

Optimal Supervisory Control of the Series HEV with Consideration of Temperature Effects on Battery Fading and Cooling Loss

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ABSTRACT

This paper develops a methodology to optimize the supervisory controller for a heavy-duty series hybrid electric vehicle, with consideration of battery aging and cooling loss. Electrochemistry-based battery aging model is integrated into vehicle model. The side reaction, reductive electrolyte decomposition, is modeled to determine battery aging rate, and the thermal effect on this reaction rate is considered by Arrhenius Law. The resulting capacity and power fading is included in the system-level study. Sensitivity analysis shows that battery aging could cause fuel economy loss by 5.9%, and increasing temperature could improve fuel economy at any given state-of-health, while accelerating battery aging. Stochastic dynamic programming algorithm is applied to a modeled system to handle the tradeoff between two objectives: maximizing fuel economy and minimizing battery aging. The strategy developed by the stochastic dynamic programming improves fuel economy by 8%, and reduces the lithium ion loss by 17% after 9e3 cycles.

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INTRODUCTION

New regulations for improving fuel economy and reducing carbon dioxide spur development of advanced powertrain technologies, and hybridization provides one of the most viable pathways. The main mechanisms of improving fuel economy with hybridization include: braking energy regeneration, engine down-sizing, and optimization of engine operation. In particular, a series hybrid electric vehicle (S-HEV) offers ultimate freedom in controlling engine operation, and maximum regeneration capability due to generous size of traction motor(s). Other attributes may be important in specialized applications, such as export power, high mobility and flexibility in packaging.

However, applying the S-HEV concept to heavy-duty vehicles brings about specific challenges. Aggressive driving missions impose severe load cycles on battery pack, and this can lead to two issues. Firstly, heavily dynamic load cycles with elevated temperature accelerate battery aging; thus reducing vehicle performance, but also introducing the replacement cost. Battery pack is often oversized in order to meet the performance requirement of the worst-case duty cycles even the end of battery life, and this comes with the weight and cost penalty. Secondly, battery generates large amount of heat under usage, and the heat accumulation can cause battery fire or explosion. Therefore, requirement for safe operation in extreme ambient conditions mandates the application of a refrigerant-based cooling, and this introduces additional parasitic losses. Issues described above create impetus for this work.

This study aims to address battery aging and cooling loss in the optimization of supervisory control strategy. In our previous work

[1], the auxiliary power consumption from battery cooling system was found to impose significant penalty on fuel economy, and optimization algorithm was able to reduce this penalty by coordinating the power system and cooling system. In this study we further integrate the impact of battery aging, and consider increasing battery lifespan as additional objective. Predictive, and yet computationally efficient battery aging model integrated into the complete S-HEV vehicle is developed first, and an optimization algorithm is setup to consider two objectives: minimization of both fuel consumption and battery aging.

Supervisory controller is critical for achieving the potential benefits of hybrids. A significant body of work on supervisory control has been published. Early work proposed the heuristic-based strategies [2,3,4] that highly relies on engineers' intuition. It is practical to implement, but requires complex parameter tuning process, and may have poor performance under some driving conditions. Instead, optimization algorithms can search the optimal strategy in systematic way. One of the best known off-line optimization approach is deterministic dynamic programming (DDP) [5,6,7,8,9]. With the whole driving mission as a prior knowledge, the algorithm provides the optimal benchmark. However, it is cycle dependent, and hence cannot be implemented directly for real-time control. Sub-optimal but real-time implementable strategies include stochastic dynamic programming (SDP) [10,11,12,13,14], model predictive control (MPC) strategy [15], equivalent consumption minimization strategy (ECMS) [16,17,18,19,20,21], and Pontryagin's Minimum Principle (PMP) [22,23,24,25]. Johri et al. [26, 27] proposed neuro dynamic programming and applied it to hybrid hydraulic powertrain system to solve large state-action problem with multiple objectives.

Most of the optimal control algorithms focus on minimizing fuel consumption as a sole objective. More recently, additional objective of reducing pollutant emissions has been studied by [8, 11, 20, 26, 27]. Extending battery lifespan was considered as additional objective by [7, 14, 23, 24, 25]. In these studies, the equivalent circuit model coupled with Ah-throughput aging model was included into the optimization of supervisory control. The Ah-throughput model is an empirical approach, easy to implement and computationally efficient. However, it requires large amount of lifetime measurements, and it cannot be extended to predict the conditions that are not measured. In addition, the temperature impact on battery aging rate and battery thermal management has not been considered.

In this paper, we develop a framework for optimizing S-HEV supervisory control considering two objectives, namely fuel consumption and battery aging. Impact of the duty cycle on the aging process is quantified by integrating an electrochemical model of battery fading into the vehicle simulation. The main contributions of the study are: (i) integration of the electrochemical battery aging model and refrigerant-based cooling model into the SHEV powertrain system, (ii) quantification of battery aging and its impact on vehicle fuel economy, and (iii) methodology for applying the Stochastic Dynamic Programming (SDP) for optimization of the S-HEV powertrain supervisory controller, with the goal of improving fuel economy and extending battery life. Full electrochemistry model is used for a sensitivity study, but the key effects are subsequently captured with a static map to speed up optimization calculations.

