INTERNATIONAL JOURNAL FOR INNOVATIVE RESEARCH IN MULTIDISCIPLINARY FIELD
ISSN(O): 2455-0620 [Impact Factor: 9.47]
Monthly, Peer-Reviewed, Refereed, Indexed Journal with IC Value : 86.87
Volume - 11, Issue - 07, July - 2025

DOIs:10.2015/IJIRMF/202507016 --:-- Research Paper / Article / Review

AI-Based Kalman Filter (KF) and Extended Kalman Filter (EKF) for SOC Estimation in Electric Vehicles: A Comprehensive Review

Suwarna Shete[1], Kamal Arora[2], and R.K.Kumawat[3]
[1]Career Point University, Kota, India
[2]Career Point University, Kota, India
[3]Sardar Vallabhbhai Patel University of Agriculture and Technology, Meerut, India

Abstract : *Developing a battery management system for an electric vehicle (EV) remains a challenging task. Due to their low weight and high charge density, lithium-ion (Li-ion) batteries have emerged as the preferred battery for electric vehicle manufacturers. An intelligent battery management system (BMS) is crucial for EVs. Accurately estimating the state of charge (SOC) of a Li-ion battery is difficult due to its extremely unstable nature. The SOC estimation techniques for a Li-ion battery are thoroughly reviewed in this paper. The strengths, weaknesses, critical explanations, and estimation errors of this paper are presented.*

Keywords : *BMS, Li-ion , EV, SOC.*

1. INTRODUCTION

The evaluation of the state of charge (SOC) is a critical component of electric vehicle (EV) battery management systems (BMS). It directly affects the general performance, driving range, and battery health of EVs. Conventional techniques for determining SOC, like Coulomb counting and open-circuit voltage (OCV) approaches, are not very accurate or dependable, particularly in rapidly changing environments. Consequently, sophisticated algorithms and machine learning methods are being used more and more to enhance SOC estimation. By analyzing data from multiple sensors and past performance, these techniques can produce more accurate and flexible readings, which will ultimately increase the longevity and efficiency of the battery systems in electric cars. To solve these problems, sophisticated estimating techniques based on the Kalman Filter (KF) and Extended Kalman Filter (EKF) have gained popularity. These methods combine the benefits of model-based approaches and real-time data processing to generate reliable and accurate SOC estimates. Focusing on their comparative performance, innovations, and useful

An essential part of lithium-ion battery management systems (BMS), especially in electric vehicles (EVs) and renewable energy systems, is the estimation of the state of charge (SOC). Longevity, safety, and optimal battery performance are guaranteed by precise SOC estimation. Conventional techniques for estimating SOC, like open-circuit voltage (OCV) measurement and Coulomb counting, frequently have accuracy issues in dynamic operating environments. Researchers have increasingly used sophisticated filtering methods, such as the Kalman filter (KF) and Extended Kalman filter (EKF), in conjunction with machine learning (ML) techniques to address these issues. With an emphasis on lithium-ion batteries, this review investigates the combination of AI-based methods and Kalman filters for SOC estimation.

2. ARTIFICIAL INTELLIGENCE SOC TECHNIQUES

Support vector machines (SVM) and artificial neural networks (ANN) are two cutting-edge AI techniques that outperform conventional approaches in terms of accuracy and efficiency when determining the State of Charge (SoC) of lithium-ion batteries used in electric vehicles. Training the ANN-based model on actual battery test results is a crucial component that improves its performance over conventional techniques. Temperature, voltage, and current must be supplied as input parameters for AI-based models to correctly estimate the State of Charge (SoC). The models are able to comprehend the complex relationships between the battery's charge state and operating conditions thanks to the parameters. Both ANN and SVM can adapt to variations in battery performance by incorporating real-time data, which enhances prediction accuracy and battery management systems as a whole [1].

Battery management systems must estimate the state of charge accurately in order to guard against damage and prolong battery life. Advanced techniques are necessary for accurate state of charge prediction in order to guarantee safe battery charging and discharging while increasing its lifespan. After examining several existing techniques for estimating SoC, such as Coulomb counting, open circuit voltage, and the Kalman filter, the study recommends using AI to precisely predict the state of charge for advanced battery management systems [2].

A lithium-ion battery's state of charge (SoC) was estimated over the course of a full cycle using an artificial neural network (ANN) model, with a mean absolute error (MAE) ranging from 0.5% to 1.4%. For an accurate SoC estimate of lithium-ion batteries used in electric vehicles (EVs), the ANN model has demonstrated exceptional promise. According to the study, the next step is to use data obtained from a physical hardware setup to assess the ANN model's performance in real time [3].

