

The Model Integration and Hardware-in-the-Loop (HiL) Simulation Design for the Analysis of a Power-Split Hybrid Electric Vehicle with Electrochemical Battery Model

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ABSTRACT

This paper studies the hardware-in-the-loop (HiL) design of a power-split hybrid electric vehicle (HEV) for the research of HEV lithiumion battery aging. In this paper, an electrochemical model of a lithium-ion battery pack with the characteristics of battery aging is built and integrated into the vehicle model of Autonomie® software from Argonne National Laboratory. The vehicle model, together with the electrochemical battery model, is designed to run in a dSPACE real-time simulator while the powertrain power distribution is managed by a dSPACE MicroAutoBoxII hardware controller. The control interface is designed using dSPACE ControlDesk to monitor the real-time simulation results. The HiL simulation results with the performance of vehicle dynamics and the thermal aging of the battery are presented and analyzed. The research laid a solid foundation for the future work on HiL design of HEV control with the consideration of battery aging and the component-in-the-loop study of the lithium ion battery running in real-time.

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INTRODUCTION

In recent years, the study of Hybrid Electric Vehicles, Plug-in Hybrid Electric Vehicles (PHEVs) and Electric Vehicles (EVs) have been drawing more and more attentions due to the shifting of transportation options from conventional internal combustion engine powered vehicles to more electrified alternatives for the purpose of fuel consumption and emission improvement.

Among the current studies towards HEVs, PHEVs, and EVs, the battery pack usage has been one of the most discussed issues. Auto manufacturers have been trying to make the best usage of the battery packs to achieve the better goals of fuel economy and emission and at the same time ensure that the depreciation rate of the vehicle can be competitive compared with the conventional vehicles. One of the key factors is to improve the battery aging performance. The aging of the battery packs usually involves the increase of internal resistance and the decrease of battery capacity, which will lower the battery power and energy performance respectively.

To improve the battery aging performance especially in the HEVs and PHEVs, researchers have looked into the improvement for the supervisory controller of the vehicles with the goal of optimizing both the fuel economy and battery performance. Examples can be found from the work of Serrao et al. [1] and the research from Moura et al. [2]. These studies considered the operational conditions of the HEVs and PHEVs and the advanced algorithms to operate the vehicle with the optimized engine/motor torque distribution.

The proposed supervisory control algorithm can be optimized theoretically and the performance of the proposed algorithm can be validated with the simulation results using the model of hybrid vehicle and sometimes even the detailed battery packs model for the purpose of battery aging simulation. However, to realize the proposed algorithm in production ECU, further adjustment needs to be made for the control and more rigorous validation and evaluation need to be done.

The HiL development method has been used broadly in the automotive industry in terms of product development and rapid prototyping [3]. By using the HiL, the performance of the studied component can be learned in real-time mimicking the operational conditions that the vehicle will be operated in the real world. The developed algorithm can be tested using the rapid prototyping system and validated in the HiL setup. For the case of industrial product development, Hil development is more time-efficient and cost-effective. It also enables the system integration and debugging to be done at the earliest stage of product development [3]. For the study in research institutes and universities, the HiL development will bring the research one step closer to the real applications. Especially, the HiL setup will enable the analysis of the feasibility of certain advanced algorithm to be used in real life.

In the work of Ramaswamy et al. [4], a HiL system, which also incorporates the OnBoard Diagnostic (OBD) simulation is built to test the Electronic Control Unit (ECU) developed and to facilitate the whole product development process of HEV.

[3], the HiL setup is built to test and verify the battery algorithm for applications in various kinds of vehicles. In the work of Li et al. [5], a single-shaft parallel hybrid electric vehicle together with individual components and controllers' models are built and run in the dSPACE simulator with the electric motor controller running in dSPACE MicroAutoBox. The application of HiL has been used beyond the automotive engineering in other new energy areas that come along with the increasing popularity of electrified transportation. In the work of Ramaswamy et al. [4], a HiL system is developed and used to test the control algorithm and the strategies for a microgrid.

In this paper, an electrochemical model is integrated with the Prius 04 power-split HEV model by replacing the original equivalent circuit model of the battery pack. The battery model of A123 26650 LiFePO₄-Graphite Li-ion cell is inherited from the work of Prada et al. [6]. The studied model has the battery aging features of capacity loss and resistance increase. The vehicle model and parameters are from the Autonomie vehicle simulation software [7]. The rule-based hybrid controller manages the energy distribution between the engine and electric power source. This hybrid controller, which is inherited from the original Autonomie software, is tested while being compiled and run in the MicroAutoBoxII rapid prototyping system. The Prius MY04 power-split hybrid electric vehicle together with the individual component controllers' models are run in the dSPACE EcoLine Simulator. The hybrid controller and the simulator are running in real-time while the hybrid controller gathers the necessary vehicle information and calculates the engine torque request, the engine on/off request, the brake torque request and regen state and the torque requests of two motors. The calculated values of these real-time control variables are then sent back to the simulator which completes the whole closed-loop system.

