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Simulation Framework for the Optimization of HEV Design Parameters: Incorporating Battery Degradation in a Lifecycle Economic Analysis

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Abstract: The optimal design of hybrid electric vehicle powertrains from a systems perspective is critical to realize the maximum benefits of hybridization for a given application, especially in the heavy-duty vehicle space due to the large number of unique applications. This paper proposes a novel framework that enables parametric design optimization of hybrid electric vehicles while accounting for the degradation of the electric battery and its impact over the lifecycle of the vehicle. This framework captures the impact of battery degradation on fuel consumption and battery replacement over the vehicle life by integrating a battery model capable of predicting degradation, and degraded performance, into the drivecycle simulation. These results are incorporated into a lifecycle economic analysis that enables the use of specific economic metrics (including net present value, payback period, and internal rate of return) as optimization objectives. To demonstrate the framework, the electric motor and battery sizes are optimized for a North American transit bus application. The results show that the optimal component sizes depend on the metric of interest, i.e. different optimum parameter sets are obtained when the objective is different. Further, these optimum parameter sets are different if the objective is simply the "day 1" fuel consumption. For example, while optimizing for fuel consumption leads to selection of the largest available battery pack and electric motor, optimizing for payback period leads to the selection of a smaller battery back. Lastly it was also observed that the fuel consumption increases by up to 10% from "day 1" to End-of-Life of the battery. These results highlight the utility of the proposed framework in enabling better design decisions as compared to methods that do not capture the evolution of vehicle performance and fuel consumption as the battery degrades.

Keywords: Hybrid electric vehicles, powertrain simulation, battery life, design optimization.

1. INTRODUCTION

Hybrid electric vehicles (HEVs) can provide a significant improvement in fuel economy over conventional vehicles powered only by an internal combustion engine (ICE). To realize the maximum fuel economy benefit it is critical to optimally size the powertrain components and tune the power-management strategy for the specific application. A significant number of studies have tackled this problem with varying scope and focus areas.

(Rousseau et al. 2008) demonstrated the use of the DIRECT (DIviding RECTangles) algorithm to optimize the parameters of a rule-based power management strategy for a parallel Plug-in Hybrid Electric Vehicle (PHEV). (Patil et al. 2013) used a sequential approach to first optimally size the electric motor and battery for a series PHEV to meet a certain All-Electric Range (AER) and then size the engine for maximum fuel economy with the selected motor and battery size.

In the medium/heavy duty vehicle space a detailed design study of a medium-duty military vehicle was presented with a sequential methodology for the simultaneous optimization of design and control parameters (Filipi et al. 2004). Various sizing methodologies for different medium/heavy duty HEV applications have been proposed in (Fauvel et al. 2012).

The studies cited above do not consider the degradation of the battery. Optimizing HEV design and controls to extend battery life is a critical challenge as battery replacement adds a significant cost to the HEV value proposition. This is especially true in the heavy-duty vehicle space where vehicle power demand can be high, applications are diverse and customers' appetite for risky investments is lower.

(Smith et al. 2012) motivated the opportunity for battery life extending control by demonstrating varying degradation rates with varying duty cycles using semi-empirical battery degradation models. (Masih-Tehrani et al. 2013) proposed a method to optimally size and control a hybrid energy storage system consisting of a Li-ion battery and a super-capacitor pack for a series HEV transit bus, to extend the life of the Li-ion battery. (Kim et al. 2012) have proposed a frequency domain power distribution strategy to mitigate soot emissions

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and extend battery life. (Hu et al. 2015) apply convex optimization to the sizing and energy management problem while accounting for battery life for a fuel cell hybrid bus.

