Improvement of Battery Charging Efficiency using 2-Clutch System for Parallel Hybrid Electric Vehicle

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Abstract

A battery charging control using a driving motor is proposed for an AT based parallel HEV. To charge the battery using the driving motor, a 2-clutch system control is proposed which uses the engine clutch and the clutch inside the transmission. The battery charging efficiency is estimated from the engine fuel consumption and efficiency of the power electronics. To evaluate the performance of the suggested battery charging control, HEV performance simulator is developed and simulations are performed for FTP-72 mode. Simulation results show that battery charging using the driving motor has a higher charging efficiency and faster charging speed compared with the conventional battery charging system using the ISG.

Keywords: 2-clutch system, ISG(integrated starter generator), driving motor

1 Introduction

The currently developed or mass-produced hybrid electric vehicle(HEV) are classified as the series type, parallel type and power split type. In parallel type HEV, transmission plays the key role, which combines and distributes the power of the engine and the motor. Automatic transmission(AT), continuously variable transmission, dual clutch transmission, automated manual transmission have been adopted as the transmissions for HEVs. In Fig.1 an AT based parallel HEV is shown, which is under study[1].

The target HEV has an engine clutch that connects or disconnects the engine with the motor, which provides the electric vehicle (EV) mode or the hybrid electric vehicle (HEV) mode. The HEV starts in EV mode and the operation mode is shifted to HEV mode when the driver wants to accelerate the vehicle [2].

The mode shift is performed by the ISG(integrated starter generator). The ISG of the HEV under
study (Fig. 1) is connected to the engine through a belt drive. When the mode shift begins, the ISG operates to increase the engine speed to the target speed for the engagement of the engine clutch[3]. Another important role of ISG is to charge the battery as a generator. The battery SOC (state of charge) might be lower than the lower-limit. In this case, the EV mode is limited until the battery SOC is recovered to the normal state. Moreover, if the battery SOC drops below the lower limit frequently, durability of the battery might be reduced. However, since the ISG uses a small motor with relatively low efficiency compared with driving motor, this charging process may decrease the total system efficiency. In this study, a battery charging control is proposed using a driving motor during vehicle stops to obtain the improved charging efficiency. To evaluate the charging efficiency, HEV performance simulator is developed and fuel economy of the 2-clutch system is investigated.

2 Battery charging system

2.1 Battery energy management strategy

For the battery management of the target HEV, the following battery SOC state are defined: SOC_High, SOC_Normal, SOC_Low[4].

1) SOC_High : In this mode, the battery is mostly used. The engine operation is decreased while the motor operation is increased.

2) SOC_Normal : In this mode, the engine and motor are working together under normal condition.

3) SOC_Low : In this mode, the engine is mostly used and the battery is charged. The engine operation is increased while the motor operation is decreased.

Fig. 2 shows the battery energy management strategy. \( SOC_{HtoN} \), \( SOC_{NtoH} \), \( SOC_{NtoL} \), \( SOC_{LtoN} \) are used to determine the battery SOC state. If \( SOC > SOC_{NtoH} \), the battery SOC state is changed to SOC_High. If \( SOC < SOC_{NtoL} \), the battery SOC state is changed to SOC_Low. If \( SOC_{LtoN} < SOC < SOC_{HtoL} \), the battery SOC state is changed to SOC_Normal. Battery charging during the vehicle stop is only performed when SOC_Low.

![Figure 1: Structure of AT based parallel HEV](image)

![Figure 2: Battery energy management strategy](image)
2.3 Charge by driving motor (Control 2)

Since a 30kW driving motor has a higher efficiency and power generation capacity than the 8.3kW ISG, it can restore the battery SOC to a stable range within a shorter time. Therefore, it is more advantageous to charge the battery by the motor than the ISG during the vehicle stop.

To charge the battery using the driving motor, a 2-clutch system control is proposed which uses the engine clutch and the clutch inside the transmission.

Structure of the 6-speed AT and operation of the friction elements are shown in Fig. 4 and Table 1. To transmit the power from the engine or motor to the driveshaft, at least two friction elements should be engaged (Fig. 4, Table 1). However, when the battery is charged by the driving motor, the driving motor and engine should be decoupled from the driveshaft. Therefore, one friction element of AT is disengaged to disconnect the motor from the driveshaft. For example, at 1st gear, the brake BK1 and one way clutch are engaged to transmit the power. To charge the battery using the driving motor, BK1 is disengaged while one way clutch is engaged [5-8].