The paper is organized as follows. Next section describes vehicle configuration and the integrated simulation framework. Section 3 introduces the baseline strategy, thermostatic SOC control, coupled with thermal management strategy. Section 4 presents the battery model, and analyzes the impact of battery aging on system efficiency. Section 5 proposes the methodology to optimize the supervisory controller using SDP and a cost function that captures both fuel consumption and battery fading. This is followed by a presentation and discussion of results. The paper ends with conclusion and suggestions for future work.

VEHICLE CONFIGURATION AND SIMULATION TOOL

This study focuses on the off-road series hybrid electric truck with four in-hub motors. S-HEVs offer great potential for reducing fuel consumption, improving packaging efficiency, extending silent operation, and providing onboard power [28]. Figure 1 shows the power flow diagram in our S-HEV system. The primary power source is the power pack consisting of internal combustion engine coupled with a generator. Thus, the engine has no mechanical connection with wheels, and there is full flexibility in engine operation control. Battery provides bidirectional power flow, and the cooling system keeps the battery pack within desired temperature range. Four in-hub electric motors are incorporated into wheels and provide traction power exclusively. During braking, electric motors work as generators and convert braking power to electric power. All power

flows are integrated via a powerbus. Supervisory controller aims to control the power flow in the system. It receives driver's command, and sends commands to all components based the embedded supervisory control strategy. Table 1 shows the vehicle specifications. Powertrain is designed to provide outstanding mobility and satisfy duty cycles under extreme ambient conditions.

This simulation is based on Matlab/Amesim co-simulation. Figure 2 shows the integrated model of S-HEV powertrain system. The integrated simulation framework integrates models of key components, including engine/generator, driver, battery, and emotores. The battery thermal submodel is a lumped-parameter thermal model introduced by Forgez et al [29]. It is described by two states, battery core temperature and heat removed by circulating air, and then rejected to surroundings by the refrigeration-based cooling system. In the cooling model, the compressor and air fan consume power, and this is considered in addition to vehicle propulsion requirement.

The electrochemical aging model of LiFePO₄-Graphite Li-Ion battery is based on work by Prada et al [30]. The reductive electrolyte decomposition on negative electrode is considered as the major source of aging, with irreversible lithium ion losses. The decomposition product builds up a solid electrolyte interphase film (SEI) that covers the electrode surface, and the growth of SEI film increases internal resistance. The thermal effect on battery aging rate is modeled by Arrhenius law [30]. In this work, the partial differential equations of lithium ions concentration are solved by finite difference method explicitly. No side reaction is considered in positive electrode, due to the stabilization of LiFePO₄ material, and the negative impact under cold temperature or battery aging during storage is not covered in this study. Battery aging model was tested under dynamic load cycles [30], and hence enables accurate prediction of battery aging with the command from series HEV supervisory control.

The fully integrated S-HEV model enables quantification of battery aging process and the thermal impact on both battery aging rate and system efficiency. At the same time, it achieves fast computation for system-level analysis.

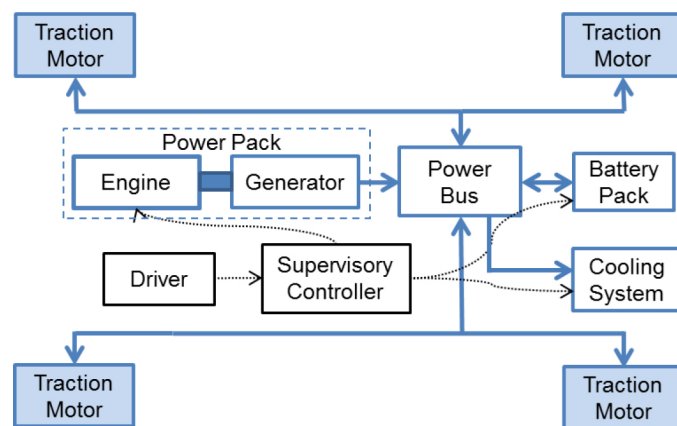


Figure 1. Series HEV powertrain configuration. Blue solid lines show the power flow, and black dot lines show the control signal flow.

Table 1. Series HEV Specifications.

