Optimizing Li-Ion Battery Models through Enhanced Communication in State and Sensor Bias Estimation Using Extended Kalman Filtering

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Abstract

This paper investigates the application of Extended Kalman Filter (EKF) and Dual Extended Kalman Filter (DEKF) techniques for State of Charge (SOC) estimation in lithium-ion batteries, a critical component in the battery management systems of electric vehicles. Accurate SOC estimation is vital for ensuring battery reliability, longevity, and safety. However, the precision of SOC estimation is often compromised by sensor noise and bias, leading to inaccurate readings and inefficient battery usage. To address these challenges, we propose a robust estimation framework using EKF and Dual EKF, known for their efficacy in handling non-linear systems and measurement uncertainties. The research evaluates the performance of these advanced filtering techniques under various operating conditions, including temperature variations and aging effects. By comparing the estimation accuracy with traditional KF methods, the study highlights the superior capability of EKF and Dual EKF in dealing with the complexities of lithium-ion battery models.

Ⅰ. Introduction

The environmental impact of technology, especially in the transportation sector, is seeing a surge in demand for eco-friendly solutions. Electric vehicles (EVs) that store energy in batteries and use them later, are becoming increasingly popular because of their potential to reduce emissions. Among many types, lithium-ion batteries are preferred because they are lightweight and have high electrochemical potential and energy density, allowing the EV to travel about 180-350 km. However, the efficiency and safety of these vehicles rely heavily on battery management systems (BMS), especially accurate state of charge (SOC) estimation. This paper attempts to address issues related to SOC estimation of lithium-ion batteries, especially sensor noise and bias, and changes in battery parameters.

SOC estimation is essential for effectively managing the battery system within the EV and is similar to the fuel gauge of an internal combustion engine vehicle [1]. However, unlike the fuel gauge, SOC depends on the electrode concentration of the lithium ion and cannot be measured directly due to differences between the cells. This paper uses model-based estimation techniques, especially Extended Kalman Filtering (EKF), to improve SOC estimation under various operating conditions.

The main objective of this study is to develop and test SOC estimation algorithms using a secondary RC equivalent circuit model for lithium-ion batteries. Algorithms will be evaluated in a variety of operating scenarios including sensor noise and bias fluctuations to evaluate their robustness and accuracy. This study aims to improve the reliability of SOC estimation of lithium-ion batteries used by electric vehicles, thereby enhancing safety and efficiency.

Ⅱ. Method

The Extended Kalman Filter (EKF) is employed as a nonlinear estimator for the State of Charge (SOC) and sensor biases in lithium-ion batteries [2]. The implementation begins with the development of a discrete-time state-space model derived from the continuous-time equivalent circuit model of the battery, as explained earlier. The EKF operates in two main steps: Prediction and Update. Mathematically, the implementation uses the following equations:

$$\hat{x}_{k|k-1} = f(\hat{x}_{k-1|k-1}, u_{k-1})$$
$$P_{k|k-1} = F_{k-1}P_{k-1|k-1}F_{k-1}^T + Q_{k-1} \tag{1}$$

$$K_k = P_{k|k-1}H_k^T(H_kP_{k|k-1}H_k^T + R_k)^{-1}$$
$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(y_k - h(\hat{x}_{k|k-1}, u_k)) \tag{2}$$
$$P_{k|k} = (I - K_kH_k)P_{k|k-1}$$

Dual EKF (DEKF) is employed to estimate both the state of the system and parameters (or biases) simultaneously [2]. It involves running two EKFs in parallel: one for the system state and the other for parameter estimation. The implementation involves augmenting the state vector to include the parameters (or biases) and then applying the EKF methodology to this augmented state. Both filters share information and update their estimates based on the measurements and model predictions. The DEKF methodology provides a more comprehensive estimation by simultaneously capturing the dynamics of both the system state and varying parameters or biases.

In the domain of parameter estimation with EKF, there are several approaches to achieve the same overall objective. Joint EKF, runs a single filter that directly implements the augmented state space shown above. DEKF, on the other hand, performs two simultaneous and coupled filters. One for state estimation and the other for parameter estimation.