The major contributions of the paper are:

1. The electrochemical lithium ion battery model is integrated with the whole hybrid electric vehicle model. The entire vehicle model is proved to be feasible to be running in the real-time simulator environment with the sampling time of 0.01s.
2. The electrochemical battery model running in real time is able to provide quantified aging characteristics for the increase of internal resistance and decrease of battery capacity.
3. The setup of the whole HiL system provides a solid foundation for the future research of the hybrid controller with a possibly more advanced control algorithm and the consideration of battery aging improvement.

The rest of the paper is arranged as follows: First, the vehicle model and the battery model are discussed and the system integration is laid out. Secondly, the electronic communication signals are listed and discussed. And finally, the online simulation results of different driving cycles are presented and analyzed.

VEHICLE MODEL AND BATTERY ELECTROCHEMICAL MODEL

The Power-Split Hybrid Electric Vehicle Model

In this paper, the vehicle model used is the Prius MY04 power-split HEV provided by Autonomie vehicle simulation software [8] and the model layout is shown in Figure 1. This HEV is the very first generation of Prius power-split hybrid electric vehicles.

The complete model consists of driver's model, environment model, the battery model, the power electric drive models, the motor models, the engine model, the planetary gear set model, the final drive model, the chassis model and the hybrid controller model.

As shown in Figure 1, the hybrid controller has been removed from the whole vehicle model and placed separately to run in the MicroAutoBoxII controller. The battery pack model has been replaced by an electrochemical battery pack with the A123 26650 LiFePO₄-Graphite Li-ion cells.

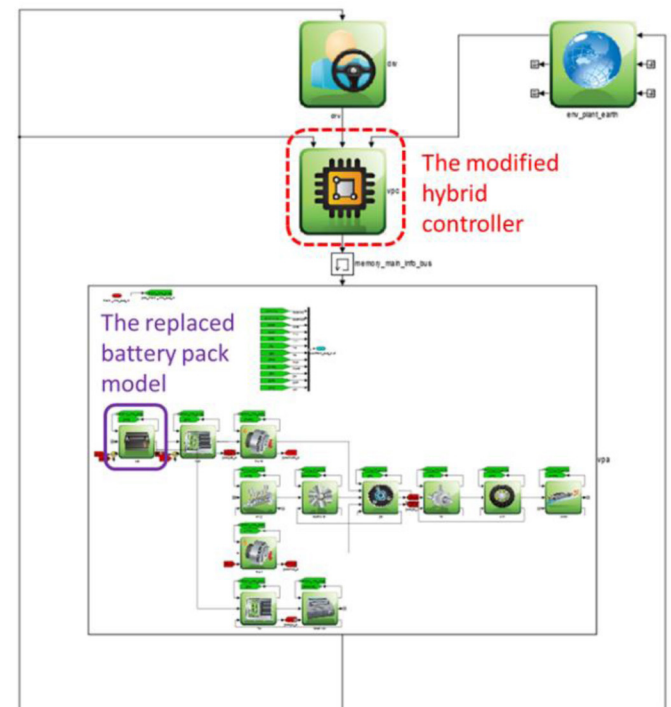


Figure 1. The layout of the complete hybrid electric vehicle model

For the mechanical/electrical powertrain of the power-split Prius 04, the planetary gear is a key part. The sun gear of the planetary gear is connected to a small motor while the ring gear connected to a larger driving motor. The engine is connected rigidly to the carrier of the planetary gear. The torque and speed coupling of the sun gear motor (MG1), the ring gear motor (MG2) and the internal combustion engine along with the carrier (IC engine) contributes significantly to the efficient operation of IC engine and thus the optimization of fuel consumption.

The major specifications of the individual component in the Prius MY04 model are listed in Table 1.

Table 1. The Major Model Parameters of MY04 Prius

Max. engine power	57 kW
Max. engine torque	122.8 Nm
Battery capacity	6.5 Ah
Max. battery discharge power	31 kW
Max. battery charging power	-23 kW
Curb weight	1449 kg
Continuous power of ring gear motor (MG2)	25 kW
Peak power of MG2	50 kW
Continuous power of sun gear motor (MG1)	15 kW
Peak power of MG1	30 kW
Nominal voltage of the NiMH battery pack	201.6V
Cell capacity of the NiMH battery pack	6.5Ah
Nominal voltage of the Li-ion battery pack	399V
Cell capacity of the Li-ion battery pack	6.93Ah

The Simplified Average Single Particle Model

The studies towards the electrochemical theories of the general electrochemical system of batteries and fuel cells have first been conducted by J. Newman, et al. [9]. The original pseudo two-dimensional model of lithium-ion batteries, also referred as “Newman’s model”, is developed by J. Newman, et al. [10], which laid the foundation for the future perfections of the theory.