At this moment, different from Control 1, the engine clutch is engaged and the engine operates the driving motor to charge the battery instead of ISG (Fig. 5).

2.4 Efficiency analysis for battery charging system

Fig. 6 shows the battery charging efficiency for Control 1 and Control 2. The battery charging efficiency is estimated from the engine fuel consumption and efficiency of the power electronics such as motor and inverter. Battery charging efficiency is calculated as follows:

\[
Charging\_efficiency = Engine\_efficiency \times PE\_efficiency
\]  

where the unit of the Engine efficiency is expressed as kwh/g. As shown in Fig. 6, the engine works in high efficiency region in Control 2 since the driving motor has larger power generation.
capacity than ISG, which provides the improved battery charging efficiency. The proposed battery charging control using driving motor, Control 2, shows a charging efficiency of 0.4kwh/g which is higher than ISG of 0.22kwh/g.

AT: The 6-speed AT consisted of two SPPGs (single pinion planetary gears), one DPPG (double pinion planetary gear), two wet-type multiple disc clutches, three wet-type multiple disc brakes, and a one way clutch. The operating elements of the AT such as planetary gears, clutches, and brakes were modeled using the AMESim software. The 1st step gear ratio \( N_1 \) is obtained as,

\[
N_1 = \frac{\omega_{in\_in}}{\omega_{in\_out}} = \frac{Z_{R1}}{Z_{S1}} \times \frac{Z_{R3}}{Z_{S3}}
\]

where \( Z_{R1} \) is the teeth number of the ring gear(R1), \( Z_{S1} \) the teeth number of the sun gear(S1), \( Z_{R3} \) the teeth number of the ring gear(R3), \( Z_{S3} \) the teeth number of the sun gear(S3), \( \omega_{in\_in} \) the AT input speed, \( \omega_{in\_out} \) the AT output speed. Gear ratios of the 2nd, 3rd, 4th, 5th and 6th gear steps can be obtained in a similar way.

Vehicle: The vehicle model consisted of a drive shaft, tires, and a running resistance model. The longitudinal vehicle dynamic equation is represented as,

\[
\dot{V} = \frac{1}{m_{veh} + \frac{1}{R_i^2(N_f/N_{in}T_e)}} - F_i - F_b
\]

where \( F_i \) is the road load, \( F_b \) the brake force, \( J_e \) the engine inertia, \( J_{cl} \) the clutch inertia, \( J_{in} \) the AT inertia, \( J_w \) the wheel inertia, \( T_e \) the engine torque, \( m_{veh} \) the vehicle mass, \( R_i \) the tire radius, \( N_f \) the final reduction gear ratio, \( N_{in} \) the AT gear ratio, and \( V \) the vehicle velocity.

A HEV performance simulator was developed based on the dynamic models of the HEV powertrain(Fig. 7)
4 Simulation results

To evaluate the performance of the suggested battery charging control, simulations were performed for FTP-72 mode using the HEV performance simulator. As shown in Fig. 8, in region (a), the battery SOC by Control 1 and Control 2 shows the same performance since the HEV is travelling. In region (b), Control 2 shows higher battery SOC compared with Control 1 because the driving motor operates with higher efficiency. Battery charging speed of Control 2 (0.28% per sec) is faster than Control 1 (0.08% per sec). As a result, the battery SOC state is recovered to SOC_Normal (SOC > SOC_Low) while the battery SOC of Control 1 still remains in the SOC_Low. In region (C), due to the difference of the battery SOC state, the engine output power of the Control 1 becomes larger than that of Control 2. Therefore, the battery SOC difference between Control 1 and Control 2 is reduced. It is seen from the simulation results that the final battery SOC of Control 2 (38.8%) has higher value compared with that of Control 1 (37.2%).

5 Conclusions

A battery charging control using a driving motor was proposed for an AT based parallel HEV. To charge the battery using the driving motor, a 2-clutch system control was proposed which uses the engine clutch and the clutch inside the transmission. In this control, one friction element of AT should be disengaged to disconnect the motor from the driveshaft. The engine clutch is engaged and the engine operates the driving motor to charge the battery instead of ISG. The battery charging efficiency is estimated from the engine fuel consumption and efficiency of the power electronics. The proposed battery charging control has a charging efficiency of 0.4kwh/g which is higher than ISG charging efficiency of 0.22kwh/g.

To evaluate the performance of the suggested battery charging control, a HEV performance simulator was developed and simulations were performed for FTP-72 mode. Simulation results show that the battery charging using the driving motor has a higher efficiency and faster speed compared with the conventional battery charging system using the ISG.
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References


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