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Power Management of a Hybrid Electric Vehicle During Warm-up Period Considering Energy Consumption of Cabin Heat Components

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Abstract: This paper proposes a predictive control for hybrid electric vehicles (HEVs) under conditions that exhaust heat power from an internal combustion engine (ICE) is needed. Owing to motor-generators (MGs) and a battery, the ICE in an HEV can be selectively operated under high efficiency conditions. This aims to reduce the amount of fuel converted into exhaust heat power as low as possible. However, this may cause a lack of heat power when an ICE is warming up or when the cabin heating system is operating in cold weather. Under such conditions, the ICE and MGs should be controlled to balance heat power, fuel consumption and electricity usage. In this paper, a predictive control is used with models for ICE, MG, battery, cabin heat components and ICE coolant. This control determines ICE power by minimising a cost function that includes predicted warm-up time and fuel consumption. Finally, the effectiveness of the control is demonstrated by simulation.

Keywords: Automotive control, Power management, Prediction method, Hybrid electric vehicle, Fuel efficiency

1. INTRODUCTION

Growing environmental awareness has motivated the development of fuel-efficient hybrid electric vehicles (HEVs) and their market share has been increasing. An HEV has an electric motor-generator (MG) as an extra driving power source, which provides more degrees of freedom to realize drivers' demands. This enables an internal combustion engine (ICE) to operate more efficiently and improves fuel efficiency. As the energy flow of HEVs becomes more complex than that of conventional vehicles, research has focused on methods to manage driving and electrical energy [Borhan, et al., 2009, Mura, et al., 2013, Beck, et al., 2006, Debert, et al., 2010, Guanetti, et al., 2014, Murgovski, et al., 2014].

Predictive control is a useful and regularly applied method. Predictive ICE and MG control include those based on battery status deterioration [Padovani, et al. 2013], driving distance [Kum, et al. 2010], driving route provided from GPS navigation system [Keulen, et al. 2010], hierarchical control with multiple sampling rates [Josevski, et al. 2014], control for gear changes [Khodabakhshian, et al. 2013]. The majority of research has focused on reducing exhaust heat power from the ICE and to transform fuel into driving power as efficiently as possible. These are valuable technologies when the ICE coolant temperature has already risen and exhaust heat power is unnecessary. However thermal constraints should be regulated when exhaust heat from an ICE is necessary such as during the warm-up phase or when supplying heat to the cabin in cold weather.

In recent years, several studies on these issues have been reported. Some examples include, energy management of HEV considering an ICE exhaust heat recovery system [Merz, et al. 2012], control considering heat energy for catalyst [Boehme, et al. 2013], ICE control on optimal engine power line during cabin heat system operation [Tashiro, et al. 2012], cabin heat thermal management controlling fuel consumption and battery state of charge (SOC) [Esen, et al. 2014].

This paper also concerns energy management of HEVs considering thermal constraints. The objective is to control ICE and MG power to reduce the ICE warm-up period and fuel consumption. In general, ICE power during the warm-up period is set higher than that required for driving, as determined from acceleration pedal operation, to generate excess ICE exhaust heat power. The MG uses this excess power to generate electricity. However, a high ICE power increases fuel consumption. When the battery SOC is high and close to its upper limit, the MG cannot generate electricity. Therefore, control needs to consider the balance of fuel consumption, coolant temperature and SOC. Our group has proposed control for balancing these parameters while the vehicle cabin heat system is not operating [Tashiro, et al. 2015]. However, this paper proposes an ICE and MG power control method, which also considers an operating cabin heat system.

In this paper, it is assumed that an HEV has two types of cabin heat components installed. The first is a heater core (HC) that uses exhaust heat power from the ICE accumulated in the coolant. This is used in conventional cars and is the main heat component on HEVs. Owing to the decreasing of the coolant temperature caused by taking heat, using an HC extends the warm-up period and reduces fuel economy. The second is an electrical heating component, such as a positive temperature coefficient (PTC) heater, which transforms

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battery-stored electricity into heat. This is a secondary component to compensate for low heat power from the HC at low coolant temperatures. It is necessary to account for the characteristics of these components to reduce the warm-up period and to avoid fuel consumption.

Here, an ICE and MG power control is designed which predicts future SOC and coolant temperature with models of ICE, cabin heat components, MG, battery and coolant. The ICE and MG power are determined by minimising a cost function, which considers warm-up time and fuel consumption. Performance and effectiveness of the control are verified by simulation.