3. KALMAN FILTER (KF) TECHNIQUES

The Kalman Filter (KF) is a mathematical algorithm that uses noisy observations to estimate the state of a system. It performs particularly well in scenarios involving linear system dynamics and measurement protocols. However, in the context of battery SOC estimation, the system dynamics are inherently nonlinear due to factors like temperature fluctuations, hysteresis, and battery polarization. To address this nonlinearity, the Extended Kalman Filter (EKF) was developed. The EKF extends the traditional KF and is suitable for nonlinear systems by linearizing the system dynamics around the present state estimate.

EKF and ANN are two methods for figuring out the state-of-charge (SOC) of a battery. To collect data for comparing the two methods, a pulse-discharge test was performed on a Li-ion battery cell. The results of the two SOC estimating methods, ANN and EKF, are presented and contrasted in the article [4].

The process of identifying lithium-ion battery parameters using a second-order RC (2-RC) Equivalent Circuit Model (ECM) involves modeling the battery and measuring various operating conditions (temperature, load current, and terminal voltage) in order to obtain initial values for the filtering methods. Applying Kalman Filter (KF), Extended Kalman Filter (EKF), and Unscented Kalman Filter (UKF) techniques reduces SOC estimation error and bound error based on the determined ECM parameters. A data-driven Deep Feed-Forward Neural Network (DFNN) technique is used to increase the accuracy of SOC estimation using 20 iterations and data epochs. Determining the parameters of lithium-ion batteries using a second-order RC (2-RC) Equivalent Circuit Model (ECM) By modeling batteries and keeping an eye on a number of operating conditions, including temperature, load current, and terminal voltage, initial values for the filtering methods are obtained. Applying Kalman Filter (KF), Extended Kalman Filter (EKF), and Unscented Kalman Filter (UKF) techniques reduces SOC estimation error and bound error based on the determined ECM parameters. A data-driven Deep Feed-Forward Neural Network (DFNN) technique is being used to improve the accuracy of SOC estimation using 20 iterations and data epochs [5].

Recursive Least Square variable directional forgetting (RLS-VDF) technique for determining the parameters of the battery model The RLS-VDF technique is used in combination with various non-linear Kalman filters, such as extended Kalman, adaptive extended Kalman, unscented Kalman, and adaptive improved unscented Kalman filters, for state of charge (SoC) estimation. Assessing the accuracy and robustness of different Kalman filter techniques using experimental data from a commercial Li-ion battery [6]

4. EXTENDED KALMAN FILTER (EKF) TECHNIQUES

A type of Recurrent Neural Network (RNN) called Long Short-Term Memory (LSTM) is used to estimate a lithium-ion battery's State of Charge (SoC) under different load and temperature conditions. This aids in overcoming the Extended Kalman Filter (EKF) approach's drawbacks [7].

The EKF method, developed to predict battery hysteresis based on different charge and discharge OCV curves, outperformed other advanced techniques in estimating SOC. The NN-EKF model for SOC estimation yielded the best results with and without temperature data [8].

The study investigates the use of Formal Methods (FM) and Artificial Intelligence (AI) techniques to precisely estimate the State of Charge (SoC) for smart battery management systems and battery-supported Cyber-Physical Systems (CPS). The study found that the proposed approach can yield more accurate SoC measurements for smart battery management systems and battery-supported CPS [9].

The integrated methodology that combines the two significantly improves the estimation accuracy of battery state of charge (SOC) when compared to using either machine learning techniques or the Kalman filter framework alone. The Random Forest algorithm has the highest estimation accuracy and performs well in real-time among all the integrated algorithms. Because of their high speed and accuracy, pure machine learning techniques like Random Forest and XGBoost can be applied to applications with demanding real-time requirements [10].

The study develops a closed-loop combination technique that combines the variance-compensation extended Kalman filter (VCEKF) and the back-propagation (BP) neural network for accurate state of charge (SOC) estimation. This approach increases the precision and reliability of SOC monitoring in comparison to traditional single-loop and open-loop techniques.

The parameters of a second-order resistance–capacitance model are determined using the forgetting factor recursive least square (FFRLS) method. The variance compensation algorithm continuously adjusts the process noise covariance of the extended Kalman filter, while the BP neural network provides a compensation value to enhance the final SOC estimation [11].

The study suggests a hybrid method that combines the artificial neural network (ANN) and adaptive extended Kalman filter (AEKF) to estimate the state of charge (SOC) of lithium-ion batteries in electric vehicles (EVs).