Component	Specification
Vehicle	Hybridized mid-size Truck
Vehicle Weight	14,000kg
Frontal Area	5.72 m ² (Width/Height: 2.49/2.7 m)
Engine	I8 Turbo-Diesel Engine: 330 kW
Generator	Permanent Magnet: 330 kW
Battery	Li-ion Battery Pack: 9 kWh
Motors	Permanent Magnet: 4*95 kW (Continuous)

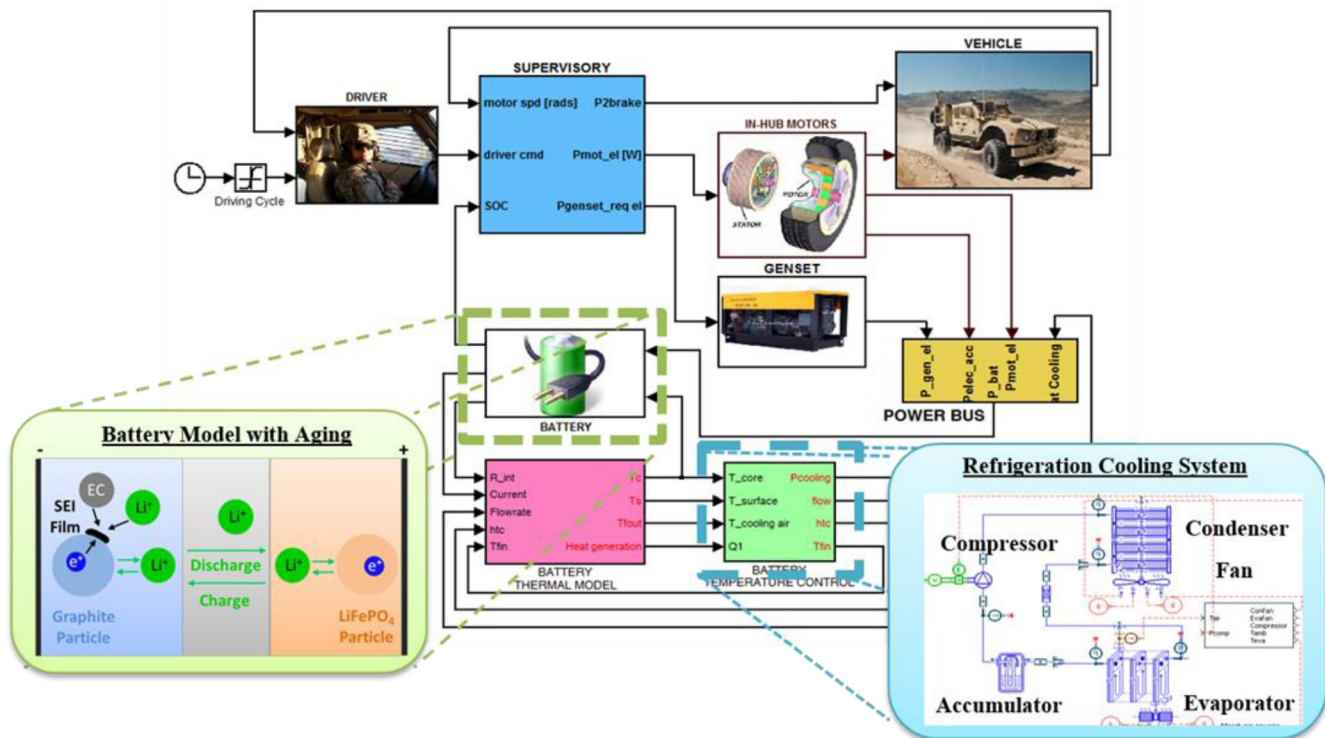


Figure 2. Integrated S-HEV Powertrain System Simulation Framework

BASLINE SUPERVISORY CONTROL STRATEGY

The section presents the baseline control strategy, and it is used for analyzing the impact of battery aging on powertrain system. In the baseline strategy, the control of power system and cooling system is designed separately. The power pack is controlled by the Thermostatic SOC control strategy, a typical heuristic power management strategy for S-HEVs. It is robust and effective in sustaining battery state of charge (SOC), and it is combined with rules that keep engine/generator operation on the best efficiency line.

Figure 3 shows the thermostatic control logic: the power command is the desired electric power output of the engine-generator power pack; it is a function of battery state of charge (SOC). When SOC decreases below the low threshold (Target SOC), threshold power command is sent to the power-pack to prevent further SOC drop. If the vehicle power demand is higher and the SOC keeps dropping below SOCthreshold the engine power command linearly increases up to the

maximum output power. As SOC restores and rises above the high threshold (Target SOC+Deadband), engine is turned off or commanded to idle. The dead band is designed to avoid frequent engine shut-downs when power demand is fluctuating. To protect battery health, engine also turns on whenever the vehicle power demand exceeds battery discharging limit.

The power-pack desired operation points are determined by the analysis of combined BSFC map (shown in Figure 4). Combined BSFC is defined in equation(1); it combines the engine fuel efficiency and generator efficiency (η_g).

$$BSFC_{comb} = \frac{\dot{m}_{fuel}(g/h)}{P_e(kW) \cdot \eta_g} \quad (1)$$

where P_e is engine power and $\dot{m}_{fuel}$ is the fuel rate