EVS27 Symposium
Barcelona, Spain, November17-20, 2013

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

Minseok Song[1], Seokhwan Choi[1], Gyeonghwi Min[1], Jonghyun Kim[2], Hyunsoo Kim[1*]

[1] *School of Mechanical Engineering, Sungkyunkwan University, 300 Chunchun-dong, Jangan-gu, Suwon 440-746, Korea(aneol23@skku.edu)*

[2] *Hybrid Electric Vehicle Design Team, Hyundai-Kia R&D Center, 772-1 Jangduk-dong, Hwasung-si 135-080, Korea*

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.

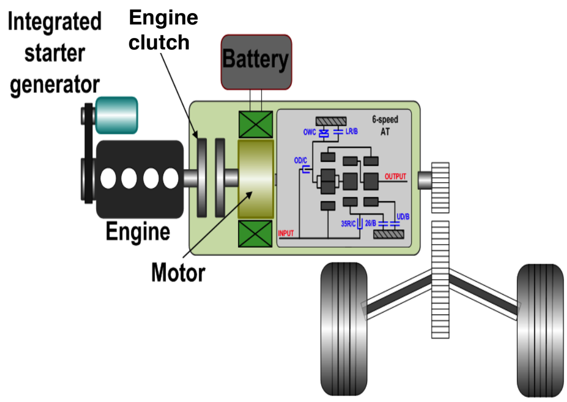


Figure1: Structure of AT based parallel HEV

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 $SOC_{LtoN} < SOC < SOC_{HtoN}$, the battery SOC state is changed to SOC_Normal. Battery charging during the vehicle stop is only performed when SOC_Low.

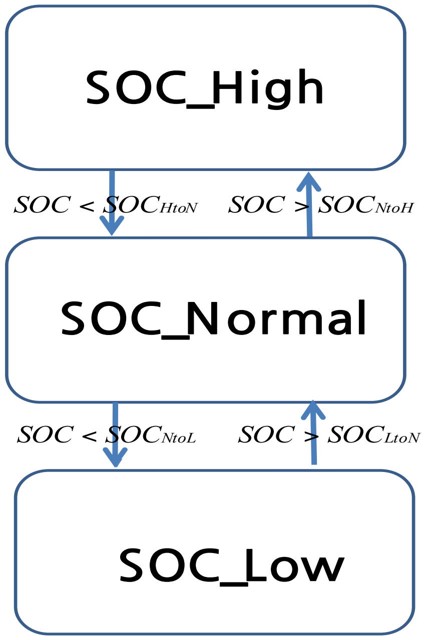


Figure2:Battery energy management strategy

2.2 Charge by ISG(Control 1)

The ISG is used as a generator which has a power capacity of 8.3kw. The engine operates the ISG, which generates the electric power to charge the battery. The engine power is determined depending on the electric load of the ISG. The engine clutch is disengaged (Fig. 3), which means that the engine and ISG are decoupled from the driveshaft.

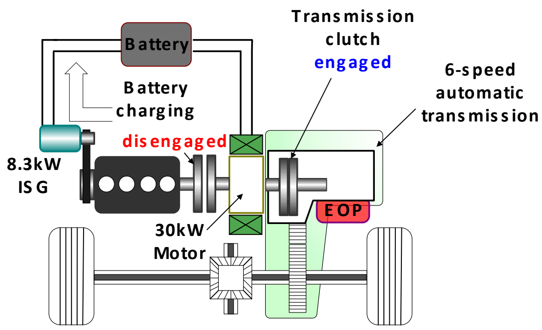


Figure3:Charge by ISG (Control 1)

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, Table1). 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).

