# LITHIUM-ION BATTERY STATE OF CHARGE (SOC) PREDICTION FOR ELECTRIC VEHICLES

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## ABSTRACT

State of Charge (SoC) prediction for lithium-ion batteries indicates the amount of electrical energy available for usage by the drivers of the electric vehicle (EV).

Understanding and accurately measuring SoC levels allows effective battery management. Charging infrastructure operates at its optimal point with known battery SoC levels, therefore increasing the optimal performance in various applications such as electric vehicles. A model was developed using simple battery equivalent circuits for prediction of the SoC using data analysis predictive tools. The limitations on SoC prediction using this methodology using the ratio of the remaining capacity of the battery after use to its rated nominal capacity was revised to reflect the actual SoC remaining based on aging factors. Advantages in accurate SoC estimation were drawn from its help in managing the device usage plans, enabling battery management systems for optimal usage, contributing to the overall health of the battery, and improving the safety of users. Past literature recorded many factors (temperature, current load, age, and self-discharge), but limited information is available on improved life from varying battery chemistry.

Keywords: lithium-ion battery, state of charge (SoC)

## 1. INTRODUCTION

The State of Charge (SoC) of the battery is defined as the ratio of the remaining battery capacity available for discharge after usage to the rated nominal capacity [1].

This parameter is typically expressed as a percentage between 0-100% depending on its level of charge. SoC in electric vehicles (EVs) is analogous to a fuel tank gauge in traditional internal combustion engine vehicles. The greater the SoC level is, the more drivers may sit back and relax until it's discharged to a level that requires them to recharge. Ideally, there are recommended levels of 20% SoC when drivers must return for charging. Many major benefits of SoC estimation are enumerated below:

- It improves the management of the device usage and recharging plans.
- It improves the reliability of the battery management system to engage drivers in planning the next recharge.
- It contributes to improved health of the battery.
- It contributes to improved longevity of the battery.
- It increases the safety of the operation and application in major applications such as electric traction and electric vehicles.
- For energy storage systems the SoC levels allow preparedness for discharge into the power system.

There are several factors that must be studied that influence the lithium-ion battery SoC level, which include temperature, current load, age, and self-discharge. Self-discharge reduces the battery SoC level and its efficient delivery of energy for the electric vehicles. Energy efficiency from battery and renewables integration in [2], [3] and [4] motivates to develop SoC predication methods. Predictive self-discharge characteristics curves together with SoC prediction improves the lost 1-2% SoC level due to discharge. Measurement of the battery SoC is performed using various methods:

- Coulomb Counting- It is a simplistic way of counting the outflow of the current from the battery. This is a significantly accurate method, but the equipment requires recalibration at frequent intervals to mitigate any compromised measurements.
- Voltage Method- Battery voltage measurement estimates the battery SoC. Different levels of voltages correspond to SoC values for a given battery. But accuracy of this inexpensive method is questionable when there is interference of factors such as temperature and the connected loading of the battery.
- Impedance Spectroscopy: The internal resistance of the battery is estimated by sending a small AC current. This increases the accuracy of the measurement by measuring the voltage response from the AC current engagement.
- Open Circuit Voltage Method: Open Circuit Voltage and the SoC have characteristic curves with polynomial functions available in both extrapolating and interpolating the curves to predict the SoC.

The above methods are traditionally known but some advanced methods to address the challenges mentioned above required researchers to develop better SoC estimation techniques as mentioned below:

- Kalam Filter [5]: Battery is modeled using set algorithms to estimate SoC.
- Extended Kalam Filter [6]: It is applicable for non-linear systems for estimation of the SoC.
- Artificial Neural Networks: The use of machine learning and AI allows better predictive SoC models.
- Fuzzy Logic: It allows us to solve the non-Boolean problems by answering the uncertainties in battery characteristics at given conditions.

