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Long-term assessment of economic plug-in hybrid electric vehicle battery lifetime degradation management through near optimal fuel cell load sharing

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HIGHLIGHTS

- A near-optimal PHEV multi-component degradation management process is proposed.
- A 6 year-long economy-focused PHEV degradation management scenario is solved.
- Battery degradation management is found to be a strong cost reduction mechanism.
- Significant battery lifetime gains between 18 and 41% are achieved.
- Overall long-term PHEV operating costs are improved by a slight 3–6% margin.

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ABSTRACT

This work evaluates the performance of a plug-in hybrid electric vehicle (PHEV) energy management process that relies on the active management of the degradation of its energy carriers – in this scenario, a lithium-ion battery pack and a polymer electrolyte membrane fuel cell (PEMFC) – to produce a near economically-optimal vehicle operating profile over its entire useful lifetime. This solution is obtained through experimentally-supported PHEV models exploited by an optimal discrete dynamic programming (DDP) algorithm designed to efficiently process vehicle usage cycles over an extended timescale. Our results demonstrate the economic and component lifetime gains afforded by our strategy when compared with alternative rule-based PHEV energy management benchmarks.

1. Introduction

Hybrid electric vehicles (HEVs) [1] are the transportation industry's current answer to dwindling fossil fuel reserves, global climate change and the associated economic, social and political complications. Far from being a perfect solution, this electrification of mass transports still requires major breakthroughs in order to compete, both performance [2,3] and economy-wise [4], with the ubiquitous internal combustion engine (ICE). Prominent among these solution's shortcomings is the accelerated degradation their energy carriers, such as lithium-ion batteries [5] and polymer electrolyte membrane fuel cells (PEMFCs) [6], experience when submitted to typical driving conditions, leading to impaired

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performance and hastening their replacement [7]. However, active control methods can act on several degradation mechanisms to reduce this damage; some of which, like controlling battery discharge currents and temperature variations, require the judicious use of systems already on-board most current HEV platforms. Unsurprisingly, each of these countermeasures also implies an additional cost; therefore, it is imperative that these processes are optimized. This paper directly addresses this issue and determines the economic performance of such an optimal process over a long-term horizon representative of a HEV battery pack's entire useful lifetime.

To achieve this, we propose a scenario, detailed in Sections 1.2 and 4.1, in which a PHEV is submitted to a naturalistic 24-h daily driving pattern; during this period, the degradation of this vehicle's batteries and fuel cell, as well as its grid plug-in and fuel expenses, are optimized towards a minimal economic operating cost over the entirety of the pack's lifetime. Using this process, we aim to provide useful contributions to the current body of scientific literature concerned with the dynamics of PHEV component degradation according to specific points of interest:

- A macroscopic approach to PHEV component degradation management that can process the entire useful lifetime of its battery pack within a near-optimal structure.
- The simultaneous inclusion of both battery pack and PEMFC degradation, as well each component's primary energy source, within the same PHEV energy management process.
- Bolster our results by adopting economy-centric optimization criteria, providing easily-interpreted performance gains and incentives for its theoretical application.

This article is structured as follows: the current section presents the background which motivated this research, Section 2 presents the PHEV models built for this experiment, Section 3 explains the optimization strategy and the process' overall structure, Section 4 discusses the comparative results obtained from our method's application and Section 5 concludes on our findings.

1.1. Background overview

Battery degradation has been the subject of much interest from a modeling standpoint [8–12] but is still seldom found in HEV energy management endeavors. Recent efforts represent their progression as a side-effect of other objectives such as autonomy extension [13] or for broad economic predictions [14]. Studies directly addressing battery degradation in HEVs include stochastic control-based studies [15], switching algorithm development [16] and vehicle-to-grid concerns [17]. Among the few optimization solutions focused on battery degradation proposed [18], discrete dynamic programming (DDP) has proven to be a well-suited tool [19]. PEMFC degradation follows a similar trend, with a large body of work available on modeling [20–23] but few direct applications within HEV management [24,25]. To the authors' knowledge, few efforts that combine the degradation of both batteries and PEMFCs in an HEV-related context have been published; the same holds true when optimal control of such a system is concerned. Practical remedies to alleviate battery degradation include simple rule-based control schemes [26] or use oversized battery packs [27]. Available research that does include some of the above parameters are conducted on short timescales [28], typically over a single standard driving cycle [29] or a few virtual days [30]. Average HEV batteries degrade over several years' time [8], while PEMFCs operate for several thousand hours [22] until end-of-life (*EoL*) conditions are reached; linear extrapolation from short-sighted data sets over long-term horizons offers questionable results given the continuous degenerative nature of degradation phenomena. Previously-published research from our team has addressed the degradation management issue in various capacities, such as the influence of degrading component cost fluctuations on their economical management [31], their characterization aboard a low-speed PHEV platform [32] and the results of high-resolution control over optimal battery degradation-focused recharge [33].

1.2. Problem statement

We consider a fully charged and fueled mid-sized PHEV, including a lithium-ion battery pack as well as a PEMFC, submitted to a repeating daily driving load. This unchecked usage pattern entails significant degradation of the battery pack, which can be mitigated via load sharing using its on-board hydrogen-fueled PEMFC. We propose an economy-centric management approach to resolve this issue and therefore aim to optimize the operating costs of said vehicle over the entire lifetime of its battery pack, while simultaneously:

- Minimizing the total operating cost of the PHEV by balancing the expenses from battery and fuel cell degradation, hydrogen fuel and grid recharge.
- Extend the battery pack and fuel cell's useful lifetime.
- Provide sufficient flexibility and computational efficiency to allow for such a large-scale optimization.

This work achieves these objectives by running PHEV models through our DDP optimization process' repeating, cumulative cycling as described in Section 3. This process is further repeated until battery *EoL* conditions are reached, thus applying our energy management strategy and monitoring its long-term development over the entirety of the PHEV's battery pack's lifetime. The methodology proposed here is designed as a simulation-based predictive tool; direct practical application will require an entirely different approach that is outside the scope of this article. Our results demonstrate the economical and component lifetime gains achieved in both short and long-term timescales, as well as insights into the dynamics at play within the proposed PHEV management strategy.

2. PHEV models

This section describes each of the numerical models used by the proposed optimization strategy. The basis for the mechanical PHEV model used in this research was patterned after the commercially available Chevrolet Volt [34]. To suit our degradation-centric purposes, its battery pack chemistry was adapted to exploit available $LiFeMnPO_4$ experimental data from our lab; it also uses a PEMFC as a secondary generator instead of its standard ICE-based engine. This is done specifically to include its degradation in our study. Nevertheless, our focus on battery degradation management motivated our choice towards a configuration involving a large battery pack supported by a smaller secondary generator (as it is found aboard the Chevrolet Volt [34]), as opposed to a full-sized fuel cell hybrid vehicle. This PHEV's general specifications are found in Table 1.

2.1. Energy balance

To properly define an energy management strategy, it is imperative to establish the relationship between each energy-processing component (1) found within the PHEV's series-configured [1] architecture.