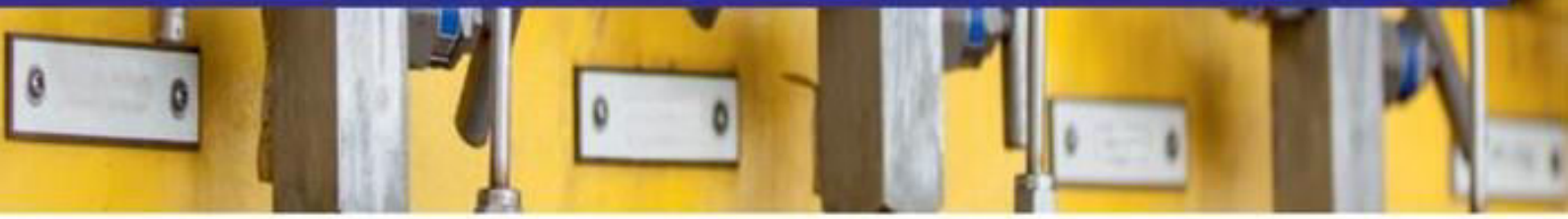


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Intelligent Battery Management System (IBMS): Advanced State Estimation, Digital Twin Technology, Hybrid Modeling & System Validation

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ABSTRACT: The paper provides an integrated analysis of intelligent battery management systems in order to enhance safety, reliability, and performance of lithium ion batteries employed in electric vehicle and renewable energy storage applications. The methods of advanced SoC/SoH estimation using EKF, MHE, and machine learning algorithms have been analyzed. The digital twin technology and hybrid modeling have been considered for improving prediction and battery degradation management. The MATLAB/Simulink framework is utilized for concept validation of the system's architecture through simulation. Hardware-in-the-Loop (HIL) validation of IBMS using STM32 microcontroller has been discussed.

KEYWORDS: battery management system, state estimation, digital twin, hybrid modelling, hardware-in-the-loop.

I. INTRODUCTION

High demands on the development of intelligent battery management systems due to the rapid development of electric vehicles and technologies for storing renewable energy make lithium-ion batteries widespread. The effectiveness and reliability of such batteries depend on the temperature during the operation of the battery, as well as the conditions of charging, loading and the ageing process. To ensure safety and efficiency, the Battery Management System (BMS) is responsible for battery parameter monitoring, battery state estimation, charging and discharging control, etc.

The State of Charge (SoC) and State of Health (SoH) estimation is needed to assess battery capacity. Nonlinear conditions of work present a challenge for conventional techniques. More precise estimations can be provided by such techniques as Extended Kalman filter, Moving Horizon Estimation, Machine learning. Also, digital twin provides support for predictive monitoring with virtual updating of battery models.

In this paper, an intelligent BMS framework including state estimation techniques, hybrid modelling and system validation is discussed. In particular, MATLAB/Simulink and hardware-in-the-loop simulation will be considered.

BMS is traditionally considered to be a pivotal element for an efficient management of lithium-ion battery packs. Today's BMS is composed of several interrelated subsystems, which means that it should include voltage measurements, current measurements, temperature measurements, estimation of state of charge, safety measures and control of battery operation. It is necessary to ensure proper integration of these subsystems in order to keep the battery functioning within the given limits. Out of all BMS tasks, attempt to identify the state of charge (SoC) and state of health (SoH) of a battery is one of the most essential as it provides information about the battery capacity. Several methods can be used for the purposes of estimation of battery parameters such as Model-based estimation techniques (such as the Extended Kalman Filter and Moving Horizon Estimation). Machine learning classifies possible approaches for battery parameters estimation. The various software packages (e.g. MATLAB) have been designed to model batteries and test the interaction of battery components. The validation process helps to recognize errors in modeling, check the accuracy of the estimation and identify the combinations of different components used in the BMS.

1.1 Background

BMSs play a critical role in ensuring the safety and efficiency of battery packs through continuous voltage, current, and temperature measurements, and SoC and SoH estimation. The Equivalent Circuit Model is a useful tool for characterizing the behavior of batteries. Modern state estimation techniques such as EKF and MHE make estimations more precise while machine learning techniques detect complicated relations from battery data sets. Digital Twin techniques help to predict battery degradation and represent virtual battery systems. All these technologies help to implement smart monitoring and energy management.