In this research paper, the emphasis is on the Extended Kalman Filter (EKF). The major benefits of the SoC prediction are for electric vehicles [7]. The SoC varies based on the type of battery chosen and so do their characteristic curves at a given temperature in [8]. Sankhwar (2024) in [9] and [10] enlisted the types of electric motors and their varying performances based on speed controls. Varying SoC levels opens the research to revise the SoC characteristics curves as presented in [8]. Figure 1 shows SoC curves documented in previous literature for a typical lithium-ion battery.
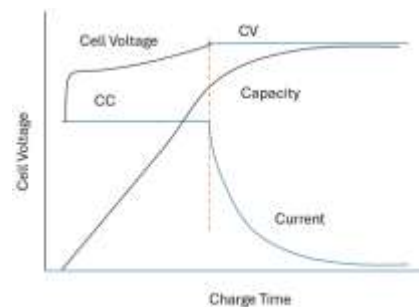


**Figure 1.** SoC Curve During Charging [8]

Several doors are open in the SoC estimation field from the past literature review. AI integration is leading in this field of innovation alongside advanced sensor-based prediction and standardization of the battery measurement tools and techniques in the whole industry. Figure 2-3 shows the battery voltage and charge level readings per [11]. Based on these reading a model for predicting the SoC levels can be developed. The benefits of the SoC estimation are attributed to the crucial role in battery management for all kinds of consumer electronics items such as phones, tablets, etc. In the power industry, electric vehicles draw advantages from the EKF method for SoC estimation. The layout of this research paper begins with an introduction, methodology, and analysis, and results, then the conclusion is appended with a discussion.
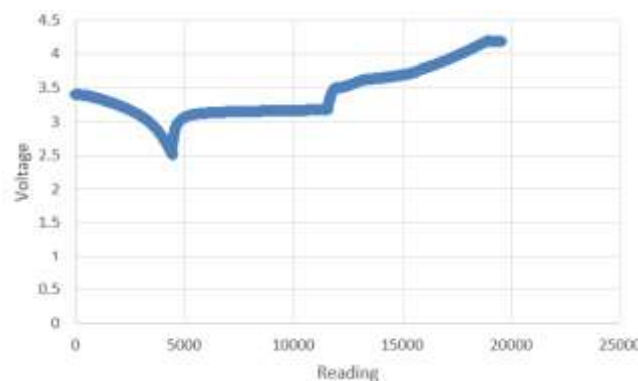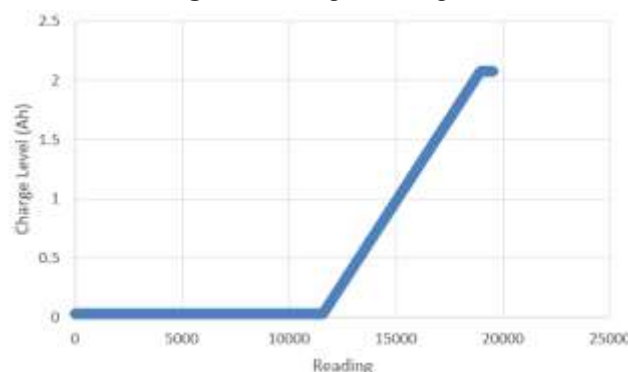


**Figure 2.** Voltage Readings



**Figure 3.** Charge Level Readings

## 2. METHODOLOGY

Extended Kalman Filter (EKF) is based on handling the non-linear dynamics of lithium-ion batteries. EKF linearizes the nonlinear dynamics by solving complex problems in obtaining a polynomial function for accurate battery SoC prediction. Rapid convergence and reduced errors improve the adaptability of EKF for Li-ion batteries. The algorithm used is shown in Figure 4.
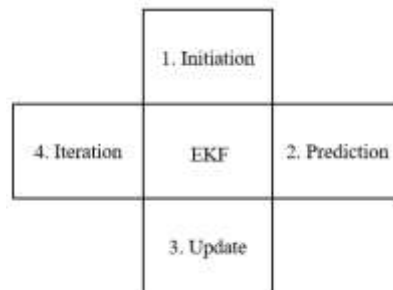


**Figure 4.** EKF Algorithm

**Analysis**

The EKF linearization at each time step approximates the non-linear battery dynamics using discretized Jacobians for SoC estimation. The Jacobians are given by the following equation (1)-(2).

