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Optimal economy-based battery degradation management dynamics for fuel-cell plug-in hybrid electric vehicles

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HIGHLIGHTS

- The design of an economy-based battery degradation management process for PHEVs.
- A sensitivity study of this process to the cost fluctuations of its energy carriers.
- An extension of proven modeling techniques used for battery degradation prediction.
- An argument for the relevance of inexpensive battery technologies aboard PHEVs.

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ABSTRACT

This work analyses the economical dynamics of an optimized battery degradation management strategy intended for plug-in hybrid electric vehicles (PHEVs) with consideration given to low-cost technologies, such as lead-acid batteries. The optimal management algorithm described herein is based on discrete dynamic programming theory (DDP) and was designed for the purpose of PHEV battery degradation management; its operation relies on simulation models using data obtained experimentally on a physical PHEV platform. These tools are first used to define an optimal management strategy according to the economical weights of PHEV battery degradation and the secondary energy carriers spent to manage its deleterious effects. We then conduct a sensitivity study of the proposed optimization process to the fluctuating economic parameters associated with the fuel and energy costs involved in the degradation management process. Results demonstrate the influence of each parameter on the process's response, including daily total operating costs and expected battery lifetime, as well as establish boundaries for useful application of the method; in addition, they provide a case for the relevance of inexpensive battery technologies, such as lead-acid batteries, for economy-centric PHEV applications where battery degradation is a major concern.

1. Introduction

Electrochemical batteries will be a lynchpin of the next global energy economy, in large part because of the shift away from the rapidly depleting fossil fuels reserves towards cleaner, more efficient energy carriers. However, current battery technology is still far from meeting this challenge; chief among their shortcomings is the decay of their electrochemical components, which results a limited lifespan. While this is a behavior shared with most similar systems, it is especially acute given the harsh operating conditions found aboard a hybrid electric vehicle (HEV). As such, it is necessary to develop effective means to manage this degradation if successful transition to electric modes of transportation is to be achieved.

This paper proposes a study on the economical dynamics of battery degradation management aboard HEVs. It is built upon numerical models validated via a physical plug-in hybrid electric vehicle (PHEV) platform; at the core of these models is a battery pack, which was enhanced to include its major degradation mechanisms. An optimization algorithm was designed using discrete dynamic programming theory (DDP) to determine an optimal strategy for operating a multi-source PHEV at minimum financial cost when battery degradation is considered. We further explore the response of such a process to the fluctuating economic parameters represented by its fuel and energy carriers.

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1.1. Literary review

This paper builds upon previous work by the author [1,2], in the hybrid electric vehicle domain; its main focal points can be summed up by the following three areas of research.

1.1.1. Electrochemical battery modeling

The economic focus of this work guided our attention to inexpensive battery technologies, such as lead-acid batteries: as one of the more mature technologies available [3], their degradation is also better understood. Lead-acid batteries have received less attention [4], since most “modern” chemistries outperform their lead-acid counterparts in every area [5], with the exception of their low cost [6] and small environmental footprint [7], which justify their market share on par with lithium-ion batteries [8]. A strong case has been made that these seemingly outdated devices remain competitive in many realms of development [9–12], and may even prove to be a key player in the future of HEVs [13].

Battery models can be divided into three general sub-groups [14]. *Electrochemical* models aim to reproduce the chemical interactions occurring at the batteries' core [15] through various means [16–18]. While these can provide a great level of precision, they are typically too computationally-demanding to be directly applicable to optimal control design [19]. *Mathematical* models, on the other hand, reduce the complexities of battery chemistry to simple generic equations [20–22]. These typically offer fast computing times, but are ill-suited to represent dynamic battery behavior [20]. The *equivalent circuit* approach represents battery behavior as an idealized electric circuit [23] and have demonstrated accurate simulation of complex battery dynamics [24], are easily characterized [25], adaptable [26] and demand manageable computing times [27], all of which agree with our design goals.

