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Online battery state of health estimation based on Genetic Algorithm for electric and hybrid vehicle applications☆

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HIGHLIGHTS

- Proposed an online battery state of health estimation method based on battery model parameters.
- Genetic Algorithm is employed to estimate the battery parameters.
- Determine the battery SOH in real time based on estimated battery parameters.
- Developed a formula to calculate the SOH based on the estimated diffusion capacitance.
- Temperature influence is considered to improve the robustness of SOH estimation.

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ABSTRACT

State of health (SOH) of batteries in electric and hybrid vehicles can be observed using some battery parameters. Based on a resistance–capacitance circuit model of the battery and data obtained from abundant experiments, it was observed that the diffusion capacitance shows great correlation with SOH of a lithium-ion battery. However, accurate measurement of this diffusion capacitance in real time in an electric or hybrid electric vehicle is not practical. In this paper, Genetic Algorithm (GA) is employed to estimate the battery model parameters including the diffusion capacitance in real time using measurement of current and voltage of the battery. The battery SOH can then be determined using the identified diffusion capacitance. Temperature influence is also considered to improve the robustness and precision of SOH estimation results. Experimental results on various batteries further verified the proposed method.

1. Introduction

Lithium-ion batteries are considered the only viable solution for electric drive vehicles (EDVs), including hybrid electric vehicles (HEVs), plug-in HEVs (PHEVs) and battery electric vehicles (BEVs). Battery safety and reliability are critical for the large-scale penetration of EDVs in the market place. A battery management system (BMS) is essential to manage, observe and protect the battery for safe and reliable operations of the vehicle. State of charge (SOC) and state of health (SOH) are very basic functions of the BMS [1–6].

Battery SOC is the ratio of available capacity and nominal capacity. It can be calculated through coulomb counting method, which is simple, direct and reliable [7]. However, this method relies on the knowledge of initial SOC. Other intelligent methods, such as neural network and extended Kalman filter (EKF), have been introduced to enhance the accuracy and precision of SOC calculations by removing measurement error and noise, as well as reliance on initial SOC [5].

Battery SOH describes the battery performance at the present time compared with the performance at ideal conditions and when the battery was new [5,8–16]. It is a measurement that reflects the battery performance and health status. Research on battery SOH has attracted wide attentions due to its importance in EDVs. In theory, by measuring the battery capacity through charging and discharging with the referenced method at certain temperature, the present capacity, hence the SOH, can be obtained.

Typically, there exist several methods to derive a battery SOH, such as comparing the internal resistance [5,11], total available capacity [7], voltage drop [17], self-discharge, number of cycles, etc. Jonghoon Kim and Cho [5] proposed a method based on an EKF

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combined with a per-unit system to identify suitable battery model parameters, which can be utilized to estimate SOC and SOH for a lithium-ion battery. The main work of Ref. [5] was to estimate SOC based on EKF and an accurate battery model. In addition, the diffusion resistance in the model proposed in the paper was changeable with battery age. It needed some particular charge/discharge steps to estimate the battery diffusion resistance, which increases the complexity of estimating the SOH. Besides, it did not consider temperature influence. In Ref. [7], the battery SOH can be determined by fully charged and discharged capacity. It was time consuming, temperature-dependent, and usually hard to realize after equipped in a vehicle. C. R. Gould et al. [15] described a new battery model and determined the SOH through subspace parameter estimation and state-observer techniques. It mainly focused on a novel battery model and a predictor/corrector observer. Based on the observer to adaptively estimate and converge on battery functionality indicators, the SOH can be estimated accordingly. They focused on a lead acid battery, whose characteristic is different from lithium-ion battery, and developed a linear equation between battery SOH and capacitance. It only considered 20% capacity drop which was too narrow to estimate the battery SOH precisely.

Some researchers have proposed other methods to estimate the SOH through analyzing the battery internal parameters. Reference [12] presented a complementary cooperation algorithm based on dual EKF combined with pattern recognition as an application of Hamming neural network to identify suitable battery model parameters for improved SOC/capacity estimation and SOH prediction. It needed about 6000 s to acquire the data to identify the battery parameters. Therefore it needed larger storage for data, and to wait longer time to estimate the SOH. A method to identify the internal resistance in a hybrid vehicles was presented and a special purpose model derived from an equivalent circuit was developed in Ref. [11]. This model contained parameters depending on the degradation of the battery cell. This method needed specific signal intervals occurring during normal operation of the battery in a hybrid vehicle which limits its application.

