PLUG-IN HYBRID ELECTRIC VEHICLES: MODELING, SIMULATION AND ENERGY MANAGEMENT

Reza Ghorbani, Eric Bibeau, Paul Zanetel and Athanassios Karlis

Mechanical and Manufacturing Engineering
University of Manitoba
Winnipeg, MB, Canada R3T 5V6

ABSTRACT
Renewable Energy Vehicle Simulator (REVS) developed at University of Manitoba provides a visual programming package to study the hybrid electric vehicles (HEV) and plug-in HEV (PHEV) configurations as well as energy management strategies. Modeling and simulation of a plug-in hybrid electric vehicle is discussed in this paper using REVS. The model of the PHEV vehicle includes various major types of components such as: electric motor, internal combustion engine, transmissions, environmental conditions, batteries, chemical reactions, fuzzy controller and support components that can be integrated to model and simulate hybrid drive trains in different configurations. The simulation is developed in the Matlab/Simulink graphical simulation package as well as IDEAS package. A series parallel hybrid electric vehicle (HEV) with a conventional internal combustion engine (ICE) and a power split device have been designed using the simulation package. Fuzzy controllers are developed to track the desired vehicle velocity and manage the energy flow of the vehicle. Simulation results of the energy management system and dynamic responses of the system are discussed for the vehicle.

Index Terms—Hybrid vehicle, Control, Simulation, Energy Management

1. INTRODUCTION
Understanding the dynamics of the hybrid vehicles is practical by developing the vehicle simulators. The results of simulators can be used to optimize the design cycle of hybrid vehicles by testing configurations and energy management strategies before prototype construction begins. Power flow management, optimization of the fuel economy and reducing the emissions using intelligent control systems are part of the current research [1, 2, 3]. Verification of the vehicle simulators through extensive experiments is an important part of ongoing researches [4, 5].

The University of Manitoba in cooperation with Democritus University of Thrace, are developing a Renewable Energy Vehicle Simulator (REVS) that enables to simulate renewable energy vehicles using the combination of a propulsion system and fuels by adapting library modules to suit particular applications. The modeling of the chemical reactions of the internal combustion engines is carried out by IDEAS [6]. The modeling of the transmission system, dynamics of the vehicle, electrical motor and power drivers is done using Matlab and Simulink. REVS can simulate different configurations of a vehicle to enable the optimization of available renewable energy resources and minimize greenhouse gases.

In this paper, the Plug-In model of Toyota Prius as a series parallel HEV drive train is presented using the REVS. The Prius’ components such as ICE, electric motor, battery and vehicle inertias were defined based on vehicle’s available information. Regenerative braking of the vehicle is inherently activated by Power Split Device (PSD). The model of the PSD and battery are explained by Liu et al. [7]. A rule-based fuzzy controller is designed to manage the output power of the electric motor based on accelerating pedal position and State of the Charge (SOC) of the batteries. Dynamics of the driver of the vehicle is modeled using a fuzzy controller, which is in parallel with a first order system. Simulation studies are performed for the regular and the plug-in version of the vehicle with low and high battery capacities. Dynamic responses of the vehicle, such as vehicle velocity, SOC and generated power (through ICE and EM) are graphically illustrated in this paper.

2. SERIES PARALLEL HYBRID ELECTRIC VEHICLE

In a typical series parallel drive train design, consisting of an ICE, an electric motor, a generator and a power split device (PSD), either the ICE or the electric motor can be considered the primary energy source depending on the vehicle design and energy management strategy. The PSD divides the output torque of the ICE, with a fixed torque ratio, into the wheels and the generator. The output power of the ICE can be divided into an infinite ratio between the wheels and
generator. This configuration is designed so that the ICE and electric motor are both responsible for propulsion or each is the prime mover at a certain time in the drive cycle. Also part of the power of the ICE transfers to the wheels while the other is used to recharge an energy accumulator, usually a battery pack. A schematic of the series parallel HEV power train is shown in Fig. 1.

Series parallel HEV consists of different elements with various configurations that make the vehicle modeling more complex by providing different number of choices and their effect on vehicle’s performance for a special mission. The modeling of Prius drive train is shown in details in Fig. 2. The ICE model was designed based on Prius torque/power/velocity data and threshold using lookup table. The permanent magnet asynchronous AC motor of the Prius model is also modeled based on available data using lookup table by considering the motor power threshold. Capacity and number of cells of the battery are assumed as an initial input parameters of the simulations. State of the charge of the battery and current load

Fig. 1. Model of the series parallel HEV in REVS.

Fig. 2. Schematic of the series parallel hybrid electric vehicle.
determine the DC bus voltage based on a battery model [7]. Regenerative braking is inherently performed through PSD and generator whenever the decreasing velocity of the vehicle is demanded by driver. A fuzzy controller manipulates the power contributions of the electric motor that is explained in detail in the next section.

Fig. 3. 3D graph of the fuzzy controller rules for power controller. Scaling factor is output the controller.

