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On power denials and lost energy opportunities in downsizing battery packs in hybrid electric vehicles

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ABSTRACT

This paper provides a methodology and identifies opportunities for battery pack downsizing in a hybrid electric vehicle (HEV). A new term of power denial and a new metric of lost energy opportunities are introduced and analyzed in addition to utilization, temperature, life, and cost. A model-based power limiting algorithm is used in computing real-time power capability of the battery. The downsized pack with a shifted SOC window is evaluated in a light-duty HEV. A parameterized electro-thermal model is used to capture voltage, state-of-charge, and temperature. A semi-empirical ageing model is integrated to predict the capacity loss and resistance increase of the downsized pack. The battery ageing model is developed based on a set of experiments carefully designed to clarify the influence of operating SOC on battery degradation. The parametric study shows that the number of cells in the pack could be reduced from 76 to 64 while shifting nominal operating SOC from 50% to 35% without changing the pack energy throughput. This would result in a 19% increase in energy utilization per cell, a 0.5% increase in capacity fade and a 2.9% increase in internal resistance, while the pack cost will be reduced by 10%.

1. Introduction

Hybrid electric vehicle (HEV) manufacturers seek to reduce the weight and cost of their vehicles to gain competitive advantage. While the battery cost is projected to decrease in terms of energy density, high power batteries for HEV are still more costly than electric vehicle (EV) batteries per kWh due to material costs and increased current carrying requirements for the cell tabbing. Therefore, sizing battery packs is still very important for hybrid electric vehicle design.

Studies on the downsizing and its associated cost and fuel consumption have been addressed in literature [1–5]. As illustrated Fig. 1, battery downsizing will increase each cell's power demand, potentially reaching the operational limits more often. In optimization or parametric studies on component sizing, simple powertrain models are typically considered; particularly, power limits (or power capability) of a battery are assumed constant or computed based on the Partnership for a New Generation of Vehicles (PNGV), Hybrid Pulse Power Characterization (HPPC) method.[1] However, the computed power limits using these approaches are overly conservative relative to the instantaneous power limits. Since the internal resistances are typically parameterized using a 10 s current pulse.

Much effort has been documented in [6–10] to accurately compute the power capability of batteries in real-time, while considering the electrical, electrochemical, and thermal constraints such as terminal voltage, battery SOC, local over potential due to Li-ion concentration, and temperature. Motivated by cost reduction, the inherent safety of a model-based power limiting algorithm allows for a less conservative pack design and ultimately fewer or smaller cells. Thus, unlike approaches in literature where the emphasis on downsizing is focused on an engine, this paper focuses on a battery, more specifically, identifying opportunities of further battery pack downsizing in consideration of a model-based power limiting algorithm in [10].

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[1] The PNGV HPPC method, developed by Idaho National Engineering and Environmental Laboratory, computes the instantaneous pulse power capability of a battery using an internal resistance, its open-circuit voltage, and predetermined current/voltage limits.

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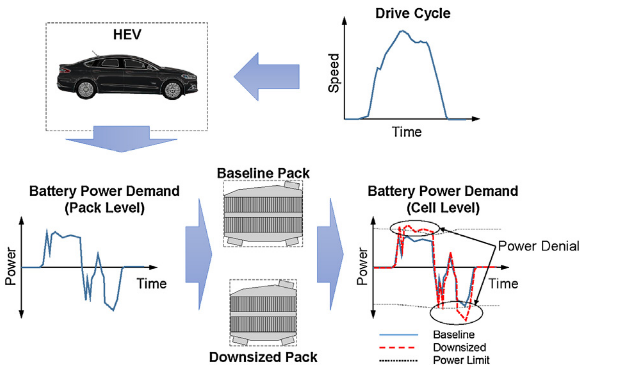

Fig. 1. A schematic diagram showing the approach considered to investigate the impact of battery downsizing on battery power demand at cell-level.

More importantly, the battery power limits, or discharge and charge energy capabilities depend on the nominal SOC operating window. In most commercial HEVs, the nominal SOC operation is centered around 50%, or higher, which allows for increased discharge power capabilities and battery efficiencies [11]. The size of the pack is defined by the discharge power at cold condition and therefore, at a high nominal operating SOC, the lower range of the SOC will rarely be used. This leads to an oversized or poorly utilized pack. Realization of this asymmetric battery use motivates a new approach to analyze battery performance (e.g., utilization, temperature, life and cost) associated with pack downsizing and with shifting operating SOC window using dynamic models and a predictive battery management technique.