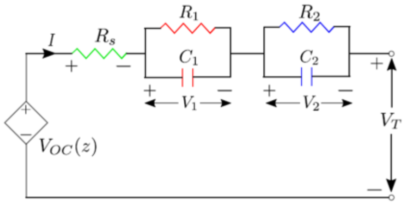

Fig. 1 Dual Polarity Battery Model (2nd Order System)

Ⅲ. Result and discussions

The performance of state and dual EKF for SOC estimation was compared. Terminal voltage deviations were added to the "truth" model, and the generated "truth" data were used for SOC estimation by EKF and DEKF algorithms. The presence of voltage deviations indicates that DEKF performs better in SOC estimation. As shown in Fig 2, dual EKF showed about 2% improvement in SOC estimation when comparing root mean values. As before, a current sensor deviation of 25 mA was added to the "truth" model and the generated data were used by both algorithms to estimate the state of charge. The figure below shows that EKF and DEKF perform well under constant current deviations. Fig 2 shows performance indicators that represent almost identical performances.

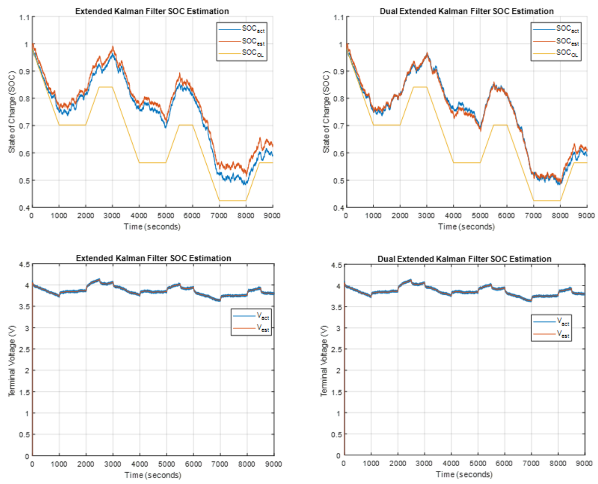

Fig. 2 EKF vs DEKF: SOC and Voltage Estimates

As the System Model and Analysis section briefly covered, every “real” system exhibits some sort of noise or bias that presents the likelihood of the distorting and degrading acceptable estimation performance. To mitigate this behavior, the following plots demonstrate the benefits of implementing a tuned DEKF as means of estimating the SOC and the sensor bias (voltage bias in this case). It should be noted that the “actual” data used as ground truth in this simulation was performed with a constant 20mV. This prescribed value allows for the following comparison in figure 4 to be made revealing a general trend of the system to approximately oscillate about the actual voltage bias.

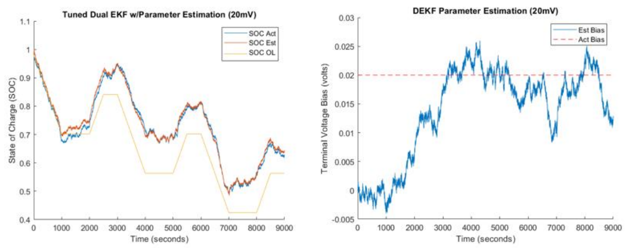

Fig. 3 (left) DEKF SOC Estimation (right) Voltage Bias Estimation [20mV]

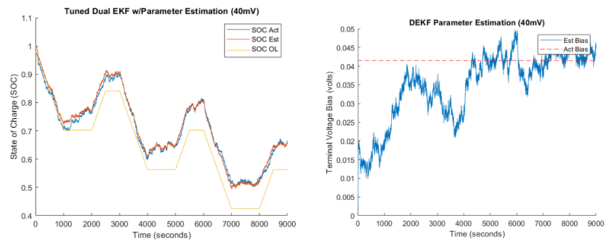

Fig.4 (left) DEKF SOC Estimation (right) Voltage Bias Estimation [40mV]

Ⅳ. Conclusion

The study demonstrates the effectiveness of EKF and DEKF Filter techniques in enhancing the State of Charge estimation of lithium-ion batteries. Through rigorous simulation and analysis, it is evident that both EKF and DEKF provide a significant improvement over traditional methods, especially in the presence of sensor noise and bias. The results underline the importance of accurate SOC estimation in optimizing battery usage, extending battery life, and ensuring the safety and reliability of electric vehicles.
Moreover, the research contributes to the understanding of battery behavior under various conditions and paves the way for more resilient and adaptive battery management systems.

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