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1.2 Problem Statement

Estimation of SoC and SoH still remains a challenging task due to nonlinearity of lithium-ion batteries in relation to temperature changes, loads, and aging processes. EKF algorithm is fast but sensitive to initial conditions and noise, while MHE technique demonstrates more robust performance but has high computational complexity. Machine learning requires adequate training datasets, but simulations do not prove its ability to perform in real-time. Thus, a compromise solution is needed which would combine the benefits mentioned.

II. LITERATURE REVIEW

Battery management has evolved from traditional estimation techniques to modern and intelligent approaches. Coulomb Counting technique gives a simple way to estimate SoC but accumulates errors. ELM models enhance the characterization of batteries by adding resistive and capacitive elements into the Equivalent Circuit Model. Such models give a basis for further advanced state estimation and battery simulation.

Extended Kalman Filter technique is one of the most widely used techniques due to the combination of precision and efficiency of estimation. Moving Horizon Estimation increases robustness of the estimation by taking into account measurements within the sliding time window. However, it uses optimization technique which consumes more computational resources. Machine Learning approach based on regression trees and neural networks gives good data-driven estimation and increased computational speed, but also requires representative datasets.

Modern trends in battery management research show Digital Twin approach as a useful tool for the prediction of battery degradation and monitoring as well as the development of predictive maintenance strategy. Combining physical battery models with data-driven estimation algorithms might increase adaptability and precision of the process. MATLAB/Simulink helps to integrate monitoring, estimation, protection, and control subsystems. Additionally, Hardware-in-the-Loop technique allows to connect simulation models with microcontrollers and investigate the feasibility of the real-time process.

2.1 Research Gaps

- Lack of integration of estimation algorithms into adaptive battery modeling systems.
- High computational needs limit advanced estimation in embedded BMS applications.
- Inadequate real-time verification links simulation results with implementation requirements.
- Limited ageing datasets impact predictive abilities of intelligent battery models.

2.2 Research Objectives

- Analysis of advanced SoC and SoH estimation methods in case of lithium-ion batteries.
- Assessment of EKF, MHE, and Machine Learning algorithms performance and capabilities.
- Exploration of Digital Twin integration for predictive battery monitoring and aging.
- Analysis of simulation-based integration and Hardware-in-Loop validation methods for BMS.

III. METHODOLOGY

According to the proposed methodology for the Intelligent Battery Management System (IBMS), a consistent four-stage process has been developed, as presented in the flowchart. The objective of this methodology is to investigate battery modelling, state estimation, BMS subsystem integration, and simulation-based validation in order to improve the safety, efficiency, and performance of lithium-ion batteries. The first step in the process is Battery Modelling. This step involves the use of an Equivalent Circuit Model (ECM) to model the electric characteristics of the lithium-ion battery during charging and discharging. At this stage, the necessary parameters of the batteries such as terminal voltage, current, internal resistance, temperature and capacity are taken into consideration to comprehend the operation of the batteries in different situations. The MATLAB and Simulink software environment is used for conducting the simulation and testing of the battery data.

The second phase involves selecting an algorithm where more advanced techniques like the extended Kalman filter, moving horizon estimation, and machine learning are seen to help estimate the State of Charge and State of Health. The extended Kalman filter employs mathematical models and measured parameters of the battery to estimate its states with a good ratio between precision and computation expense. The moving horizon estimator takes into account measurements happening in a time window in order to enhance estimation reliability in case of uncertain operating conditions but at the same time requires higher computation power. Different forms of machine learning are used as

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well for analyzing the data obtained from batteries in order to understand their specific behaviours. In the third stage, we reach the battery Management System (BMS) simulation, where both the battery model and the algorithm selected previously are integrated into the BMS. The important subsystems will include voltage monitoring, current monitoring, temperature monitoring, state estimation, battery protection, and control. Digital Twin technology will also be applied by combining physical models of the battery with algorithms based on the obtained data.