The study also builds a real-time SOC estimator using the open circuit voltage approach and Coulomb counting method to remotely monitor charging status. Thing Speak, a cloud-based Internet of Things (IoT) platform, is further integrated with this estimator. [12]

The study estimates the state-of-charge (SOC) of lead-acid batteries using an adaptive extended Kalman filter (EKF). It is discussed how EKF can be used to improve the accuracy of SOC estimation in electric vehicles (EVs). The EKF's adaptive nature allows it to adjust to changing circumstances, which enhances performance when compared to traditional techniques. The concepts offered may find broader application in EV battery management systems, despite the study's focus on lead-acid batteries. [13]

The study introduces a novel system prototype, FELL, that uses an extended Kalman filter (EKF) in conjunction with deep learning techniques to estimate the state of health (SoH) and state of charge (SoC) of electric vehicle (EV) batteries. It emphasizes how important accurate SoH forecasts are for managing and ensuring battery safety. The experimental results show significant improvements in prediction accuracy and the system's ability to provide real-time predictions and comparative analysis across multiple models for effective EV battery diagnosis [14].

Our research on estimating the State of Charge (SOC) of batteries for intelligent battery management is presented in this paper. Our goal is to study online dynamic SOC estimation by combining a neural network and Kalman filtering. First, we created a technique that uses the Extended Kalman Filter (EKF) to model battery hysteresis effects. Second, we created the NN-EKF model, a SOC estimation model that integrates the EKF's estimation into a neural network. Real data collected from two distinct batteries—a NiMH battery with 1.2V and 3.4 Ah and a lithium-ion battery U1-12XP—was used to assess the suggested approaches. When compared to other cutting-edge techniques, our experiments demonstrate that our EKF method, which was created to model battery hysteresis based on separated charge and discharge Open Circuit Voltage (OCV) curves, performed best in estimating SOC. Second, the best SOC estimation with and without temperature data was provided by the NN-EKF model [15].

The study estimates the battery's state of charge (SOC) using the GNL circuit equivalent model, which incorporates the self-discharge component and discretizes its state space equation using a matrix quadratic form. This model must accurately represent the behaviour of aging batteries.

The SOC is estimated and updated in real-time using the adaptive unscented Kalman filter technique (AUKF). The AUKF is appropriate for realistic SOC estimation in older batteries because it has been demonstrated to efficiently lower estimation errors and offer quick reaction features [16].

The study presents a genetic algorithm-optimized back propagation neural network (GA-BP) to enhance the Adaptive Extended Kalman Filter (AEKF) in assessing the state of charge (SOC) of Li-ion batteries in electric vehicles (EVs). It uses Hybrid Pulse Power Characterization (HPPC) to determine parameters and generate a 2-order RC comparable model. The AEKF, which is optimized by GA-BP, shows improved accuracy, convergence, and robustness while significantly reducing SOC estimation errors when compared to traditional Extended Kalman Filter (EKF) techniques [17].

5.COMPARATIVE ANALYSIS AND PERFORMANCE EVALUATION

Paper	Methods Used	Challenges
State of charge estimation and error analysis of lithium-ion batteries for electric vehicles using Kalman filter and deep neural network [2]	Using Kalman filtering techniques, namely the Kalman Filter (KF), Extended Kalman Filter (EKF), and Unscented Kalman Filter (UKF), the paper suggests an Equivalent Circuit Model (ECM) for precise State of Charge (SOC) estimation. With the UKF showing the lowest estimation error of 0.5%, these techniques are used to reduce SOC estimation error and bound error.	The difficulty of precisely determining the State of Charge (SOC) of lithium-ion batteries, which is essential for guaranteeing the secure and effective operation of electric vehicles (EVs), is highlighted in the paper. Numerous operating factors that can impact the battery's performance and dependability, including temperature, load current, and terminal voltage, must be taken into consideration during the estimation process.