Battery SOH is defined as:

$$h = \frac{C_{bat}}{C_{nominal}} \times 100\% \tag{1}$$

where h is SOH, C_{bat} is the present capacity and $C_{nominal}$ is the nominal capacity of the battery.

While using the above equation for SOH calculations, some difficulties arise:

- The battery needs to be fully charged and discharged to determine its present capacity, which is not realistic especially when the battery is already installed in an EDV;
- The battery capacity will change with temperature and with different charge/discharge current profiles.

In this paper, an online SOH identification method is proposed through estimating the battery diffusion capacitance of a two-order resistance–capacitance model instead of direct measurement of battery capacity. From experiments of the battery, we have found direct linkage between the battery's diffusion capacitance and the total available capacity. However, in order to estimate SOH using the diffusion capacitance, we must estimate the voltage drop on the capacitance. If the battery is under rest for a very long period of time, such as 3 h, we can assume the initial voltage drop on the capacitance is zero. When the vehicle is running, it is difficult to obtain voltage drop on the capacitance. To overcome this problem, we introduce the genetic algorithm (GA) to estimate the voltage drop on the capacitance and the battery open circuit voltage in the battery model through the use of measured battery current and terminal voltage. The diffusion capacitance, hence, the SOH is then determined.

GA is an effective tool to estimate the model parameters of a nonlinear system. Genetic algorithm is inspired by natural selection and biological evolution, and is an efficient method for solving both constrained and unconstrained optimization problems through repeatedly modifying a population of individual solutions. GA can be found with wide applications in bioinformatics, computational science, engineering, mathematics, physics, and other related fields [18–22]. Typically, GA requires:

- A genetic representation of the solution, which is so-called the population;
- A fitness function which is utilized to evaluate the solution.

A typical representation of the population is bit strings. Other representations may also be introduced, like double vector. All the populations can be used in the same way, which makes genetic algorithms more convenient to realize crossover, mutation and elite selection. A fitness function is defined to show the performance for each population. Once the genetic representation and the fitness function are defined, GA proceeds to initialize a population of solutions (usually randomly) and then to improve it through repetitive application of the mutation, crossover, inversion and selection operators.

At each step, the GA selects individuals at random from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population evolves towards an optimal solution. GA has been successfully applied in the multi objective optimization of HEV fuel economy and emissions using the self-adaptive differential evolution algorithm [22]. In this paper, GA is proposed to estimate the battery parameters based on prediction-error minimization method.

The rest of the paper is arranged as follows. Section 2 introduces the battery model that is used for SOH estimation. Section 3 explains GA and the parameter identification method. Section 4 analyzes the uniqueness of the model and convergence of the proposed GA algorithm. The experiment verification is presented in Section 5. We also add the temperature influence and build an observer of SOH with ambient temperature from 0 °C to 40 °C. Some conclusion and next step work are finally given in Section 6.

2. Proposed method

An equivalent circuit model with one open circuit voltage source, two parallel resistor–capacitor networks and a series resistor, as shown in Fig. 1, is introduced to simulate the battery dynamic and static performance [2,3,5,12,23–25]. The open circuit voltage source, which is parameterized as a nonlinear function of battery SOC and the open circuit voltage, is to describe the open circuit

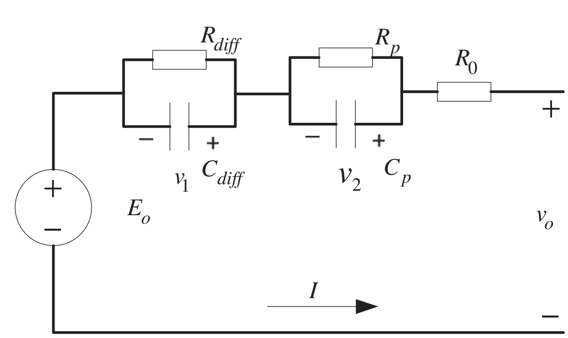

Fig. 1. Equivalent circuit model of battery cell.