Energy Management Optimization of Power Split Hybrid Electric Vehicle

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Abstract. The object of this thesis is to improve the fuel economy of a power-split hybrid driveline system with energy management. General Motors two-mode hybrid system is modeled and simulated in Matlab, and the power outputs of engine and electric motors are selected as the design targets. A rule-based controller is applied in the baseline for energy management. The optimization of fuel consumption is approached by Dynamic Programming. Then, the differences between baseline and DP are evaluated, and a modified rule-based control strategy is developed. The combined fuel economies of baseline and DP optimization are 42.06 and 55.61 mpg, respectively. The potential improvement in fuel economy is 32.21%. With the modified rule-based control strategy, the fuel economy is improved 13.36%, up to 47.68 mpg. The result shows that the modified control strategy improves fuel economy efficiently.

Introduction

Since the beginning of the industrial revolution, the global carbon dioxide increased by more than 120 ppm from burning fossil fuels. Begin from 1980, carbon dioxide raised rapidly, and half of the increase is from the last 30 years. US National Oceanic and Atmospheric Administration (NOAA) announced that the global carbon dioxide hit a record high in March 2015, which is more than 400 ppm.

The major automakers are committed to the development of new energy to replace gasoline, including electric energy, solar energy, biofuel energy, etc. Electric vehicles have high energy efficiency, and low pollution and noise. With the short driving range, high cost, and lack of charging stations, electric vehicle are not easy to popularize. Under these situation, hybrid electric vehicles (HEVs) have become the first choice of high efficiency vehicles. In the hybrid system, there are two sources of electric power; one is from the regenerative braking mechanism. During braking, the kinetic energy is converted into electrical energy to charge the battery; the second one is using the internal combustion engine (ICE) driving generator to charge the battery which solve the endurance problems of electric vehicles. HEVs also provide start-stop function at speeds approaching zero to reduce fuel consumption and emissions.

Two-Mode Powertrain System

Two-Mode Hybrid Transmission is applied for 2MT70 transmission which includes a simple planetary gear set, a compound planetary gear set, four consisting clutches, and two electric motor/generators, as shown in Figure 1. With the activation of clutches, the transmission could operates in two different electric variable transmission modes (EVT-1 and EVT-2) and four fixed gear (FG-1 ~ 4) [1,2].

Dynamic System Model

A backward calculation dynamic model was established with Matlab/Simulink, as shown in Figure 2. US FTP-75 (EPA Federal Test Procedure) patterns was applied for driving cycle simulation. According to a known speed, the vehicle dynamics model would calculate the required drive torque,
and the controller model would determine the operation mode. The transmission model would determine the speed and torque of two electric motor/generators and internal combustion engine (ICE). With the rotational speeds and torques, the ICE model could calculate the fuel consumption, and the motor models could calculate the electric consumption. The battery model would determine the state of charge (SOC) based on the charge/discharge current from the motor models.

Figure 1. Two-Mode hybrid transmission.

Figure 2. Two-Mode hybrid powertrain system model.

**Vehicle Dynamic Model**

Based on traffic patterns, the acceleration of the vehicle and the driving resistance would be determined. Then, the vehicle model would calculate the required driving torque of powertrain driving shaft, as shown in Figure 3.

Figure 3. Vehicle dynamic model.

**Control Model**

The controller model has three main functions: The first one is to determine the rotational speed and torque of the ICE based on the desired torque and the SOC; the second one is to determine the switching timing between two driving modes by vehicle speed and working condition of ICE, as shown in Figure 4; the third one is to determine whether the ICE was started or stopped according to the SOC and current driving mode.
ICE Model

For fast simulation, the ICE model employed three-dimensional look-up tables. With the engine speed and brake torque, the brake Specific fuel consumption (BSFC) look-up table would find the corresponding amount of fuel. Integrating through the driving cycle, the total fuel consumption was obtained. A 6-cylinder 3.6 liters engine efficiency map is shown in Figure 5(a).