	To improve the accuracy of SOC estimation, a data-driven method called Deep Feed-Forward Neural Network (DFNN) is also used. With a Root Mean Squared Error (RMSE) of just 0.04%, this approach significantly improves SOC estimation accuracy by about 0.46% when compared to model-based filtering techniques.	The existence of measurement noise and parametric uncertainties, which can result in errors in SOC estimation, is another issue that was covered. In order to reduce estimation errors and raise the precision of SOC predictions, the study uses sophisticated filtering techniques such as Kalman Filter (KF), Extended Kalman Filter (EKF), and Unscented Kalman Filter (UKF).
Comparative Analysis of Non-Linear Kalman Filters for Li-ion Battery SoC Estimation with RLS-VDF Technique for Parameters Identification,[6]	NLKFs (nonlinear Kalman filters) for estimating SoC.The RLS-VDF method for identifying parameters	Battery model accuracy is a prerequisite for accurate SoC estimation. The complexity of battery behavior makes parameter identification challenging. .
Analysis on SoC estimation of Lithium ion battery using EKF and LSTM [7]	Long Short-Term Memory (LSTM), a kind of Recurrent Neural Network (RNN), is used to estimate the State of Charge (SoC) of a lithium-ion battery under various temperature and load conditions. This helps to overcome the limitations of the Extended Kalman Filter (EKF) approach.	The LSTM model was used to get around the EKF method's shortcomings in precisely estimating the lithium-ion battery's state of charge.
1Towards a hybrid approach to SoC estimation for a smart Battery Management System (BMS) and battery supported Cyber-Physical Systems (CPS) [9]	SoC estimation using the coulomb counting method. Kalman Filter and Open Circuit Voltage (OCV) techniques approaches using formal methods (FM) and artificial intelligence (AI).	Prevent battery damage with precise SoC estimation. Limited battery capacity necessitates sophisticated estimation techniques.
State of Charge Estimation of Lithium Battery Based on Integrated Kalman Filter Framework and Machine Learning Algorithm [10]	Integrating Kalman filter framework algorithms (EKF, UKF, MIUKF, UKF-VFFRLS, MIUKF-VFFRLS) with machine learning algorithms (linear regression, support vector regression, XGBoost, AdaBoost, random forest, LSTM) to estimate the state of charge (SOC) of lithium batteries. 2. Considering three groups of input variables for the machine learning algorithms: measured current and voltage, features obtained from the Kalman filter framework algorithms, and the three most important features obtained from the Kalman filter framework algorithms after feature selection. 3. Using time series and statistical transformations of the input variables, such as sliding windows and statistics (mean, standard deviation, median). 4. Employing recursive feature elimination to select the three most important features from the Kalman filter framework algorithms.	The study is limited to a single discharge cycle under the UDDS working condition and 25°C temperature, and further research is needed to test the algorithm under different conditions and longer time periods. - The paper suggests that algorithms with larger parameters, such as LSTM, may perform better if the experimental data is expanded.
A new state of charge estimation technique of lithium-ion battery using adaptive extended Kalman filter and artificial neural network [11]	A hybrid approach combining adaptive extended Kalman filter (AEKF) and artificial neural network (ANN) for estimating the state of charge (SOC) of lithium-ion batteries - Validation of the hybrid technique using five different EV driving cycles (LA92, US06, UDDS, HWFET, and a mixed cycle) at four different temperature conditions (0°C, 10°C, 25°C, and 40°C) - Implementation of a real-time SOC estimator using open circuit voltage and Coulomb counting methods, and using this information to reserve charging slots for potential EV users - Use of a cloud-based IoT platform (ThingSpeak) to monitor the charging status of EVs remotely	The real-time SOC estimator and charging slot reservation system are not the main focus of the study, but are mentioned as additional features. - The use of the Thing Speak IoT platform to monitor charging status is not the main focus of the study. - The abstract does not provide details on the specific existing methods that were compared or the magnitude of the improvements in RMSE and accuracy.

Battery state of charge estimation based on a combined model of Extended Kalman Filter and neural networks [15]	Modeling battery hysteresis effects using an Extended Kalman Filter (EKF) - Designing a SOC estimation model that combines the EKF with a neural network (NN-EKF model) - Evaluating the proposed methods using real data from two different battery types (lithium-ion and NiMH)	- The real-time SOC estimator and charging slot reservation system are not the main focus of the study, but are mentioned as additional features. - The use of the Thing Speak IoT platform to monitor charging status is not the main focus of the study. - The abstract does not provide details on the specific existing methods that were compared or the magnitude of the improvements in RMSE and accuracy.