For battery performance analysis, it is essential to capture dynamic behaviors of a battery such as terminal voltage, battery state-of-charge (SOC), temperature, and capacity loss and resistance increase from ageing. Thus, an equivalent-circuit model, a lumped thermal capacitance model [12], and a semi-empirical ageing model [13] are adopted in this work. Particularly, the battery ageing model is parameterized using a set of experiments that highlight the influence of nominal operating SOC on degradation as shown in Fig. 2. The model in [13] was parameterized for a plug-in hybrid electric vehicle (PHEV) for SOCs between 25% and 45%. The experiments in this paper extend the SOC nominal operation to 66%. The results show that operating at low SOC range presents an opportunity for reduced ageing, but it requires tighter control with higher possibility for exceeding power limits.

For the cost analysis, Argonne National Laboratory's Battery Performance and Cost (BatPaC) model is used. The BatPaC model provides cost estimates based on materials and cell/pack design and hence it has been used for cost analysis in literature [14–17].

In investigating a battery pack downsizing, an actual current profile from the battery pack equipped from a light duty vehicle HEV is used. The profile assumes a fixed engine and vehicle power management and is scaled as number of cells is changed to match the total power demanded or supplied.

The main contribution of this paper is to develop a methodology for identifying downsizing opportunities for a battery pack. To that end, the new term of power denial and the new metric of lost energy opportunity (LEO) associated with the power denial are introduced and analyzed in addition to utilization, temperature, life and cost. Here, the term *power denial* refers to a battery power request greater than the limit set by a power capability prediction algorithm as shown in Fig. 1.[2] In computing real-time power

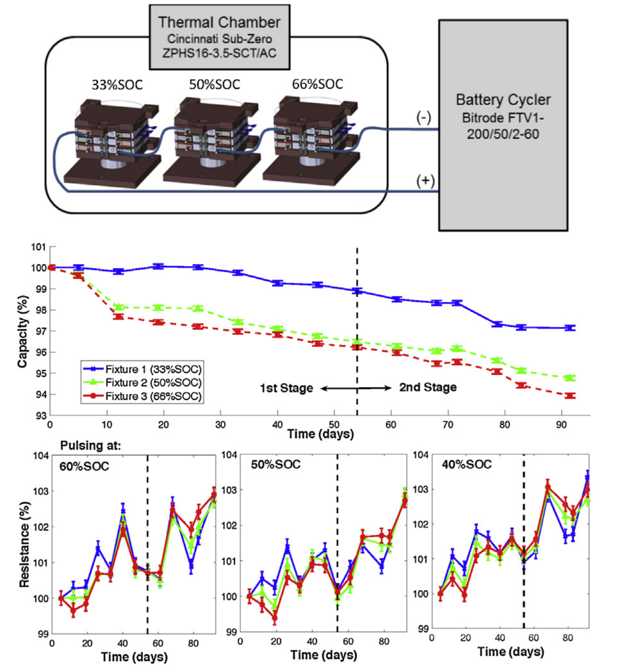

Fig. 2. Setup and results of experimental capacity fade and resistance increase testing at different SOCs.

capability of a battery, a model-based power limiting algorithm is used instead of the PNGV method to include the impact of polarization voltage dynamics on the power limits. This approach allows to further investigate the impact of nominal operating SOC on battery performance. The parametric study in this work shows that the battery pack under consideration can be scaled down from 76 to 64 cells without experiencing any discharge or charge power denials when nominal operating SOC is shifted from 50% to 35% at an ambient temperature of 25 °C. As a result of the downsizing, each cell in the pack would experience a 19% increase in energy utilization with only a 0.5% capacity fade increase and a 2.9% increase in resistance. In this case, the total cost of the battery pack would be decrease by 10%. This paper is based upon the preliminary work presented in [18]. It extends on the work in [18] by including a more detailed description of the experimental set-up and results about an increased internal resistance of the battery as a consequence of degradation. Moreover, in battery simulation, both the capacity fade and resistance increase are considered to compute power limits of the battery. Lastly, the associated cost benefit and accelerated warmup through battery downsizing are also analyzed.

The paper is organized as follows: Section 3 describes the dynamic models to capture electro-thermal behavior, capacity fade and resistance increase of the battery used in this study. A Model-based power limiting algorithm is briefly presented in the following section, and the cost model is shown in the last part of Section 3. In Section 4, simulation results are presented and discussed. Specifically in Section 5, various battery performance metrics are studied as design (number of cells in a battery pack) and operation (nominal SOC, SOC_0) change under the model-based power limiting approach. Finally, Section 6 concludes the paper with a summary of contributions and with a discussion on future extensions.

2. Hybrid electric vehicle system

The power-split of the considered LD HEV is realized by a planetary gear (PG) system consisting of a ring gear, a sun gear, and

[2] It is noted that power limits shown in this figure are for illustrative purposes. Those limits are generally dependent on battery states such as SOC and temperature.