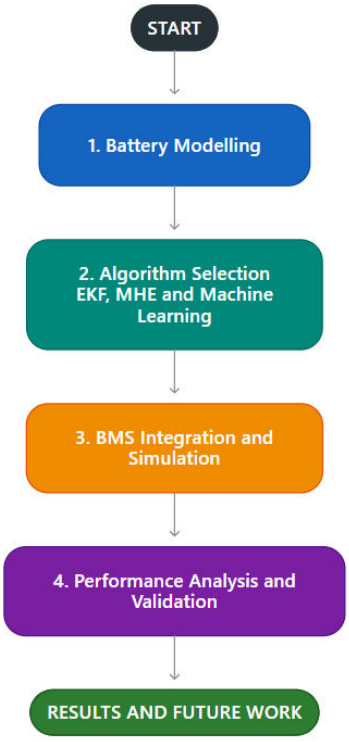


Fig.3.1 Systematic IBMS Development and Validation Process.

In the last stage, Performance Analysis and Validation are carried out, which means that the abilities of the estimation methods selected are compared based on factors like the accuracy of the estimation, computing complexity, response time, and reliability. The platform for analysing the connections among various battery management systems (BMS) components, as well as establishing the behaviour of the entire BMS, is MATLAB/Simulink. The role of Digital Twin technology in predicting battery monitoring and managing battery deterioration is also described. Besides, Hardware-in-the-Loop (HIL) validation is mentioned as a method for further making use of the STM32 microcontroller to assess the efficiency of the real-time controller. This method allows discovering difficulties in implementation and determining if the proposed intelligent BMS system is implementable. Ultimately, after conducting comparative analysis, conclusions are made regarding the strengths and weaknesses of each method and predictions about the possible improvements in the algorithm efficiency, hybrid modelling, real-time verification, and efficient battery management in the future are made.

IV. RESULTS AND DISCUSSION

The comparative analysis proves that EKF, MHE, and Machine Learning regression trees have their own performance characteristics while being applied for estimation of battery states. In particular, EKF gives good combination of accuracy and efficiency needed for estimation and real-time usage for electric vehicles. However, performance of this algorithm depends on initial conditions and measurement noise. MHE gives smoother and more precise estimation of battery states in case of uncertainty but its optimization process demands much more computational power. Machine Learning regression trees have very low iteration time – even microsecond computation level, although it still depends on quality and quantity of training dataset used. All these findings mean that selection of the estimation algorithm implies trade-offs between accuracy, computational costs and operation requirements.

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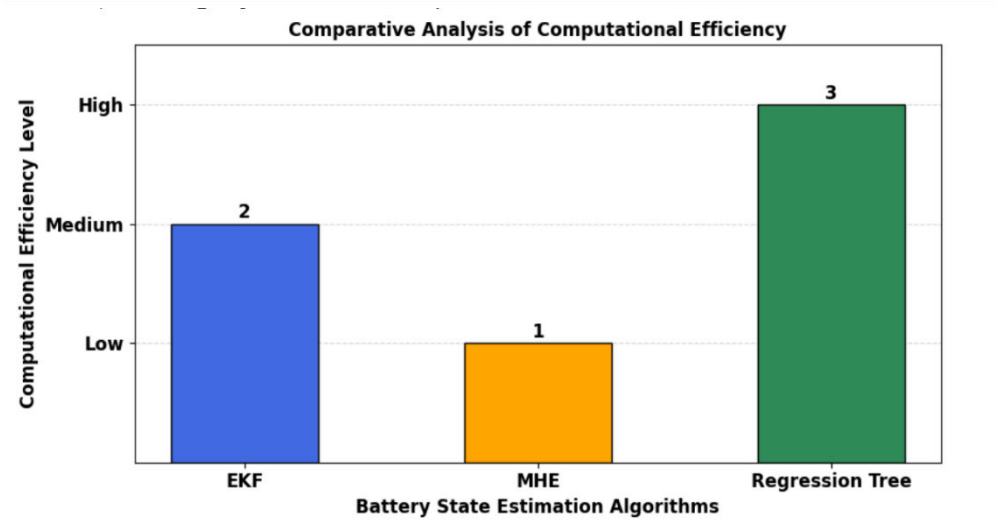


Fig.4.1 Comparative Algorithm Efficiency Analysis

Digital Twin technologies improve predictive battery monitoring thanks to integration of physical models with Machine Learning algorithms and operational data. They allow identification of battery ageing patterns and future degradation behaviour. MATLAB/Simulink gives good opportunity to integrate battery monitoring, estimation, protection and control subsystems.

