Energy Management Strategy Considering Cabin Heating for Plug-in Hybrid Electric Vehicle

Heejin Shin\textsuperscript{1}, Sunyoung Park\textsuperscript{1}, Jaemyoung Pi\textsuperscript{1}, Jingyu Choi\textsuperscript{1}, Seulgi Lee\textsuperscript{1}, Hyunsoo Kim\textsuperscript{1}, Inbeom Yang\textsuperscript{2}

\textsuperscript{1}School of Mechanical Engineering, Sungkyunkwan University, 2066, Seobu-ro, Jangan-gu, Suwon-si, Gyeonggi, Korea, bwb6387@hanmail.net  
\textsuperscript{2}Smart Vehicle Technology R&D Division Korea Automotive Technology Institute, 330 Pangse-ro, Pangse-myeon, Dongnam-gu, Cheonan-si, Chungnam, Korea, ibyang@katech.re.kr

Abstract

In this study, an integrated energy management strategy (IEMS) was proposed for a PHEV (Plug-in hybrid electric vehicle). The IEMS controls the engine on-off considering not only powertrain system (battery SOC, vehicle speed, accelerator pedal, brake pedal) but also thermal system condition such as cabin temperature. Analysis of the integrated powertrain and thermal system was conducted to enhance vehicle performances such as all electric driving range and fuel economy. To investigate the energy flow, the performance simulator was developed based on the integrated powertrain and thermal system model. The powertrain model is composed of the engine, motor-generators, power-split transmission, battery and vehicle dynamics, whereas the thermal system model is composed of the thermal engine, radiator, heater and cabin. From the simulator, the coolant temperature, cabin temperature, engine torque and engine speed were investigated. The developed simulator was validated by vehicle test results. It was found that the proposed IEMS satisfies the demanded cabin temperature while providing improved fuel consumption compared with the existing energy management system.

Keywords: integrated energy management strategy (IEMS), thermal system, plug-in hybrid electric vehicle (PHEV)

1 Introduction

According to the renewed regulation of Environmental Protection Agency (EPA) in measurement of fuel efficiency, not only the conventional vehicle but also the hybrid electric vehicle and the plug-in hybrid electric vehicle require to consider the surrounding temperature of summer and the winter for existing driving cycles, the urban dynamometer driving schedule (UDDS) and highway fuel economy test (HWFET). In response to this requirement, importance of the thermal management system has been increased\cite{1}. The thermal management system of the vehicle can be divided into the cooling system for powertrain and the air condition/heating system for the driver’s convenience. Since the thermal management system consists of many electric devices, it requires electric energy of the battery. For example, the fuel efficiency test results of the Chevrolet Volt for UDDS and HWFET showed that the usage of battery for heating aggravated the fuel efficiency further than the usage of engine\cite{2}.
In this study, an integrated powertrain-thermal management simulator of power-split type PHEV was developed and integrated energy management strategy (IEMS) was proposed to improve the fuel economy.

2 Development of the PHEV Powertrain Simulator

2.1 PHEV powertrain simulator

The thermal management system of the target PHEV is determined by the powertrain operation condition such as the battery SOC, engine torque, engine speed. Therefore, the powertrain simulator should be developed in advance for development of the integrated powertrain-thermal management simulator.

2.1.1 Structure and the specification of the PHEV

The powertrain system of the target PHEV consists of 1 engine, 2 motors (MG1/MG2), 1 battery and 1 planetary gear. The structure of the PHEV is shown in Figure 1 and the vehicle specification is shown in Table 1.

![Figure 1: Structure of the target PHEV](image)

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine</td>
<td></td>
</tr>
<tr>
<td>Displacement</td>
<td>1398cc</td>
</tr>
<tr>
<td>Max output</td>
<td>62kW/4800rpm</td>
</tr>
<tr>
<td>MG2</td>
<td></td>
</tr>
<tr>
<td>Max power</td>
<td>111kW</td>
</tr>
<tr>
<td>Max torque</td>
<td>370Nm</td>
</tr>
<tr>
<td>MG1</td>
<td></td>
</tr>
<tr>
<td>Max power</td>
<td>55kW</td>
</tr>
<tr>
<td>Vehicle</td>
<td></td>
</tr>
<tr>
<td>Final reduction gear ratio</td>
<td>2.16</td>
</tr>
<tr>
<td>Planetary gear ratio</td>
<td>83/37</td>
</tr>
<tr>
<td>Tire radius</td>
<td>0.3382m</td>
</tr>
<tr>
<td>Mass</td>
<td>1717kg</td>
</tr>
</tbody>
</table>

2.1.2 Engine and MG1/MG2 model

Engine torque is determined from the engine characteristic map by the acceleration pedal opening for the engine speed. Power loss of the MG1/MG2 is determined by the motor efficiency map (Figure 2).