1.1.2. Battery degradation modeling

Battery degradation modeling has evolved independently from classic battery modeling: battery electrical behavior is well-understood, their degradation is not [28]. The numerous mechanisms governing battery degradation are complex, non-linear and strongly interrelated [29]; moreover, they occur slowly and are sensitive to their operating conditions [30], making their practical analysis difficult. Promising solutions have been proposed to predict battery degradation, [30–38], though literature still does not provide a single, all-encompassing degradation model. We propose an amalgam of models, each based on proven techniques [30,32,33,39] adapted to use available experimental degradation data [39–42] to suit the particularities of this work.

1.1.3. HEV power management

HEV power management combines multiple energy carriers to achieve efficient mobility [43]. Proposed methods to achieve this goal include a wide range of numerical techniques [44–49]; each revolves around a precise objective [50–53]. Furthermore, if *a priori* knowledge of vehicle driving loads is available, dynamic programming [54,55], can be used as an effective tool, which we chose for the task. Regardless of the technique, significant inclusion of battery degradation within PHEV power management strategies is still uncommon [56].

1.2. Problem statement

Consider a light-duty PHEV built in a series architecture [57]. This vehicle's main energy carrier is a rechargeable battery pack of sufficient capacity to complete a known driving load; recharge is available through public grid plug-in when the vehicle is stationary. It is well-established that batteries degrade faster according to specific operating conditions, such as their depth-of-discharge (DOD)/state-of-charge (SOC) and repetitive charge/discharge cycling. Our hypothesis it that we can define an economically-advantageous recharge schedule that will maintain battery DOD at optimal levels to reduce this costly degradation. To achieve this goal, the vehicle features a hydrogen-powered polymer electrolyte membrane fuel cell (PEMFC), which can assist the battery pack at any given time and in varying amounts. This component was chosen to reinforce our hypothesis: we believe that the economic impacts of battery degradation are significant enough to warrant active management even when inexpensive batteries are weighed against an expensive fuel such as hydrogen.

Given the above conditions, we seek to define an optimal battery charging schedule using the on-board PEMFC over a day-long driving cycle, while simultaneously minimizing the PHEV's overall operating cost generated by:

1) Expenses from spent hydrogen fuel,
2) Post-cycle public grid recharge costs,
3) Degradation of the battery pack and the cost of its eventual replacement.

Because of a) the batteries' sufficient capacity to complete the driving cycle on their own and b) the relative cheapness of public-grid recharge vs. hydrogen fuel, additional fuel is expected to be used solely to manage the costs incurred by battery degradation. Since the optimal solution is focused on economic performance, this paper proposes a sensitivity study of the proposed optimal process to its fluctuating cost parameters; its goal is to validate the economic viability of the proposed solution, to evaluate the range within which its application is non-trivial and to analyze the relative influence of each individual economic parameter on its outcome.

1.3. Core contributions

This work utilizes two intertwined battery models that are validated according to lead-acid battery chemistry; its degradation model, in particular, is an original extension based on proven designs. Those are backed by original experimental data, and include a broad spectrum of parameters such as gradual performance losses and lifetime prediction. Such batteries have received little attention where PHEVs are concerned. Some literature does suggest that they could remain contenders in this arena: the results of this paper agree with those claims. As such, we provide an argument in favor of their inclusion within economical PHEV applications. The present article uses tools developed for PHEV simulation to explore the sensitivity of an optimal battery degradation management strategy to the fluctuating costs of its energy carriers. Such a degradation-focused strategy is uncommon in literature, as is the study of the dynamics caused by economic variations on such a process.

1.4. Article outline

This paper is split into the following 8 sections. Section 2 will address everything related to numerical modeling, including PHEV components and the battery electrical model; Section 3 will cover the proposed battery degradation model in detail. Section 4 will provide experimental validation for the presented models. Section 5 is concerned with the optimization process. Sections 6 and 7 will respectively provide simulation results and their analysis, while Section 8 will summarize said findings and conclude the article.