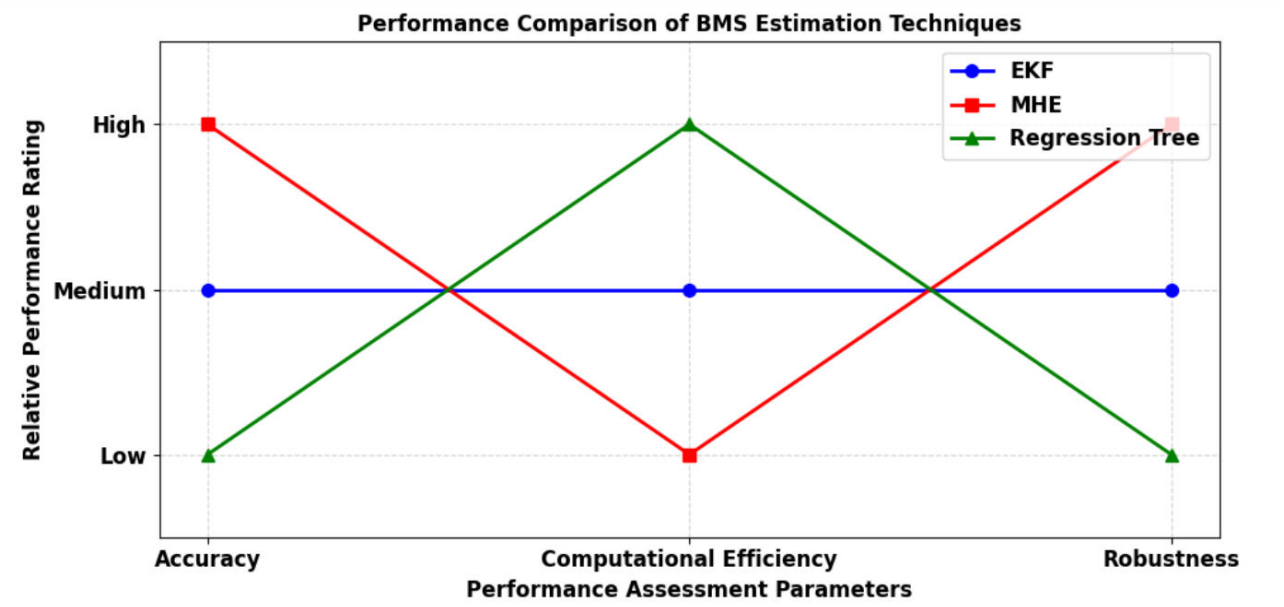


Fig 4.2 BMS Estimation Performance Comparison

Moreover, HIL validation approach with STM32 microcontrollers opens way for assessment of real-time implementation without testing physical batteries under dangerous conditions.

V. CONCLUSION

In order to ensure enhanced reliability and safety of Li-ion batteries and efficient control in terms of electric vehicles and renewable energy storage applications, Intelligent Battery Management Systems are a must. This review paper considered several advanced methods of SoC and SoH estimation that include Extended Kalman Filter, Moving Horizon Estimation, as well as Machine Learning regression trees. It becomes clear from the comparative discussion

