omission of some terms in the linearization process.

V. Conclusion

In this study, battery models and SoC determination methods in the literature for the most widely used batteries in energy storage are examined in detail. Kalman filter counting method is preferred for battery state of charge determination because it is more reliable. An algorithm for SoC determination was developed using MATLAB/Simulink software. Graphical results are plotted for varying charge and discharge values of the battery. The estimation accuracy of the Kalman filter estimation method is quite high even with noisy signals. Therefore, it is highly robust against sensor-induced noise. The initial state of charge is not important for estimation. It is the most successful estimation method under nonlinear and dynamic changes. However, the estimation accuracy varies according to the electrical circuit model selected. In this study, it is seen that the initial value is not important. The Kalman filter quickly converged to the true value after a few estimations.

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