Energy 311 (2024) 133417

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Battery state of charge estimation for electric vehicle using Kolmogorov-Arnold networks

Mohd Herwan Sulaiman [a,*], Zuriani Mustaffa [b], Amir Izzani Mohamed [a], Ahmad Salihin Samsudin [c], Muhammad Ikram Mohd Rashid [a]

[a] Faculty of Electrical and Electronics Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), 26600, Pekan, Pahang, Malaysia
[b] Faculty of Computing, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), 26600, Pekan, Pahang, Malaysia
[c] Faculty of Industrial Sciences & Technology, Universiti Malaysia Pahang Al-Sultan Abdullah (UMPSA), 26300, Gambang, Pahang, Malaysia

ARTICLE INFO

Handling editor: X Ou

Keywords:
State of charge (SoC)
Electric vehicles (EV)
Kolmogorov-Arnold networks (KAN)
Artificial neural networks (ANN)
Hybrid metaheuristic-deep learning
Battery management

ABSTRACT

Accurate estimation of the state of charge (SoC) in electric vehicle (EV) batteries is essential for effective battery management and optimal performance. This study investigates the application of Kolmogorov-Arnold Networks (KAN) for SoC estimation, comparing its performance against Artificial Neural Networks (ANN) and a hybrid Barnacles Mating Optimizer-deep learning model (BMO-DL). The dataset, derived from simulations involving a lithium polymer cell model (ePLB C020) in an electric car similar to Nissan Leaf EV, encompasses 68,741 instances, divided into training and testing sets. Three KAN models were developed and evaluated based on root mean square error (RMSE), mean absolute error (MAE), maximum error (MAX), and coefficient of determination (R^2). Residual analysis indicates that KAN-Model 1 performs the best, with residuals closely clustered around zero and no significant patterns, suggesting reliable and unbiased predictions. KAN-Model 2 also performs well but exhibits some nonlinear trends in the residuals. ANN and BMO-DL models show larger deviations and less consistent performance. These findings highlight the potential of KAN for enhancing SoC estimation accuracy in EV applications.

1. Introduction

Accurate estimation of the state of charge (SoC) in electric vehicle (EV) batteries is a critical factor for ensuring efficient battery management, optimizing vehicle performance, and extending battery lifespan [1]. However, SOC estimation remains a formidable challenge due to the intricate and nonlinear behavior of batteries [2], influenced by various factors such as temperature fluctuations, current variations, and aging effects [3,4]. Inaccurate SOC estimation can lead to suboptimal vehicle range predictions, inefficient energy utilization, reduced driving range, potential safety hazards, and premature battery degradation [5], posing significant obstacles to the widespread adoption of electric vehicles [6].

Researchers and industry practitioners have explored various approaches and methods to tackle the SOC estimation problem in the EV industry. Traditional methods, including empirical models such as the Coulomb counting method [7,8], impedance-based method [9,10], and the open-circuit voltage method [11,12], rely on simplistic assumptions and often fail to capture the intricate dynamics of modern battery systems. Physics-based models, such as equivalent circuit models and electrochemical models, offer improved accuracy but require detailed knowledge of battery parameters and are computationally intensive [13].

In recent years, the application of machine learning and artificial intelligence techniques has gained traction for SoC estimation, driven by their ability to model complex nonlinear relationships and adapt to changing operating conditions. Approaches such as Artificial Neural Networks (ANNs) [14,15], Random Forest [16–18], Long Short-Term Memory (LSTM) networks and their variants [3,19,20], Gated Recurrent Units (GRU) [21], and Convolutional Neural Networks (CNN) [22] have demonstrated significant promise in capturing temporal dependencies and spatial features in battery data. However, these methods may still struggle with capturing the complex nonlinear dynamics of battery systems and handling high-dimensional input data [23–25].

The issue of accurate SoC estimation has emerged as a critical challenge in the EV industry, garnering significant attention from researchers and practitioners. In an attempt to address this pivotal

* Corresponding author.
E-mail address: herwan@umpsa.edu.my (M.H. Sulaiman).

https://doi.org/10.1016/j.energy.2024.133417
Received 5 June 2024; Received in revised form 14 August 2024; Accepted 8 October 2024
Available online 10 October 2024