![Figure 2: Motor efficiency map](image)

2.1.3 Vehicle model

Vehicle was modelled considering the traction force, brake force and the roadload. Rolling resistance and air drag force were obtained based on the coastdown test results and the gradient resistance was calculated using vehicle dynamics. The vehicle dynamics is as follows:

\[ M \dot{V} = F_{\text{drive}} - F_{\text{brake}} - F_{\text{roadload}} \]

where M is the vehicle mass, V is the vehicle velocity, \( F_{\text{drive}} \) is the traction force, \( F_{\text{brake}} \) is the brake force, \( F_{\text{roadload}} \) is the roadload.

3 Development of the Integrated Simulator

3.1 Thermal management system simulator

The thermal management system was modelled and performance simulator was developed.

3.1.1 Structure of the thermal management system

As can be seen in Figure 3, the thermal management system consists of the radiator, thermostat, engine, PTC heater, heater core and the blower. Under the heating condition, heater core is warmed up by the coolant which is heated by the engine waste heat or the PTC heater. The air is also warmed up while passing through the heater core and flows into the cabin by the blower. The cabin temperature is determined by the heat of PTC heater, driver, loss, etc.
3.1.2 Engine thermal model

Figure 4 shows the distribution of engine fuel power. The amount of heat transferred to the coolant from the engine can be obtained as follows:

\[ Q_{\text{coolant}} = Q_{\text{fuel}} - T_e \omega_e - Q_{\text{e-loss}} \]  

(2)

where \( Q_{\text{coolant}} \) is the heat transferred to the coolant, \( Q_{\text{fuel}} \) is the total heat of fuel, \( T_e \) is the engine torque, \( \omega_e \) is the engine speed and the \( Q_{\text{e-loss}} \) is the heat loss.

3.1.3 PTC heater and the heater core model

In EV mode when the engine is not operated, the PTC element is heated from the battery power and warms up the coolant. The amount of heat transferred to the coolant from the PTC element is calculated as follows:

\[ Q_{\text{PTC-coolant}} = C_{\text{coolant}} m_{\text{coolant}} (T_{\text{PTC}} - T_{\text{in}}) \]  

(3)

where \( Q_{\text{PTC-coolant}} \) is the heat transferred to the coolant from the PTC element, \( C_{\text{coolant}} \) is the specific heat of the coolant, \( m_{\text{coolant}} \) is the coolant mass, \( T_{\text{PTC}} \) is the temperature of the PTC element, \( T_{\text{in}} \) is the temperature of the coolant which comes into the PTC heater.

3.2 Integrated powertrain-thermal management system simulator

Figure 6 shows the integrated powertrain-thermal management system simulator developed in this study.

3.2.1 Vehicle dynamo test condition

The integrated powertrain-thermal management system simulation results were compared with the vehicle dynamo test results. The test condition for CD mode is shown in Table 2.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
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<tbody>
<tr>
<td>Driving mode</td>
<td>FTP 75</td>
</tr>
<tr>
<td>Air flow</td>
<td>Max</td>
</tr>
<tr>
<td>Setting temperature(Test)</td>
<td>Max(32 °C)</td>
</tr>
<tr>
<td>Setting temperature(Simulation)</td>
<td>34 °C</td>
</tr>
<tr>
<td>Initial SOC</td>
<td>80%</td>
</tr>
<tr>
<td>Initial cabin temperature</td>
<td>7.4 °C</td>
</tr>
</tbody>
</table>
3.2.2 Comparison between the simulation and test results

In Fig. 9, the simulation results were compared with the vehicle dynamo test results. It was found that the simulation results of MG1 torque/speed(c, d), MG2 torque/speed(e, f), engine speed/torque(g, h), battery SOC(b) and cabin temperature(j) were in good accordance with the vehicle dynamo test results. However, the ECT(Engine coolant temperature)(i) was 32℃ for simulation and 42℃ for the test. This difference comes from the leakage of coolant heated by the PTC heater in the test.

![Figure 6: Comparison between the simulation and the test results for CD mode(1)](image)

Figure 6: Comparison between the simulation and the test results for CD mode(1)

4 Development of the Integrated Energy Management Strategy

4.1 Integrated energy management strategy

Existing energy management strategy(EMS) of the target PHEV can be divided into CD mode and the CS mode. In CD mode, battery is mainly used to drive the vehicle and in CS mode, the battery and the engine are both used to remain the SOC low limit.

