Overview of State of Charge (SOC) Estimation Methods of EV Batteries

FAST CHARGING SYSTEM OF ELECTRIC VEHICLE BATTERIES

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Abstract: *The State of Charge (SOC) is a pivotal parameter in the management of electric vehicle (EV) batteries, influencing their efficiency, lifespan, and overall performance. Accurate SOC estimation is crucial for maximizing battery utilization and ensuring reliable operation of EVs. This review consolidates current research advancements in SOC assessment methods, emphasizing improvements and practical applications.*

Key words: *Electric vehicle, battery, Machine-learning, Coulomb counting, Kalman filtering,*

INTRODUCTION

Amid the current global climate change crisis, the automobile industry, alongside energy sources directly linked to environmental pollution, contributes significantly to environmental damage. Consequently, a major shift towards green energy sources is underway in this field. One notable example is the electric car industry, which is beginning to surpass other sectors. Compared to traditional vehicles, electric vehicles (EVs) are increasingly popular due to their minimal environmental impact and higher efficiency when using renewable energy sources. Since their introduction to the public in the early 20th century, EVs have been well received by consumers. However, the initial lack of charging infrastructure and their somewhat shorter range compared to other fuel types delayed their widespread adoption.

Nearly a century later, ecological considerations, initially not prioritized, have become a primary focus. Environmental cleanliness is now recognized as crucial, significantly impacting human health and lifestyle. EVs are meeting global market demands due to their advanced development compared to traditional vehicles. The dominant aspect of this advancement is their batteries, which are central to the development of EVs. Improving battery characteristics is considered vital for enhancing the overall performance of EVs.

Currently, extensive research is being conducted to improve State of Charge of EV batteries through SOC estimation methods. The following sections will explore this research in detail, leading to conclusions based on the literature review.

State of Charge of Electric vehicle batteries

State of Charge (SoC) refers to the amount of energy stored within a EV battery at any given time. It is expressed in percentage (Figure 1). For electric vehicles, this metric is akin to the fuel gauge in a conventional internal combustion engine vehicle, indicating how much energy is available for propulsion. The State of Charge plays a pivotal role in the performance, efficiency, and longevity of traction batteries in electric vehicles. This information is vital for drivers to plan their trips effectively, especially considering that electric vehicles have a limited range compared to conventional internal combustion engine vehicles.

$$\mathrm{SoC}/\% = 100\frac{(Q_0 + Q)}{Q_{\max}} = \mathrm{SoC}_0/\% + 100\frac{Q}{Q_{\max}}$$

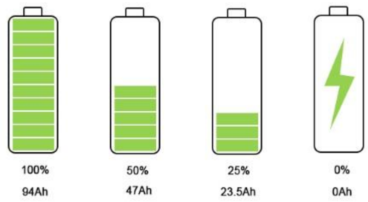

Figure 1. State of Charge of EV Batteries.

Overview of SOC Estimation Methods

Estimation methods for the State-of-Charge (SOC) of Electric Vehicle (EV) batteries are critical for accurately determining the amount of charge remaining in the battery pack. This information is essential for the driver to plan their journey effectively and for the Battery Management System (BMS) to optimize battery performance and longevity. Here are some common estimation methods used for SOC estimation in EV batteries:

- Voltage-Based Methods

Voltage-based methods derive SOC from the battery's terminal voltage. Despite their simplicity, these methods are susceptible to inaccuracies due to temperature fluctuations, varying loads, and battery aging. The nonlinear relationship between voltage and SOC complicates accurate estimation, particularly across different battery chemistries and operating conditions.

Advantages: Simple and inexpensive.

Disadvantages: Accuracy can be affected by temperature, load, and battery aging[1].

- Coulomb Counting Method

CCM is one of the simplest methods of SOC estimation. It is used to find a direct relationship between the SOC and the battery charging/discharging current. By integrating the current over time, it's possible to estimate the energy that has been added or removed, giving an approximation of the SoC.

$$\mathbf{SoC(t) = SoC(t-1) + \frac{I(t)}{Q_n}\Delta t}$$

SoC(t) = estimated State of Charge at time, t

SoC(t-1) = previous State of Charge at time t-1

I(t) = charging or discharging current at time, t

Qn = battery cell capacity

Δt = time step between t-1 and t

Initially precise, this method accumulates errors over usage, necessitating periodic recalibration to maintain accuracy. Despite its tendency for drift, Coulomb counting remains a standard approach in EV battery management.

Advantages: High accuracy if starting SOC is accurate and the current measurement is precise.

Disadvantages: Errors accumulate over time, requiring periodic recalibration[2].

- Kalman Filtering Method

Kalman filtering begins with a dynamic model that describes how the SOC changes over time based on inputs such as current (charge/discharge rate) and voltage. This model typically includes parameters that characterize the battery's behavior under different operating conditions. The filter makes a prediction of the SOC based on the current state estimate and the dynamic model. It predicts what the SOC should be at the next time step considering the current conditions and the battery's characteristics. As new measurements become available (such as voltage and current readings from sensors), the Kalman filter updates its prediction of SOC. It combines the predicted SOC from the model with the actual measurements, adjusting the SOC estimate based on how closely the measurements match the predictions. The Kalman filter iterates between prediction and measurement update steps continuously as new data comes in. Each iteration refines the SOC estimate, balancing the accuracy of the model predictions with the precision of the measurements. One of the key strengths of Kalman filtering is its ability to handle uncertainties and noise in the measurements. It uses statistical methods to weigh the reliability of the model predictions against the precision of the actual sensor data, ensuring that the SOC estimate remains accurate and stable over time.

