Degradation Mechanisms and Hybrid Modeling of Lithium-ion Batteries under Electrified Transportation Scenarios

The performance evolution of lithium-ion batteries under diverse operational scenarios is critical to the reliability and safety of electrified transportation systems. Yet the impacts of multi-physics stressors—mechanical swaying, vibration, elevated temperature, and over-discharge—on degradation pathways and state estimation have not been comprehensively elucidated. Controlled aging experiments were conducted using a six-degree-of-freedom platform to reproduce swaying and vibration, together with elevated-temperature and over-discharge cycling. Incremental capacity (IC) analysis, electrochemical impedance spectroscopy (EIS), and post-mortem scanning electron microscopy (SEM) were employed to identify and quantify degradation modes. Results reveal that vibration at room temperature moderately mitigates capacity fade, while elevated temperature accelerates both capacity loss and impedance growth. Over-discharge induces severe degradation, with distinct mechanisms observed at 105% and 120% depth-of-discharge (DOD). To enhance state estimation accuracy under complex conditions, we develop a hybrid data-driven single-particle model (SPM). The modified SPM incorporates swaying-induced polarization effects, with electrode overpotential and solid-phase surface concentration as key parameters. Furthermore, a data-driven method integrating sliding-window feature extraction and differential voltage analysis is proposed to improve adaptability under high-rate discharge and mechanical disturbances. The hybrid framework enables robust joint estimation of state of charge (SoC) and state of health (SoH), validated under multi-stress aging conditions. This work provides new insights into the degradation mechanisms of lithium-ion batteries under realistic transportation scenarios and develops a transferable modeling framework for accurate state estimation, offering theoretical and methodological support for advanced battery management system design.

Keywords: Lithium-ion battery; Electrified transportation; Degradation mechanism; Single-particle model (SPM); Data-driven model; State of charge (SoC); State of health (SoH)

Biographical Note

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Sidun Fang (Senior Member, IEEE) was born in Chongqing, China, in 1991. He received the B.E. degree from the School of Electrical Engineering, Chongqing University, Chongqing, China, in 2012, and the Ph.D. degree in power system and its automation from the School of Electronics Information and Electrical Engineering, Shanghai Jiao Tong University, Shanghai, China, in 2017. He is currently a Full Professor with Chongqing University. His research interests include integrated energy system and energy-transport integration. Dr. Fang was the recipient of the Outstanding Graduate Prize of Shanghai Jiao Tong University. His doctoral dissertation was nominated as the Excellent Dissertation Papers in Shanghai Jiao Tong University in 2017. He is also an Associate Editor for IEEE Transactions on Industrial Cyber-Physical Systems, IEEE Transactions on Industry Applications, and IET Renewable Power Generation.