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On-line estimation of state-of-charge of Li-ion batteries in electric vehicle using the resampling particle filter

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ABSTRACT

Accurate battery state-of-charge (SOC) estimation is important for ensuring reliable operation of electric vehicle (EV). Since a nonlinear feature exists in the battery system and particle filter (PF) performs well in solving nonlinear or non-Gaussian problems, this paper proposes a new PF-based method for estimating SOC. Firstly, the relationships between the battery characteristics and SOC are analyzed, then the suitable battery model is developed and the unknown parameters in the battery model are on-line identified using the recursive least square with forgetting factors. The proposed battery model is considered as the state space model of PF and then SOC is estimated. All experimental data are collected from the running EVs in Beijing. The experimental errors of SOC estimation based on PF are less than 0.05 V, which confirms the good estimation performance. Moreover, the contrastive results of three nonlinear filters show PF has the same computational complexity as extend Kalman filter (EKF) and unscented Kalman filter (UKF) for low dimensional state vector, but PF have significantly better estimation accuracy in SOC estimation.

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Introduction

Electric vehicle (EV) powered by onboard batteries has advantages over traditional vehicle in energy saving and environment protection. However, these batteries are very sensitive to over-charge and deep-discharge. How to make the best use of batteries become increasingly important for EV. As one of the most important parameters for vehicular battery management system (BMS), the state-of-charge (SOC) directly affects battery life and battery system. Therefore, the estimation of battery SOC is a key point for BMS. Moreover, the uncertainty and complexity of the battery system add to the difficulty of SOC estimation.

The SOC is defined as the ratio of the remaining capacity to the nominal capacity at a given rate. The above definition is given in terms of the single cell. However, EV is powered by many battery packages in which some single cells are equally installed. In application, the battery packages are set in a big cell.

At present, there are two categories of methods for estimating SOC: physical methods and mathematic methods. In physical methods, SOC is estimated using physical properties of battery.

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- One of the physical methods is discharge test which is one of the most reliable methods for SOC estimation. However the method can only be applied in the laboratory since a test consumes too much time and the system can be forced to be interrupted during the test (Piller et al., 2001). Therefore, the method cannot estimate SOC dynamically.
- Measuring the physical properties of the electrolytes is another physical method to estimate SOC accurately. At the same time, the method is feasible only for lead-acid batteries where electrolytes can be measured (Piller et al., 2001).
- Open-circuit voltage (OCV) is widely used to determine SOC in many papers (He et al., 2012; Roscher and Sauer, 2011; Windarko and Choi, 2010). In order to achieve stable state of OCV, the batteries must be rest for a long time which may be more than 10 h. Therefore, the method is not practical for the running vehicles. In general, OCV is used combining with other methods discussed in Lee et al. (2008), Cheng et al. (2011), Snihir (2006).
- Impedance spectroscopy is a common method for electrochemical process in all battery applications. Impedance spectroscopy method for SOC estimation is described explicitly in Rodrigues et al. (2000), Huet (1998). However, this approach is strongly affected by temperature and requires some additional measurements which can only be statically obtained in laboratory test (Yoon et al., 2011). In (Coleman et al., 2007), the proposed model of SOC determination combines changing parameters such as terminal voltage, current load, and impedance spectroscopy.
- Internal resistance method is similar to the impedance spectroscopy method. However, the internal resistance method cannot precisely measure the cell resistance due to the influence of the time interval. The method applies to SOC estimation in post-discharge (Piller et al., 2001).

  The above methods are more suitable to do experiments in the laboratory and cannot meet requirement of SOC estimation for the running EV. With the development of EV, BMS has higher requirements for SOC accuracy. Therefore, various mathematic methods start to be used in SOC estimation.
- Ampere hour counting (Ah counting) is the most common technology for SOC estimation. So many papers (Lin et al., 2006; Coleman et al., 2007; Li et al., 2010; Ng et al., 2009) focus on using the Ah counting method or the improved Ah counting method to determine SOC. However, there are two issues for these applications: First, incorrect current accumulating for a long time can cause large error of SOC estimation. Second, when the batteries experience high temperature or strong current shock, the estimation error will increase. From these two points, we can see that Ah counting method is not suitable for high precision estimation.
- Linear model gives a mathematic relationship among SOC at various times, the current and the voltage. The model is applicable in the low-current condition and SOC changes slowly. In addition, it has high robustness in measurement errors and the initial conditions. The method is only developed in lead-acid battery.
- The Battery system is very complicated and certain relationships among the various parameters are unknown. Some researchers (Shen et al., 2005; Shen, 2010; Bi et al., 2012) start to focus on some intelligent methods such as artificial neural network (ANN). ANN considers the battery system as a black box and establishes an unknown relationship to estimate SOC by online training network. Another advantage of ANN is suitable for all battery applications.
- Kalman filter (KF) is a powerful intelligent method to accurately estimate the state of any linear-Gaussian system. Some papers (Bhangu et al., 2005; Plett et al., 2002a,b; Plett, 2004; Han et al., 2009; Vasebi and Bathaee, 2008; Charkhgard and Farrokhi, 2010) have introduced KF or extend Kalman filter (EKF) to estimate SOC. Though having been widely used in many non-linear systems, EKF has many constraint conditions such as requiring probability density function which follows Gaussian distribution.

As a nonlinear filter, particle filter (PF) is a novel and interesting class of algorithms to approximate the solution of nonlinear filtering problems. More importantly, PF should have significantly better estimation accuracy than EKF and unscented Kalman filter (UKF). In fact, the battery system is a strongly nonlinear and non-Gaussian system. At this point, PF is the right technology to estimate SOC. At present, even though application of SOC estimation in the field of PF has little discussed, Different from the previous paper (Schwunk et al., 2013), on the one hand, we estimate SOC according to give a suitable state space model of PF for battery system and identify the unknown parameters of the model. On the other hand, the Li-ion batteries in EVs are the research object and all experimental data of batteries are derived from the practical processes of EVs in operation instead of laboratory test.

This paper is organized as follows. Section 2 simply introduces the background of data collection. Section 3 proposes the battery model. Section 4 presents the parameters identification of this model. Section 5 shows the description of PF. Section 6 carries out experiments. Finally, Section 7 gives some conclusions and directions to the future work.

Background of data collection

To begin with we will provide a brief background on the data collection. Nowadays there are many applications of EVs such as electric taxis, electric buses, and electric sanitation trucks running in Beijing. Each EV has 120 Li-ion cells equally installed in 2 or 4 packages as power resource. The various on-line data collected by the BMS and the motor system can be transmitted to a data collection equipment in EV through the vehicular CAN bus. Moreover, the GPS system in the data collection equipment also collects GPS data such as position state, vehicle speed and mileage. All acquired data are packaged to be stored locally in the build-in flash memory of data collection equipment every 5 s. In addition, these data simultaneously packaged are wirelessly transmitted to the Service Center of Electric Vehicle by wireless GPRS communication

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