In this study, an integrated energy management strategy(IEMS) was proposed to control the engine on/off. The IEMS was developed by considering not only the powertrain system but also the thermal management system. The IEMS is composed of 3 controls: 1) Engine on/off control, 2) Driving mode control, 3) PTC heater power, coolant valve and the thermostat control.

![Figure 7: Integrated energy management strategy and control signals](image)

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4.1.1 Engine on/off control

The engine is turned on if the battery SOC is higher than SOC_{low limit}, the cabin temperature is lower than the setting temperature and the PTC heater consumes more than 50% of the battery power. If not, the engine is turned off and the vehicle is driven under the EV mode.

4.1.2 Driving mode control

Mode shift maps were used in driving mode control as shown in Figure 8. For the engine off signal, CD mode shift map which consists of EV#1 and EV#2 modes is used. For the engine on signal, CS mode shift map which consists of Series, Power-split and EV modes is used.

4.1.3 PTC heater power, coolant valve and the thermostat control

If the cabin temperature is lower than the setting temperature, PI control is used for PTC heater power control. The coolant valve and the thermostat control change according to the engine on/off signal and coolant temperature.

4.2 Comparison between EMS and IEMS

4.2.1 Simulation condition

Simulation results of the EMS and the IEMS were compared(Figure 10). The simulation condition is shown in Table 3.

![Diagram](image)

**Figure 8: Driving mode shift map and control signals**

**Table 3: Simulation condition**

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving mode</td>
<td>FTP 72</td>
</tr>
<tr>
<td>Initial battery SOC</td>
<td>35%</td>
</tr>
<tr>
<td>Initial cabin temperature</td>
<td>5 ℃</td>
</tr>
<tr>
<td>Setting temperature</td>
<td>22 ℃</td>
</tr>
</tbody>
</table>

**Figure 9: Comparison between EMS and IEMS**

It is seen from the simulation results in Figure 9 that in the IEMS, the engine is turned on in the initial driving stage(b) and the battery SOC is not depleted(c). The engine is turned off at t=226sec(point P) and vehicle is driven under the EV mode.

In the EMS, the engine is turned off in the initial driving stage(b) since the battery SOC is higher than SOC_{low limit}(c). The engine is turned on at
t=595sec(point Q) when the battery SOC reaches SOC_{low limit}(c). In Figure 9, it is seen that the IEMS provides 14.8% higher equivalent fuel economy than that of EMS.

![Figure 10: Equivalent fuel economy of EMS and IEMS](image)

5 Conclusion

The integrated energy management strategy (IEMS) was proposed by considering the powertrain and thermal management system. To develop the IEMS, the integrated simulator was developed, which is composed of powertrain simulator and the thermal management simulator. And it was validated with the vehicle dynamo test results. The IEMS consists of 3 controls: 1) Engine on/off control, 2) Driving mode control, 3) PTC heater power, coolant valve and the thermostat control. It is found from the simulation results that the equivalent fuel economy of the IEMS showed the improved fuel economy compared with the existing EMS.

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References


Authors

Heejin Shin received B.S. and M.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2013 and 2015. Her research interests include the modeling, design, and embedded systems for electric vehicles and hybrid electric vehicles. Since 2015, she has worked as an engineer in Hyundai Motor Company.

Sunyoung Park received B.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2014, where she has been working toward the M.S. degree. Her research interests include the powertrain system, control strategy of electric vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles.

Jaemyoung Pi received B.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2014, where he has been working toward the M.S. degree. His research interests include the design and control of hybrid electric vehicle.

Jingyu Choi received the B.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2012, where he has been working toward the M.S. degree. His research interests include the control of the powertrain system for Plug-in hybrid electric vehicle, and HMT.

Seulgi Lee received B.S. and M.S. degree in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2013 and 2015. His research interests include the powertrain system, control strategy of electric vehicles, hybrid electric vehicles, and HMT.
vehicles and plug-in hybrid electric vehicles. Since 2015, he has worked as an engineer in Hyundai Motor Company.

Inbeom Yang received a Ph.D. degree in control and instrumentation engineering from the Korea University, Seoul, Korea. He is the leader of the Smart Vehicle Technology R&D Division Korea Automotive Technology Institute. His main research interests include intelligent control system and control algorithms of hybrid electric vehicles.

Hyunsoo Kim received a Ph.D. degree in mechanical engineering from the University of Texas at Austin, Texas, USA, in 1986. Since 1986, he has worked as a Professor at Sungkyunkwan University. His main research interests include transmission system design, regenerative braking, power-distribution algorithms, vehicle stability control for hybrid electric vehicle and In-wheel Electric Vehicles.