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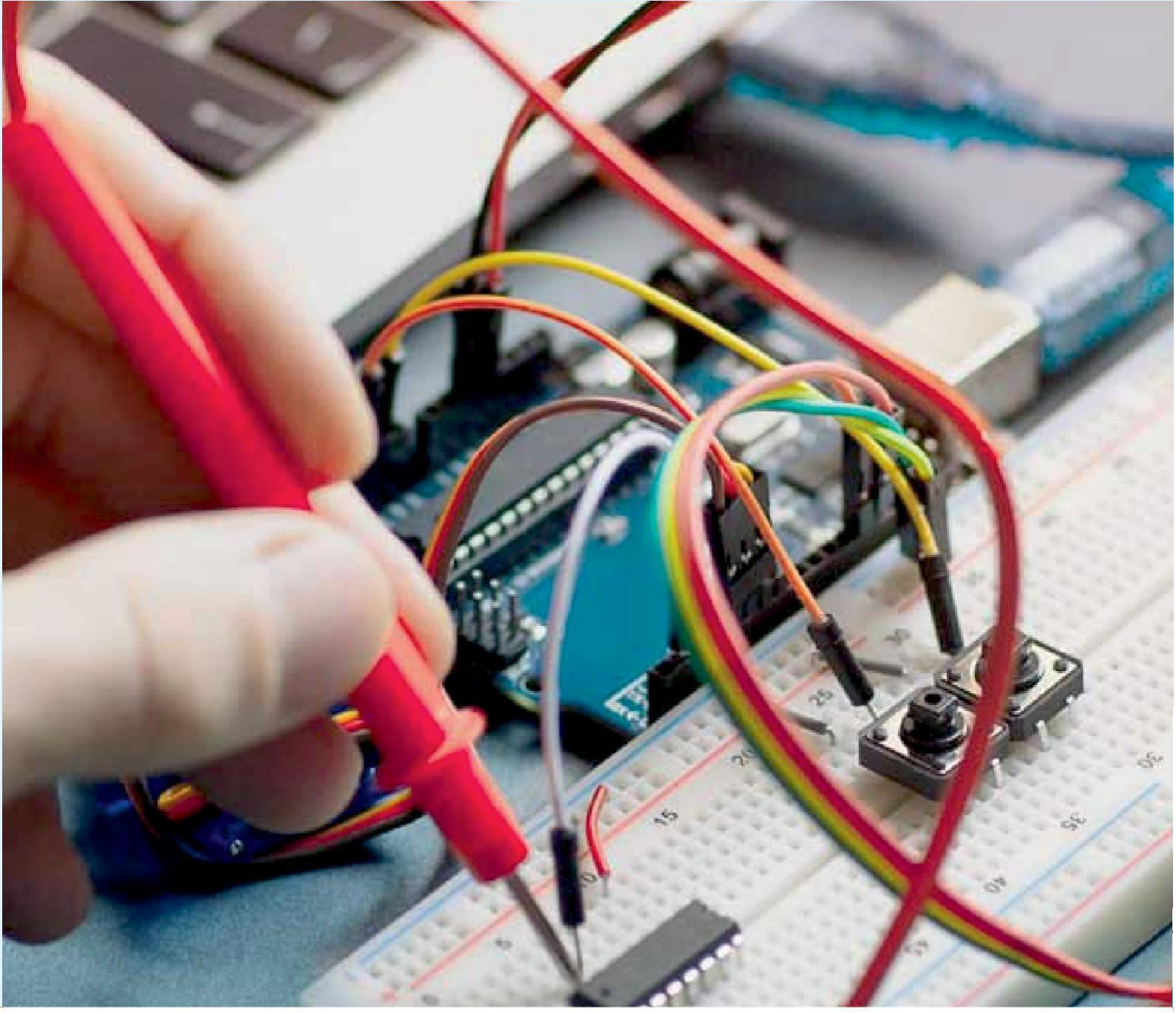
above that the EKF provides the best balance between estimation accuracy and computational efficiency, MHE offers increased robustness and accuracy, and regression trees offer fast computation with some limitations concerning prediction accuracy.

The introduction of digital twin technology offers great advantages for the virtual monitoring of batteries, their degradation prediction and, ultimately, predictive maintenance. Physical modeling of battery characteristics together with application of the data-driven approach can increase adaptability and support intelligent battery management. For the sake of modeling and integration of subsystems, the MATLAB/Simulink environment can be effectively utilized. The path towards hardware realization is Hardware-in-the-Loop validation with the use of STM32 microcontrollers.

It should be noted that no method alone can solve all battery management issues. In this regard, a hybrid framework that combines EKF, MHE, machine learning approach, as well as digital twin technology is a perspective direction in battery management. Future research efforts should be directed at enhancing computational performance, building battery databases, strengthening HIL validation process and development of cloud-based learning framework.

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