In the pseudo-two-dimensional model, both the anode and cathode are filled with small particles to and from which lithium ions transfer in and out as the battery is charged or discharged. Inside the battery, the lithium ions are transported between electrodes and separators through the electrolyte by multiple driving force. Outside the battery, the electrons are transmitted by the potential differences between the two ends of the battery. The goal of the battery model is to describe the electrochemistry phenomena that happens inside the battery such as the charge transfer kinetics at the surface of the electrode particles and the ions transportation in the electrolyte.

The governing equations for the pseudo-two-dimensional battery model include the Butler-Volmer equation, the conservation of charge equation at the electrolyte phase, the conservation of mass equation at the electrolyte phase, the conservation of mass equation at the solid phase.

Since the pseudo-two-dimensional model (Newman’s model) involves three domains (positive and negative electrode and separator), two different phases (solid and electrolyte) and two states

(lithium concentration and electric potential) with equations and boundary conditions coupled together, solving the PDEs requires excessive computational work even for each time step defined. To reduce the computational load, the pseudo-two-dimensional model has been simplified by mathematical reduction to models such as a model with a polynomial approximation or single particle model [11].

The simplified average single-particle model used in this study is from the study of Prada et al. [6][11], which is developed based on the average model from Domenico et al. [12].

The average single-particle model could be summarized as [6]

$$\begin{aligned}
 V(t) &= U_p \left(\frac{c_{s,p}^s}{c_{s,p,max}} \right) - U_n \left(\frac{c_{s,n}^s}{c_{s,n,max}} \right) \\
 &+ \frac{2RT}{F} \ln \left(\frac{\frac{-R_{s,p}}{6\varepsilon_{s,p}i_{0,p}A\delta_p} I + \sqrt{\left(\frac{R_{s,p}}{6\varepsilon_{s,p}i_{0,p}A\delta_p} I \right)^2 + 1}}{\frac{R_{s,n}}{6\varepsilon_{s,n}i_{0,n}A\delta_n} I + \sqrt{\left(\frac{R_{s,n}}{6\varepsilon_{s,n}i_{0,n}A\delta_n} I \right)^2 + 1}} \right) \\
 &+ (1 - t_+) \frac{2RT}{F} \ln \frac{c_e(L)}{c_e(0)} - \frac{I}{2A} \left(\frac{\delta_n}{\kappa_n^{eff}} + 2 \frac{\delta_{sep}}{\kappa_{sep}^{eff}} + \frac{\delta_p}{\kappa_p^{eff}} \right).
 \end{aligned} \quad (1)$$

where $c_{s,p}$ and $c_{s,n}$ are the concentration of lithium ions in the solid phase (mol/cm²) at the positive and negative electrode; $c_{s,p,max}$ and $c_{s,n,max}$ are the maximum concentration of lithium ions at the positive and negative electrode; U_p and U_n are the electric potential at the positive and negative electrodes determined by the lithium ion concentration at the surface of solid phase particles; $R_{s,p}$ and $R_{s,n}$ are the solid phase particle size at each electrodes; $\varepsilon_{s,p}$ and $\varepsilon_{s,n}$ are the active material volume fracture for two electrodes; A is the electrode plate area; $i_{0,p}$ and $i_{0,n}$ are the exchange current density for the Butler-Volmer equation; δ_p , δ_n and δ_{sep} are the thickness for the positive, negative electrodes and the thickness of separator; I is the applied current; R is the ideal gas constant; T is the temperature of the cell; F is the Faraday constant; $c_e(L)$ and $c_e(0)$ are the lithium ion concentration in the electrolyte at the positive and negative current collector; κ_n^{eff} , κ_p^{eff} and κ_{sep}^{eff}

are the effective ionic conductivity of electrolyte phase in the negative, positive electrode and the separator.

Figure 2 shows the voltage output of the single cell lithium ion battery while being full discharged from 100% State of Charge (SOC). The voltage output is determined by the hysteresis electric potential of the positive and negative electrode, all the overpotential due to the particle movement and Butler-Volmer equation and the overpotential from the Solid-Electrolyte Interface (SEI) layer due to battery aging.