$$F_k = 1 - \frac{TCI}{Q} \qquad (1)$$

$$H_k = \frac{dV}{dZ} \quad (2)$$

where, T is the sample time (s), C is the Coulombic efficiency, I is the current (A), V is the open-circuit voltage and Z is the independent variable. The real-time SoC can be estimated using this linearization using EKF. However, the challenges remain with this method are its initial sensitivity and computational complexity in deriving a polynomial equation with linearized characteristics. A typical battery circuit is shown in Figure 5.
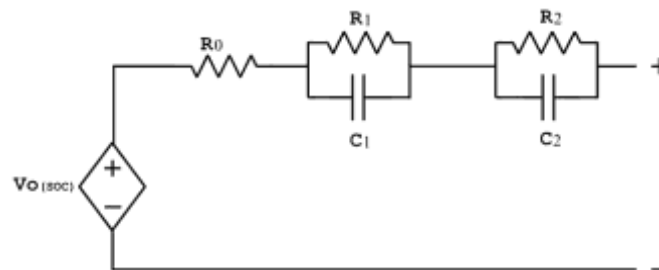


**Figure 5.** Battery Equivalent Circuit [12]

The equivalent circuit is given by equation (3) as below:

$$V(t) = V z(t) - i(t)R - Vc (t) \qquad (3)$$

## 3. RESULTS

Using a segment of the data from Figure 2-3 the relationship between the charger capacity and the voltage was plotted as shown in Figure 6.
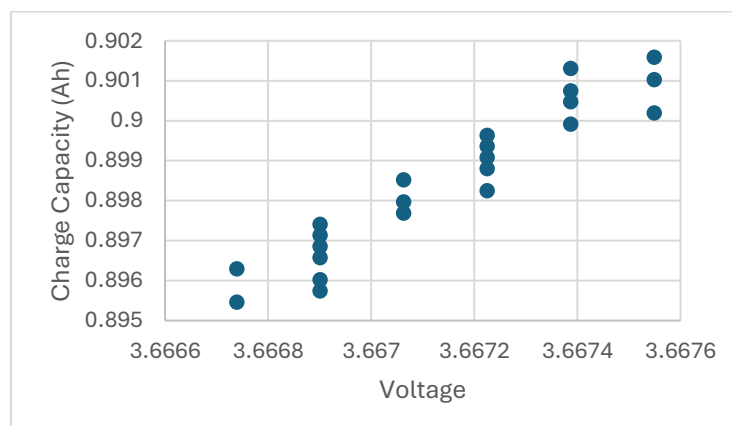


**Figure 6.** Charge Capacity vs Voltage

## 4. CONCLUSION

EKF method generally provides accurate predictions using the linearization techniques for the non-linear data. A regression analysis yields a linear relationship from the charge capacity vs voltage characteristics obtained. The advantages of the traditional methods in the measurement of the in and out of charge using the Coulomb counting method are beneficial when studying the EKF method. Advanced electrical machines operating with battery storage systems or battery packs require SoC monitoring to ensure the healthiness and longevity of the battery. Available literature was reviewed to get the characteristics curves for SoC for lithium-ion batteries. Varying chemistries may provide improved performance with SoC levels and low leakages but an accurate prediction of SoC remains a subject of research.

## 5. DISCUSSION

The Extended Kalman Filter (EKF) is a popular method used for predicting the State of Charge (SoC) of a battery, especially in applications like electric vehicles (EVs) and renewable energy systems. The traditional Kalman Filter (KF) works well for linear systems, but since battery behavior is inherently nonlinear due to complex electrochemical processes, the EKF is employed to handle these nonlinearities. The EKF operates by combining real-time battery measurements, such as voltage and current, with a dynamic battery model to estimate the SoC. It uses a two-step process: prediction and update. In the prediction step, the EKF uses the system's previous state and control inputs (like current and voltage) to forecast the new SoC. The update step corrects this prediction using new measurements and sensor data. By iterating through these steps, the EKF continually refines its estimate of the battery's state. One key advantage of the EKF is its ability to provide more accurate and reliable SoC estimates compared to simpler methods like open-circuit voltage or Coulomb counting, especially when the battery is under varying load conditions. The EKF can also account for measurement noise and uncertainties, which are common in practical battery systems. However, it requires careful tuning of the system model and noise parameters for optimal performance.

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