BATTERY HEALTH-CONSCIOUS POWER MANAGEMENT FOR PLUG-IN HYBRID ELECTRIC VEHICLES VIA STOCHASTIC CONTROL

Scott J. Moura[1,2] **Jeffrey L. Stein**[1] **Hosam K. Fathy**[2*]
[1]Automated Modeling Laboratory
[2]Control Optimization Laboratory
Department of Mechanical Engineering
University of Michigan
Ann Arbor, Michigan 48109-2125
Email: {sjmoura,stein,hfathy}@umich.edu

ABSTRACT

This paper investigates power management algorithms that optimally manage lithium-ion battery pack health, in terms of anode-side film growth, for plug-in hybrid electric vehicles (PHEVs). Specifically, we integrate a reduced electrochemical model of solid electrolyte interface (SEI) film formation into a stochastic dynamic programming formulation of the PHEV power management problem. This makes it possible to optimally trade off energy consumption cost versus battery health. A careful analysis of the resulting Pareto-optimal set of power management solutions provides two important insights into the tradeoffs between battery health and energy consumption cost in PHEVs. First, optimal power management solutions that minimize energy consumption cost tend to ration battery charge, while the solutions that minimize battery health degradation tend to deplete charge aggressively. Second, solutions that balance the needs for minimum energy cost and maximum battery health tend to aggressively deplete battery charge at high states of charge (SOCs), then blend engine and battery power at lower SOCs. These results provide insight into the fundamental tradeoffs between battery health and energy cost in PHEV power management.

1 INTRODUCTION

This paper investigates supervisory control algorithms that manage the tradeoff between battery pack health and energy consumption cost in plug-in hybrid electric vehicles (PHEVs). This study leverages both stochastic control theory and reduced electrochemical battery models to achieve its goal. Such health-conscious power management algorithms have the potential to increase the useful life and long-term energy capacity of battery packs. This is critically important for large-scale battery energy storage systems - ranging from PHEVs to stationary grid-scale storage - where replacement cost and cycle life are inhibiting factors. This paper's overall goal is therefore to design power management algorithms that manage battery health degradation, in the specific context of PHEVs, in some optimal sense. We pursue this goal specifically for a power-split hybrid configuration with a battery pack consisting of lithium-ion cells. Managing degradation is particularly challenging because the associated mechanisms are typically simulated using computationally intensive electrochemistry-based models that may not be directly conducive to control design. This fact is underscored in the context of the present work, which leverages dynamic programming techniques and the associated "curse of dimensionality". Moreover, PHEV power management is, by itself, a non-trivial problem that requires the solution of an optimal control problem with multiple inputs, stochastic dynamics, state and control constraints. Therefore we extend our previous research on PHEV power management [?] and lithium-ion battery health degradation simulation and model reduction [?] to solve the present problem. The resulting control algorithms tradeoff energy consumption cost with battery life by combining, for the first time, dynamic PHEV models, stochastic drive cycle models, and reduced electrochemical battery degradation models.

Three general categories of research provide the foundation for battery-health conscious hybrid vehicle power management. First, there exists a large body of literature on modeling degradation in lithium-ion batteries, including phenomena

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[*] Address all correspondence to this author.

such as solid electrolyte interface (SEI) film formation, carbon dissolution, electrolyte degradation, and electrode structural distortion. An excellent review by Aurbach surveys these various mechanisms in depth [**?**]. We leverage a model particularly well-suited for model reduction and control applications that accounts for lithium diffusion dynamics, intercalation kinetics, and electrochemical potentials developed by Doyle, Fuller, and Newman [**?**, **?**]. Ramadass *et al.* [**?**] added a degradation component to this model by including an irreversible solvent reduction reaction at the anode-side solid/electrolyte interface that generates a resistive film which consumes cyclable lithium. This mechanism has been identified as one of the chief contributors to capacity and power fade, whose effect is also representative of other mechanisms. The second relevant body of research considers the general HEV power management problem. A broad spectrum of optimal control techniques have been developed to solve the power management problem. Examples include equivalent consumption minimization strategy [**?**], model predictive control [**?**], deterministic dynamic programming [**?**, **?**], and stochastic dynamic programming [**?**, ?]. These strategies are optimized for objectives such as fuel consumption [?, ?, ?, ?, ?], emissions [**?**], drivability [**?**], and/or combined fuel/electricity consumption [?]. Our focus is to apply stochastic dynamic programming with the objective of minimizing anode-side film growth, using a reduced form version of a degrading electrochemical battery model. Several more recent studies have considered the HEV power management problem for extending battery life. These studies focus on depth of discharge control [**?**, **?**], power electronics management [**?**], and temperature management [**?**]. To date, however, no studies have applied models that explicitly account for specific electrochemical degradation mechanisms in the context of an optimal control framework, to the authors' knowledge.

The main goal of this paper is to extend and connect the above research on battery health management and PHEV power management by adding three important and original contributions. First, we directly model daily vehicle trip lengths using a Markov chain with a terminal state, identified from real-world survey data. Second, we formulate a multi-objective optimal control problem that seeks to manage power flow in a power-split PHEV to minimize both health degradation and energy consumption cost. Third, we analyze the interplay between energy consumption cost and battery health degradation to understand the fundamental tradeoffs. The results of this research provide useful insight into health-conscious power management of lithium-ion battery storage systems.

The outline of this paper is as follows: Section 2 describes the model development, including the PHEV model, stochastic drive cycle model, and anode-side film growth model. Section 3 concisely summarizes the optimal control problem formulation. Section 4 presents and discusses the main results, including a tradeoff analysis of battery health and energy consumption cost. Finally, Section 5 summarizes the paper's main contributions and conclusions.