2. STRUCTURE AND COMPONENTS

Figure 1 is a schematic of a power-split type HEV, as assumed in this paper. Two MGs, MG1 and MG2, are installed and MG2 is directly linked to the driving axle. Gear ratios among the ICE, the MG1 and the driving axle are set continuously by the power-split device with a planetary gear.

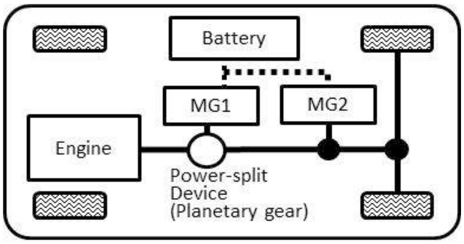

Fig.1. Configuration of a Power-split Hybrid Powertrain.

This car has two kinds of cabin heat components, the HC and PTC heater. The PTC heater is an extra cabin heat power source that compensates for the lack of cabin heat power from the HC at low coolant temperatures.

Figure 2 shows a block diagram of the control system with principal signal flows. The HEV control is verified using a simulation model. Its inputs are instruction signals for the ICE, MG1 and MG2. The outputs are signals relating to the HEV motion and parameters such as fuel consumption L_{fuel}, coolant temperature T_{clt}, battery SOC S_{oc}, etc. Details of the HEV simulation model are explained in Section 5.

There are four controllers — propulsion control, HEV management, powertrain control and cabin heat control — in the system. Among these, the propulsion control, cabin heat control and powertrain control, are assumed to have been previously designed. The propulsion control determines the requested driving power P_d from the acceleration pedal angle, operated by a driver. The cabin heat control operates the HC and PTC heater, and sends requested HC heat power H_{hc} and PTC heat power H_{ptc} to the HEV management. The powertrain control determines operation signals for the ICE, MG1 and MG2 in the HEV simulation model from the outputs of the HEV management.

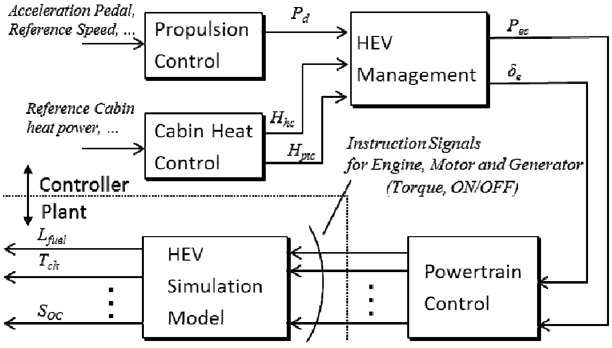

Fig.2. Block Diagram of the Control System.

An HEV management is designed in this paper. Its input signals are the driving power P_d, the battery SOC S_{oc}, coolant temperature T_{clt}, requested HC heat power H_{hc} and PTC heat power H_{ptc}. The output signal is requested ICE power P_{ec} and ICE ON/OFF signal δ_e. The ICE ON/OFF signal δ_e is set as (1).

$$\delta_e(t) = \begin{cases} 1 & ,ICE \quad working \\ 0 & ,ICE \quad stop \end{cases} \tag{1}$$

The HEV management includes an HEV prediction model that considers characteristics of fuel consumption and coolant heating of the ICE, battery SOC, heat and electrical power consumption of the HC, electricity consumption of the PTC heater, and coolant temperature.

3. PREDICTION MODEL

3.1 Overview

The prediction model accounts for the typical characteristics of an HEV to provide an HEV management function. The model comprises an ICE model, cabin heat components model, MG & battery model and coolant model. It is not necessary to distinguish between MG1 and MG2 in Fig.1 for control, so these are modelled as a single MG. The requested driving power P_d, is related to the requested ICE power P_e, and the requested MG power P_m can be expressed by (2).

$$P_d(t) = P_e(t) + P_m(t) \tag{2}$$

$$P_e(t) = \delta_e(t) \cdot P_{ec}(t) \tag{3}$$

Transmission losses in the HEV are ignored. P_d is determined from the acceleration pedal angle operated by the driver, and P_e is determined as (3) from the output of the HEV management. Consequently, P_m is automatically derived from (1). When P_m is positive, the MG consumes electricity and generates driving power, and when P_m is negative, the MG consumes driving power and generates electricity.

3.2 ICE model

The ICE model considers characteristics of fuel consumption and coolant heating. In general, the characteristics of fuel consumption are described from a table of ICE torque T_e and rotation speed ω_e. However, in this paper, fuel consumption is expressed by f_{Lfuel} in (4) as a function of P_e.

$$\dot{L}_{fuel}(t) = f_{Lfuel}(P_e(t)) \cdot P_e(t) \tag{4}$$