ADVANCED MODELING APPROACHES FOR STATE-OF-CHARGE ESTIMATION AND STATE-OF-HEALTH MONITORING IN LITHIUM-ION BATTERIES FOR ELECTRIC VEHICLES

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Abstract: This work reviews battery modeling approaches for electric vehicles, focusing on monitoring State of Health and estimating State of Charge. Key modeling strategies including electrochemical, equivalent circuit, mathematical, and data-driven methods are discussed in terms of their advantages and limitations. Accurate models enable reliable state estimation, enhance battery safety, optimize charging and discharging, and support extended battery life, making them essential for efficient Battery Management Systems and sustainable transport operation.

Key words: Battery modelling, electric vehicles, Battery Management System, electrochemical models, Equivalent Circuit Models.

In recent years, the urgent need to reduce greenhouse gas emissions and mitigate the environmental pollution caused by fossil fuels such as gasoline and diesel has accelerated the search for sustainable and eco-friendly alternatives. Among the available renewable energy solutions, chemical energy storage systems have emerged as highly reliable technologies. Their primary advantage lies in the ability to provide portable power across a wide range of applications, making them one of the most widely adopted forms of renewable energy storage.

Batteries, the focus of this study, are electrochemical systems that convert stored chemical energy into electrical energy through specific electrochemical reactions. Lithium-ion batteries, in particular, have gained significant attention due to their high energy density, superior power density, and excellent overall performance. As a result, they are extensively employed in diverse applications, including portable electronics such as laptop computers, household load-leveling systems, and, most importantly, electric vehicles, which form the central subject of this work. Batteries represent the most widely used technology for electrical energy storage. Their importance has grown substantially in recent years, as modern mobile systems, including electric vehicles, smartphones, and laptops. The depend on the energy stored within these devices for operation. With the increasing penetration of battery-powered technologies, the need for accurate modeling of charging and discharging profiles has become critical to ensure optimal performance, efficiency, and longevity. This paper provides a comprehensive review of battery modeling approaches, including electrochemical models, mathematical models, circuit-based models, and hybrid frameworks, applied to different battery types.

The lifetime of a battery is largely governed by its intrinsic physical and chemical properties. However, the aging behavior of battery cells is inherently nonlinear and influenced by multiple operational factors. Extending battery life cannot be achieved solely by reducing power consumption at isolated points in time. Instead, it is determined by the overall usage profile, including patterns of power demand, current extraction rates, and operating current levels.

The primary function of a Battery Management System is to ensure the safe and efficient operation of batteries by regulating charging and discharging processes, performing cell balancing, providing over-temperature protection, and estimating the state-of-charge based on voltage, current, and temperature measurements. In addition, the Battery Management System continuously monitors key operational parameters such as state-of-charge, state-of-health, depth of discharge, and temperature. Since these states cannot be directly measured, they must be inferred through estimation techniques that rely on appropriate battery models. Consequently, accurate battery modeling plays a critical role in studying, estimating, and predicting the real-time performance and reliability of battery systems.

1. Significance of Battery Modeling

Mathematical modeling of batteries holds substantial importance for both research and practical applications, as it enables a deeper understanding and optimization of battery performance. The key reasons include:

Facilitating the development of efficient Battery Management Systems (BMS): Accurate models serve as the foundation for advanced control strategies.

Improving charging and discharging techniques: Modeling contributes to enhanced energy efficiency and maximized battery capacity.

Capturing the impact of power consumption patterns: Models allow analysis of how load variations affect performance and degradation.

Preventing damage from overcharging or over-discharging: Reliable models support the implementation of effective protection mechanisms.

Providing a safe and accelerated testing environment: Virtual simulations based on models enable the study of battery behavior under diverse operating conditions without physical risks.

Defining optimal operating limits: Modeling helps identify conditions that maximize lifetime and ensure reliability for specific applications.

A wide range of battery models with varying levels of complexity have been developed to address different application requirements. Based on the degree of physical insight incorporated, these models are generally categorized into three levels: white-box models (electrochemical models), grey-box models (circuit-oriented models), and black-box models (data-driven approaches such as artificial neural networks). A critical aspect of battery modeling is the accurate estimation of model parameters, as these directly influence the precision of state estimation and performance prediction. To this end, several modeling strategies have been employed, including electrochemical models, mathematical formulations, equivalent circuit models, and data-driven methods, each offering distinct advantages and limitations depending on the intended application.