Motor/Generator Model

The electric motor/generator model employed the efficiency look-up table to construct two 60kW permanent magnet AC motors. The efficiency map of the electric motor/generator is shown in Figure 5(b). Power calculation of the motor/generator is as follows:

\[ P_{MG} = \omega_{MG} T_{MG} \eta_{MG}^{k} \]

Where \( P_{MG}, \omega_{MG}, \) and \( T_{MG}, \) are power, speed and torque of the motor/generator, respectively. If the speed and torque values are the same sign, the motor/generator is motoring. If the speed and torque values are in opposite sign, the motor/generator is generating. \( \eta_{MG} \) represents the motor/generator efficiency, and \( k \) indicates the direction of energy flow.

Battery Model

The electrical energy required for the motor/generators is provided by the battery. Power required by the electric motor is as follows.

\[ P_{batt} = T_{MG1} \omega_{MG1} \eta_{MG1}^{k} + T_{MG2} \omega_{MG2} \eta_{MG2}^{k} \]

where \( \eta_{c} \) is the converter efficiency. \( k \) is the direction of energy flow. When battery is discharged, \( k = -1 \). When battery is charged, \( k = 1 \).

The battery model employed an equivalent circuit[3], comprising the open-circuit voltage \( V_{oc} \) and the battery resistance \( R_{batt}, \) as shown in Figure 6.

Battery equivalent circuit diagram.
Energy Management Optimization

Dynamic Programming in Hybrid System

Dynamic programming (DP) was applied for the optimization of vehicle fuel economy simulation[4,5]. The constraints applied on DP were

$$P_{em,min}(k) \leq P_{em}(k) \leq P_{em,max}(k) \quad (3)$$

$$P_{eng,min}(k) \leq P_{eng}(k) \leq P_{eng,max}(k) \quad (4)$$

$$SOC_{min}(k) \leq SOC(k) \leq SOC_{max}(k) \quad (5)$$

Where $P_{em,min}$ and $P_{em,max}$ were motor minimum power and maximum power, respectively. $SOC_{min}$ and $SOC_{max}$ were battery minimum and maximum state of charge(SOC), respectively.

The cost function was defined as the total fuel consumption during the driving cycle.

$$J = \sum_{k=0}^{N-1} \tilde{m}_f(x_k, u_k) \Delta t$$

where $\tilde{m}_f(x_k, u_k)$ was the instantaneous fuel consumption of the $k^{th}$ second.

Simulation Results and Discussion

The backward calculation dynamic model was employed for fuel economy simulation, and the vehicle parameters were shown in Table 1. US FTP-75 patterns was applied for simulation driving cycle. During the driving cycle, the battery SOC was maintained between 40 to 80%.

Table 1. Vehicle parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Weight (kg)</td>
<td>1600</td>
</tr>
<tr>
<td>Tire Radius</td>
<td>0.352</td>
</tr>
<tr>
<td>Vehicle Front Area (m2)</td>
<td>2.642</td>
</tr>
<tr>
<td>Aerodynamic Dragging Coefficient</td>
<td>0.386</td>
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<tr>
<td>Displacement (L)</td>
<td>3.6</td>
</tr>
<tr>
<td>Maximum Power (kW)</td>
<td>188@6300rpm</td>
</tr>
<tr>
<td>Maximum Torque (Nm)</td>
<td>340@3200rpm</td>
</tr>
<tr>
<td>Maximum Speed (RPM)</td>
<td>10000</td>
</tr>
</tbody>
</table>

The Baseline Model

The baseline model employed a rule-base controller. With the driving resistance ($T_d$) and battery SOC as inputs, the controller would determine the engine torque ($T_E$) and engine speed ($\omega_E$) according to the control rules which were presented in the Table 2.

Table 2. Control rules.
To reduce the fuel consumption during the driving, the ICE would turn on/off based on the engine control strategy. The strategy flow chart was presented in Figure 7.

![Strategy Flow Chart](image)

**Figure 7.** The state of the internal combustion engine control logic.

With the vehicle driving simulation, the fuel economy was 44.38 mpg for city cycle, and 39.53 mpg for highway cycle. The composite fuel economy was 42.06 mpg. Comparing the simulation results with the vehicle factory data, the difference was about 0.66% which was within an acceptable range. The model established in this study was close to reality.