The battery models used in the above studies are of the equivalent circuit type, and are used in conjunction with semi-empirical degradation models fit to experimental data. A key gap in previous studies however, that this paper aims to address, is the incorporation of battery degradation impact on vehicle fuel consumption, and lifecycle cost, during life of the vehicle. While past studies have considered Net Present Value (NPV) over the lifecycle as an objective for optimization (Vijayagopal et al. 2010) the vehicle model itself is considered to remain the same over the entire life of the vehicle. In reality, as the battery approaches the end of its useful life there will be an increase in the fuel consumption of the ICE as well. In addition, as the battery ages, the input/output power history for the battery will change, resulting in aging progression that is different from the case in which the “day 1” power profile is assumed.

This paper proposes a simulation framework wherein the vehicle model is simulated in conjunction with a physics-based electrochemical battery model over the entire operational life of the vehicle. This allows for the prediction of the increasing fuel consumption as the battery degrades as well as prediction of battery replacement. Further, these simulation results are incorporated into a lifecycle economic analysis that allows for optimization of a specific financial metric such as NPV or payback period. This framework enables a more accurate analysis of the impact of design and control decisions on the value proposition of a HEV, especially when comparing it with different powertrain options such as a conventional or hydraulic hybrid powertrain. To demonstrate the utility of such a framework the North American urban transit bus application (parallel HEV, Manhattan drivecycle) is considered in this paper.

The paper is organized as follows: first the models used for Li-ion battery simulation, HEV powertrain simulation and power management are described. Next the simulation procedure and the economic calculations are described. Then the results of an example demonstration of this framework to optimize the electric motor and energy storage system (ESS) size for a transit bus are discussed and the insights gained through this approach are highlighted. The paper concludes with possible extensions of this work.

2. MODELS

2.1 Li-ion Battery Model

To simulate the battery pack the AutoLion-ST software from EC Power is chosen as it offers a physics-based 1-d electrochemical cell model which can be extended to various battery chemistries. However the framework proposed here is not limited to this specific battery model. Any battery model can be used that is capable of predicting the degradation of the cells and change in the dynamic response of the cells as a function of this degradation.

This model captures the nonlinear electrochemical dynamics of Li-ion transfer in a cell, including diffusion in the solid-state electrode, electrochemical reaction at the electrode-electrolyte interface, and transport through diffusion and ionic conduction in the liquid-phase electrolyte (Smith et al. 2007). The model also captures the two primary degradation mechanisms observed in Li-ion batteries:

1. Growth of Solid-Electrolyte Interface (SEI) layer: This has a direct impact on the internal resistance of the cell.
2. Loss of active material: This has a direct impact on the usable energy capacity of the cell.

(EC Power LLC 2014; Smith et al. 2007) list the governing equations describing the electrochemical model.

A Lithium Ferrous Phosphate (LFP) cell is chosen as it is a popular choice in current production vehicles and the AutoLion-ST software includes a characterized model of this cell. The ESS specifications are listed in *Table 1*.

Table 1. ESS nominal specifications

Parameter	Value
Cell capacity	4.4 Ah
No. of cells in parallel	4
No. of cells in series	100
V_{NOM} (Nominal Cell Voltage)	3.3 V
V_{MAX} (Maximum Cell Voltage)	3.6 V
V_{MIN} (Minimum Cell Voltage)	2.8 V
End-of-life criteria for ESS capacity fade	35 %

Based on the instantaneous open circuit voltage V_{OC}, terminal voltage V_T and battery current I_T, an effective internal resistance is dynamically estimated as follows:

$$R_{INT} = \frac{V_{OC} - V_T}{I_T} \tag{1}$$

This effective resistance is used by the battery management system (BMS) to impose charge/discharge power limits:

$$P_{MAX\_DIS} = \frac{(V_{OC} - V_{MIN}) * V_{MIN}}{R_{INT}} \tag{2}$$

$$P_{MAX\_CHG} = \frac{(V_{MAX} - V_{OC}) * V_{MAX}}{R_{INT}} \tag{3}$$

where, V_{MAX} & V_{MIN} are BMS control parameters that represent the maximum and minimum voltage allowed at the cell terminals during charging and discharging respectively.