In the prediction step, the Kalman filter predicts the current SOC based on the previous SOC estimate and the dynamic model of the battery. The prediction equation is:

$$\hat{x}_{k|k-1} = F_k \hat{x}_{k-1|k-1} + B_k u_k$$

In the update step, the Kalman filter combines the prediction with the actual measurement (typically voltage and current readings) to refine the SOC estimate. The update equation is:

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k (z_k - H_k \hat{x}_{k|k-1})$$

The Kalman gain Kk is computed as:

$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1}$$

Advantages: High accuracy, adaptive to changes in battery behavior.

Disadvantages: Complex implementation and requires a good battery model[3].

- Machine Learning and Data-Driven Methods

Machine learning algorithms predict SOC by analyzing large datasets, learning complex patterns and relationships that influence battery performance. While powerful in capturing nuanced dependencies, these methods require substantial computational resources and extensive training datasets to achieve optimal accuracy. The methodology for SOC estimation utilizing machine learning encompasses three primary phases: data collection and preparation, model selection and training, and model evaluation and tuning (Figure 2).

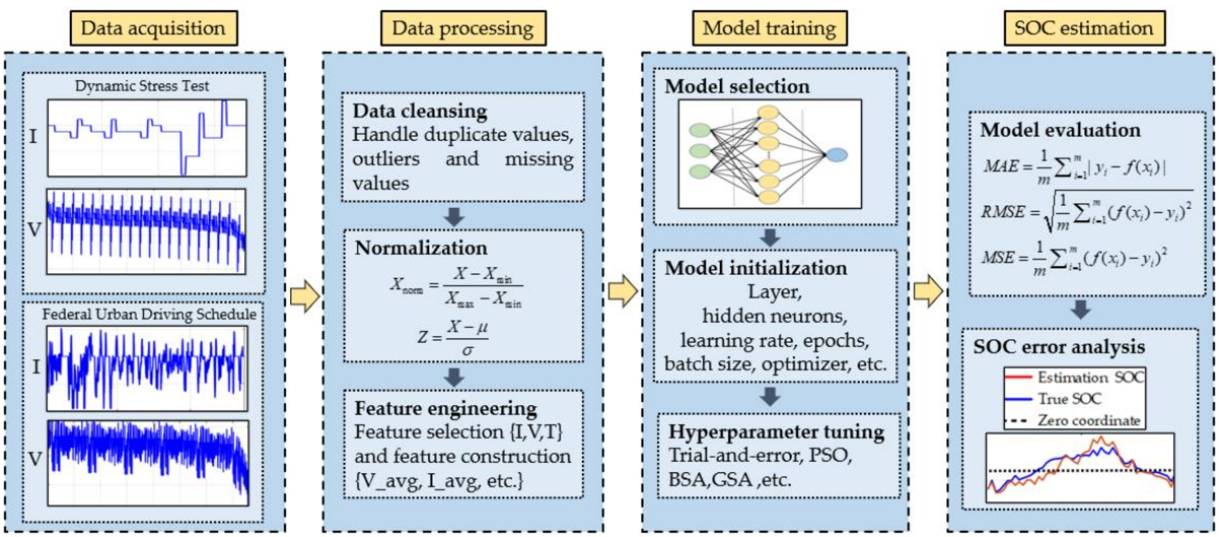

Figure 2. Machine learning SOC estimation method.

Advantages: Can capture complex relationships and adapt to different battery conditions.

Disadvantages: Requires extensive data and computational resources[4].

Comparative Analysis of SOC Estimation Methods

"A Review of the State of Health and State of Charge Estimation Techniques for Lithium-Ion Batteries in Electric Vehicles" offers a comprehensive comparison of SOC estimation methods. Voltage-based methods are straightforward yet less precise, while Coulomb counting, despite its accuracy initially, suffers from cumulative errors. Kalman filtering strikes a balance between accuracy and resilience to disturbances, whereas machine learning excels in handling diverse data but requires careful calibration and computational resources[5].

- Hybrid Methods

Integrating multiple SOC estimation techniques mitigates individual method limitations. For example, combining Coulomb counting with Kalman filtering enhances accuracy by periodically correcting drift errors.

Advantages: Balances accuracy and practicality.

Disadvantages: Increased complexity and need for calibration[6].

Practical Applications and Tools

- Battery Management Systems (BMS)

BMS integrate SOC estimation methods into EVs, utilizing sensors and algorithms to monitor and optimize battery performance. This integration enhances operational safety and efficiency [7].

- Simulation Tools

MATLAB/Simulink facilitates the modeling and simulation of SOC estimation algorithms, aiding in the evaluation and validation of different methods under various scenarios [8].

Current Research and Future Directions

- Machine Learning Approaches

Ongoing research explores machine learning's potential in refining SOC estimation accuracy, leveraging extensive datasets to enhance predictive capabilities under diverse operational conditions.

- Impact of Battery Aging

Understanding the effects of battery aging on SOC estimation guides the development of adaptive algorithms that maintain accuracy throughout the battery's lifecycle. Integrating aging models into SOC algorithms is crucial for sustained performance[9].

- Comparative Analysis of Battery Chemistries

Different battery chemistries influence SOC estimation methods differently. Comparative studies tailor SOC algorithms to specific battery types, optimizing reliability and performance across diverse applications [10].

CONCLUSION

Accurate SOC estimation is essential for optimizing EV battery performance and longevity. While traditional methods have inherent limitations, advanced techniques such as Kalman filtering and machine learning offer significant improvements. Hybrid approaches and adaptive algorithms show promise in addressing current challenges and enhancing SOC estimation accuracy. Future research should focus on integrating these advancements into practical applications, ensuring the efficient and reliable operation of electric vehicles.

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