6.CONCLUSION

The application of AI-based Kalman Filter (KF) and Extended Kalman Filter (EKF) techniques for SOC estimation in electric vehicles has been the subject of extensive research in recent years. These strategies have demonstrated significant improvements in accuracy, robustness, and adaptability when compared to traditional methods. Combining KF and EKF with other state-of-the-art techniques like artificial neural networks, fuzzy logic, and deep learning has further enhanced their performance. Robust and creative variants, including the Robust Function Correction-Adaptive Extended Kalman Filter (RFC-AEKF), Threshold Extended Kalman Filter (T-EKF), and Adaptive Extended Kalman Filter (AEKF), have been developed to address specific challenges in SOC estimation under different operating conditions. In practical applications, these techniques have been demonstrated to be effective in improving the efficiency, security, and usability of electric vehicles. As the need for EVs continues to grow, further advancements in AI-based KF and EKF techniques will be crucial to overcoming the challenges related to SOC estimates and promoting the widespread adoption of EVs.

REFERENCES

1. A Hussein ".Kalman Filters versus Neural Networks in Battery State-of-Charge Estimation: A Comparative Study," 2014
2. Rimsha, S. Murawwat, M. Gulzar, Ahmad Alzahrani, Ghulam Hafeez, Farrukh Aslam Khan, A. Abed ".State of charge estimation and error analysis of lithium-ion batteries for electric vehicles using Kalman filter and deep neural network, "Journal of Energy Storage·2023
3. T. P, S. P. "Artificial Intelligence based State of Charge estimation of Li-ion battery for EV applications," International Conference on Communication and Electronics Systems·2020
4. Hussein "Kalman Filters versus Neural Networks in Battery State-of-Charge Estimation: A Comparative Study," 2014
5. Himanshu Jaiswal, Swapnil Sanjay Ghule, Varsha A. Shah"Comparative Analysis of Non-Linear Kalman Filters for Li-ion Battery SoC Estimation with RLS-VDF Technique for Parameters Identification,"
6. Ponukupati Ravi Teja, R. Shanmughasundaram ".Analysis on SoC estimation of Lithium ion battery using EKF and LSTM," IEEE Madras Section Conference (MASCON)·2021·
7. ZhiHang Chen, Shiqi Qiu, M. Masrur, Y. Murphey ".Battery state of charge estimation based on a combined model of Extended Kalman Filter and neural networks,"
8. K Man "Towards a hybrid approach to SoC estimation for a smart Battery Management System (BMS) and battery supported Cyber-Physical Systems (CPS)," Baltic Congress on Future Internet Communications 2012 ·
9. Hong Yuan 'State of Charge Estimation of Lithium Battery Based on Integrated Kalman Filter Framework and Machine Learning Algorithm," Energies 2023 ·
10. "Data-Driven State of Charge Estimation for Power Battery With Improved Extended Kalman Filter," IEEE Transactions on Instrumentation and Measurement 01 Jan 2023
11. Syed Najeeb Ali Kazmi, Abasin Ulasyar, Abraiz Khattak " A new state of charge estimation technique of lithium-ion battery using adaptive extended Kalman filter and artificial neural network," Transactions of the Institute of Measurement and Control 10 Nov 2022-
12. Jaehyun Han, Dongchul Kim, Myoungho Sunwoo "State-of-charge estimation of lead-acid batteries using an adaptive extended Kalman filter," Journal of Power Sources 15 Mar 2009
13. David Chunhu Li, Javio Renja Felix, Yi-Ling Chin "Integrated Extended Kalman Filter and Deep Learning Platform for Electric Vehicle Battery Health Prediction," Applied Sciences 21 May 2024
14. ZhiHang Chen, Shiqi Qiu, M. Masrur, Y. Murphey "Battery state of charge estimation based on a combined model of Extended Kalman Filter and neural networks," International Joint Conference on Neural Networks 2011
15. Xiang-Wu Yan, Yu-Wei Guo, Yang Cui "Electric Vehicle Battery SOC Estimation based on GNL Model Adaptive Kalman Filter," 01 Sep 2018
16. "SOC Estimation for a Li-ion battery based on the AEKF optimized by GA-BP Neural Network," 28 Oct 2022
17. R. K. Kumawat and D. K. Palwalia, "A novel PWM control for symmetric multilevel inverter based on half bridge module," IEEE 7th Power India International Conference (PIICON), India, pp. 1-5, 2016.
18. R. K. Kumawat and D. K. Palwalia, "Half bridge module asymmetric multilevel inverter based on novel PWM control strategy," 6th International Conference on Computer Applications in Electrical Engineering-Recent Advances (CERA), Roorkee, pp. 303-307, 2017.
19. Suwarna Shete, R. K. Kumawat and D. K. Palwalia"Battery Management System for SOC Estimation of Lithium-Ion Battery in Electric Vehicle: A Review" 2021 6th IEEE International Conference on Recent Advances and Innovations in Engineering (ICRAIE),10.1109/ICRAIE52900.2021.9703752