**Dynamic Programming**

With the DP optimization, the fuel economy was 58.68 mpg for city driving cycle, and 52.26 mpg for highway driving cycle. Comparing with the fuel economy of baseline model, the improvement was 32.2% for both city and highway cycles, as shown in Table 4.

**Improved Baseline Model**

By examining the DP optimization, the control rules of baseline model had room for improvement. The improved rules of rule-based control was presented in Table 3.

With the improved control rules, the fuel economy was 51.71 mpg for city driving cycle, and 43.54 mpg for highway driving cycle. The improvement was 16.5% for city cycle, and 10.1% for highway driving cycle, as shown in Table 4.

### Table 3. Improve the design after Rule-based control rules.

<table>
<thead>
<tr>
<th>Td</th>
<th>SOC</th>
<th>$x &lt; 0.4$</th>
<th>$0.4 &lt; x &lt; 0.5$</th>
<th>$0.5 &lt; x &lt; 0.6$</th>
<th>$0.6 &lt; x &lt; 0.7$</th>
<th>$0.7 &lt; x &lt; 0.8$</th>
<th>$0.8 &lt; x$</th>
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<tbody>
<tr>
<td>0 s</td>
<td>60 s</td>
<td>90 s</td>
<td>120 s</td>
<td>150 s</td>
<td>180 s</td>
<td>210 s</td>
<td>240 s</td>
</tr>
<tr>
<td>0 s</td>
<td>30 s</td>
<td>50 s</td>
<td>70 s</td>
<td>90 s</td>
<td>110 s</td>
<td>130 s</td>
<td>150 s</td>
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<tr>
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<td>10 s</td>
<td>30 s</td>
<td>50 s</td>
<td>70 s</td>
<td>90 s</td>
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<td>130 s</td>
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<td>25 s</td>
<td>35 s</td>
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<td>10 s</td>
<td>20 s</td>
<td>30 s</td>
<td>40 s</td>
<td>50 s</td>
<td>60 s</td>
</tr>
<tr>
<td>0 s</td>
<td>0.1 s</td>
<td>9 s</td>
<td>19 s</td>
<td>29 s</td>
<td>39 s</td>
<td>49 s</td>
<td>59 s</td>
</tr>
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</table>

### Table 4. Improve the fuel consumption before and after comparison design.

<table>
<thead>
<tr>
<th></th>
<th>City fuel economy (mpg)</th>
<th>Highway fuel economy (mpg)</th>
<th>Composite fuel economy (mpg)</th>
<th>City FE improvement</th>
<th>Highway FE improvement</th>
<th>Composite FE improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base model</td>
<td>44.38</td>
<td>39.53</td>
<td>42.06</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Dynamic Programming</td>
<td>58.68</td>
<td>52.26</td>
<td>55.61</td>
<td>32.2%</td>
<td>32.2%</td>
<td>32.2%</td>
</tr>
<tr>
<td>Improved base model</td>
<td>51.71</td>
<td>43.54</td>
<td>47.68</td>
<td>16.5%</td>
<td>10.1%</td>
<td>13.4%</td>
</tr>
</tbody>
</table>
**Summary**

In this study, a backward calculation Matlab/Simulink model was developed for HEVs fuel economy simulation, and the simulation result of baseline model was validated with the vehicle data. To achieve the optimization of fuel economy, the Dynamic Programming (DP) was applied to optimize the fuel consumption during the driving cycle. Since DP required the whole driving pattern in advance, DP could not be applied in vehicle real time control. Based on the simulation result of DP, a modified rule-based control was applied on the baseline model to improve the fuel consumption. With the composition fuel economy simulation, the fuel economy of baseline model was 42.06mpg, DP was 55.61 mpg, and the improved baseline model was 47.68mpg. The improved baseline model had a 13.36% improvement, as shown in Table 4. With the modified control rules, the operating region of engine was closed to the optimum working area, which efficiently reduced fuel consumption.

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**References**