3. ENERGY MANAGEMENT

The energy management strategies of the vehicle are described in this section. In developing the energy management block, two important factors are considered. Firstly, the driver inputs (from the brake and the accelerating pedals) are to be consistent with conventional vehicle (driving the series parallel HEV should not “feel” different from driving a conventional vehicle). secondly, the state of charge of the battery is to be sufficient at all times. As shown in Fig. 1, the power controller determines the power needed to drive the wheels and to charge the batteries. It also commands the required power of the electric motor. In this configuration, the batteries can be charged while power are assigning to the electric motor. The ICE through PSD, provides the power for both charging of the batteries and driving the wheels. More details of the power controller are discussed in the next section.

3.1. Power Controller

As shown in Fig. 1, a fuzzy logic controller determines the output power of the EM with regard to the inputs of the accelerator pedal and the SOC of the battery. The acceleration pedal signal is normalized to a value between zero and one (zero: pedal is not pushed, one: pedal is completely pushed). The normalized signal of the braking pedal is directly connected to the vehicle dynamic block to subtract braking forces from wheel forces. The output of the power controller block is the scaling factor of the EM power which is also normalized between zero and one. The scaling factor is multiplied by the maximum available power of the EM. The normalized value of the acceleration pedal is multiplied by the maximum available power of the ICE. By this configuration, the driver can command the complete range of available power. The maximum available power of the EM and ICE are a function of the vehicle’s velocity and engine temperature, which are computed through a 2D look-up table.

Here, The EM scaling factor, which is computed through fuzzy logic controller, is proportional to the acceleration pedal and is adjusted to be zero when the SOC of the battery is too low. In order to prevent battery damage in that situation, the EM is not generating power to drive the wheels. When the SOC is high enough, the scaling factor is adjusted to be equal one. To illustrate the fuzzy logic rules, Fig. 3 shows the scaling factor as a function of the acceleration pedal and the SOC. As it is shown in Fig. 3, the scaling factor is zero when the SOC is below 0.8.

3.2. Velocity Tracking Controller

Combinations of a low pass filter and a fuzzy controller are assumed to model the driver for tracking the desired velocity of the vehicle. Velocity error is the input signal of the low pass filter, which here is equal to \( \frac{0.6}{0.025s+1} \). It is also assumed as the input signal of the driver fuzzy controller. The summation of the output signals of the low pass filter and the driver fuzzy controller, command the acceleration pedal. Fig. 4 shows the functionality of the driver fuzzy controller.

4. SIMULATION RESULTS

The vehicle has been simulated with REVS while the input of the system is the desired velocity of the vehicle. The pa-
<table>
<thead>
<tr>
<th>Definition</th>
<th>Values</th>
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<tr>
<td>Curb weight</td>
<td>1600 Kg</td>
</tr>
<tr>
<td>Max ICE power</td>
<td>57 kW 5,000 r.p.m.</td>
</tr>
<tr>
<td>MAX ICE torque</td>
<td>115 Nm 4,200 r.p.m.</td>
</tr>
<tr>
<td>EM power</td>
<td>50 kW 1200 - 1540 r.p.m.</td>
</tr>
<tr>
<td>Maximum voltage</td>
<td>500 V</td>
</tr>
<tr>
<td>Maximum EM torque</td>
<td>400 N.m 0 - 1200 r.p.m.</td>
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Table 1. Parameters used in paper.

Parameters of the vehicle are listed in Table 1. A cyclic desired vehicle velocity is commanded to the vehicle for examining the response of the system in two cases with the different battery capacities. The battery capacity of the regular and PHEV vehicles are equal to 2\[\text{KW h}\] and 25\[\text{KW h}\], respectively. The results of the simulations are shown in Figures 5 and 6. The desired velocity signal of the vehicle (shown by solid line), actual vehicle velocity (shown by dashed line), SOC, scaling factor, acceleration pedal, electric motor power (KW), ICE power (KW) and the generator power (KW) are shown in Figures 5 and 6. As shown in Figures 5 and 6, the vehicle can reasonably track the desired velocity. It has also shown that the SOC is kept higher than 0.8. In both cases, the main power of the vehicle during the cruise period, after 110 second, is provided by ICE. In regular hybrid, the acceleration period is longer than the second case caused by lower battery capacity. This illustrates that lower power from electric motor is used in regular hybrid vehicle. The results of the regular hybrid vehicle in Fig. 5, shows a periodic change in SOC during driving cycle. The results of PHEV case in Fig. 6, show that the SOC of the battery is relatively high (between 0.89 and the maximum 0.96) in whole period of driving cycle. It also demonstrates that the controller is successful to minimize the velocity error. In both cases, the SOC is increased during the deceleration period which shows the power regenerating cycle.

5. CONCLUSIONS

A renewable energy vehicle simulator (REVS) has been presented in this paper for modeling, simulations and analysis of a hybrid vehicle drive train. The major goal of developing the REVS is to study the issues of the plug-in hybrid electric vehicle design such as dynamics, energy management and fuel economy. The modeling of a series parallel electric vehicle, Toyota Prius, was presented. Fuzzy controller was used to control the power flow as well as to track the vehicle velocity. The simulation results of vehicle were shown to examine the dynamics of the vehicle in two cases of a series parallel HEV and a series parallel PHEV. The results illustrated that the controller can successfully track the desired vehicle velocity for both cases.

6. REFERENCES


Fig. 5. Results of the simulation for a cyclic desired vehicle velocity with battery capacity = 2[kWh].

Fig. 6. Results of the simulation for a cyclic desired vehicle velocity with battery capacity = 25[kWh].