Equivalent Circuit Models (ECMs) are among the most widely used approaches for battery modeling due to their balance between simplicity and accuracy. These models represent the dynamic electrical behavior of a battery using electrical circuit components such as resistors, capacitors, and voltage sources. The fundamental concept is to approximate the internal electrochemical processes of the battery through equivalent electrical elements, thereby enabling easier analysis and implementation.

The simplest ECM is the RINT model, which represents the battery as an ideal voltage source in series with an internal resistance. While computationally efficient, this model is limited in its ability to capture dynamic behaviors such as transient response and diffusion effects. To address these limitations, more advanced ECMs have been developed, such as the Thevenin model and the Randles model, which incorporate additional resistor-capacitor (RC) networks. These extensions improve accuracy in simulating dynamic characteristics like charge transfer resistance, double-layer capacitance, and diffusion dynamics.

ECMs are particularly advantageous for real-time applications, including integration into Battery Management Systems, because of their relatively low computational cost and straightforward parameterization. However, they are inherently empirical in nature and require periodic parameter identification to maintain accuracy under varying operating conditions such as temperature, aging, and load profiles.

Conclusion

Battery modeling plays a vital role in understanding, predicting, and optimizing the performance of modern energy storage systems, particularly lithium-ion batteries used in electric vehicles and portable electronics. Accurate models not only support the development of efficient Battery Management Systems but also enhance safety, extend battery lifetime, and enable reliable real-time operation. Among the different approaches, electrochemical, equivalent circuit, mathematical, and data-driven models each provide unique strengths, making the selection of an appropriate modeling strategy highly dependent on the application requirements.

References

1. Chaudhari, K.; Kandasamy, N.K.; Kanamarlapudi, R.K.; Gooi, H.B.; Ukil, A. "Modeling of charging profiles for stationary battery systems using curve fitting approach". In Proceedings of the IECON 2017-43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, China, 29 October–1 November 2017; pages. 2777–2781.

2. Moura, S.J.; Chaturvedi, N.A.; Krsti´c, M. "Adaptive partial differential equation observer for battery state-of-charge/state-of-health estimation via an electrochemical model". *J. Dyn. Syst. Meas. Control* 2014, *136*, 11.

3. He, H.; Xiong, R.; Guo, H.; Li, S. "Comparison study on the battery models used for the energy management of batteries in electric vehicles". *Energy Convers. Manag.* 2012, *64*, pages 113–121.

4. Grandjean, T.R.B.; McGordon, A.; Jennings, P.A. "Structural identifiability of equivalent circuit models for Li-ion batteries". *Energies* 2017, *10*, 90

5. Jongerden, M.R.; Haverkort, B.R.H.M. "Battery Modelling". University of Twente, Faculty of Mathematical Sciences: Enschede, The Netherlands, 2008; ISBN 1381-3625.

6. Li, S.; Ke, B. "Study of battery modeling using mathematical and circuit-oriented approaches". In Proceedings of the 2011 IEEE Power and Energy Society General Meeting, Detroit, MI, USA, 24–28 July 2011; pages. 1–8.

7. El Ghossein, N.; Salameh, J.P.; Karami, N.; El Hassan, M.; Najjar, M.B. "Survey on electrical modeling methods applied on different battery types". In Proceedings of the 2015 Third International Conference on Technological Advances in Electrical, Electronics and Computer Engineering (TAEECE), Beirut, Lebanon, 29 April–1 May 2015; pages. 39–44.

8. Timmermans, J.-M.; Nikolian, A.; De Hoog, J.; Gopalakrishnan, R.; Goutam, S.; Omar, N.; Coosemans, T.; Van Mierlo, J.; Warnecke A.; Sauer, D.U.; et al. "Batteries 2020—Lithium-ion battery first and second life ageing, validated

battery models, lifetime modelling and ageing assessment of thermal parameters". In Proceedings of the 2016 18th European Conference on Power Electronics and Applications (EPE'16 ECCE Europe), Karlsruhe, Germany, 5–8 September 2016; pages. 1–23.

9. Thirugnanam, K.; TP, E.R.J.; Singh, M.; Kumar, P. "Mathematical modeling of Li-ion battery using genetic algorithm approach for V2G applications". *IEEE Trans. Energy Convers.* 2014, *29*, 332–343.

10. Muenzel, V.; de Hoog, J.; Brazil, M.; Vishwanath, A.; Kalyanaraman, S. "A multi-factor battery cycle life prediction methodology for optimal battery management". In Proceedings of the 2015 ACM Sixth International Conference on Future Energy Systems, Bangalore, India, 14–17 July 2015; pages. 57–66