Fractional Partial Differential Equation Modeling of Battery Charge Dynamics with High-Accuracy Numerical Approximation Schemes

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Abstract

Fractional partial differential equations (FPDEs) provide an advanced framework for modeling battery charge dynamics by capturing memory and anomalous diffusion effects that classical integer-order models fail to represent [5]. In this work, a time-space FPDE model is formulated to describe charge transport in electrochemical batteries, incorporating fractional-order diffusion mechanisms and nonlocal operators [4]. A suitable high-accuracy numerical approximation, including finite difference, spectral, and meshless schemes, is developed to efficiently handle the nonlocal behavior and ensure stability and convergence.

The proposed approach improves the accuracy of state-of-charge prediction and internal electrochemical dynamics compared to classical models. Recent advances in fractional-order battery modeling and data-driven techniques further confirm the effectiveness of FPDE-based frameworks for enhancing battery performance analysis and battery management systems [1, 2].

Keywords: Fractional partial differential equations, lithium-ion batteries, charge transport modeling, anomalous diffusion, nonlocal operators, high-accuracy numerical schemes, spectral methods, finite difference methods, meshless methods, state of charge estimation, physics-informed neural networks.

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