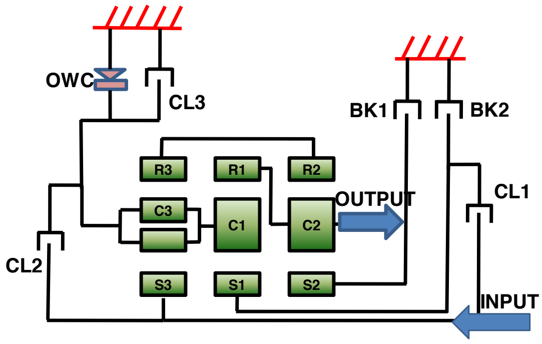


Figure4: Structure of the 6-speed AT

Table1:Friction elements operation

	BK1	BK2	CL1	CL2	CL3	OWC
1ST	O					O
2ND	O	O				
3RD	O		O			
4TH	O			O		
5TH			O	O		
6TH		O		O		

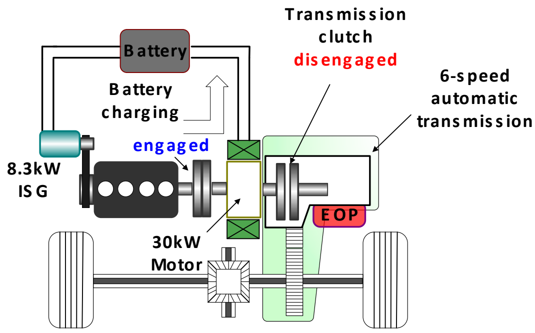


Figure5: Charge by driving motor (Control 2)

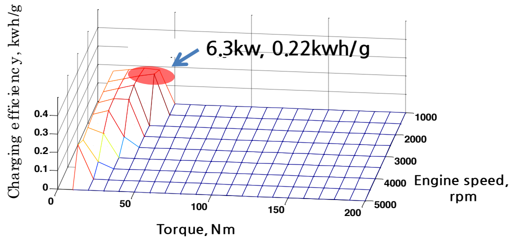
2.4 Efficiency analysis for battery charging system

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:

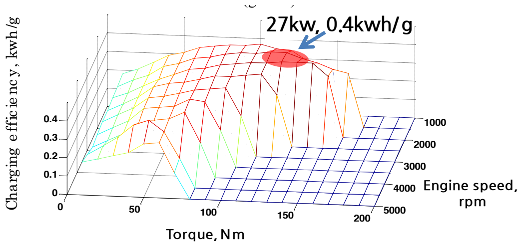
$$Charging\_efficiency = Engine\_efficiency \times PE\_effcinecy \quad (1)$$

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.



(a) Control 1



(b) Control 2

Figure6:Battery charging efficiency

3 HEV Performance Simulator

To evaluate the fuel economy of the battery charging control, dynamic models of the relevant HEV powertrain and HEV performance simulator were developed.

Engine: The engine was modeled using the engine characteristic map. The engine output torque was modeled as a first order system.

Motor: The motor is used as electric motor when driving and as a generator during regenerative braking. The ISG cranks the engine during the engine start. The motor and ISG were modeled using characteristic curves and efficiency maps.

Battery: The input and output currents of the battery were calculated using the internal resistance model. For the battery internal resistance, the experimental results according to the battery SOC were used.

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,

$$N_1 = \frac{\omega_{tm\_in}}{\omega_{tm\_out}} = \frac{(\frac{Z_{R1}}{Z_{S1}}+1)(\frac{Z_{R3}}{Z_{S3}})}{\frac{Z_{R1}}{Z_{S1}}} \quad (2)$$

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), ω_{tm_in} the AT input speed, ω_{tm_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,

$$\dot{V} = \frac{\frac{1}{R_t}(N_f N_{tm} T_e) - F_l - F_b}{m_{veh} + \frac{1}{R_t^2(N_f^2 N_{tm}^2 (J_e + J_c) + N_f^2 J_{tm} + 2J_w)}} \quad (3)$$

where F_l is the road load, F_b the brake force, J_e the engine inertia, J_c the clutch inertia, J_{tm} the AT inertia, J_w the wheel inertia, T_e the engine torque, m_{veh} the vehicle mass, R_t the tire radius, N_f the final reduction gear ratio, N_{tm} 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)

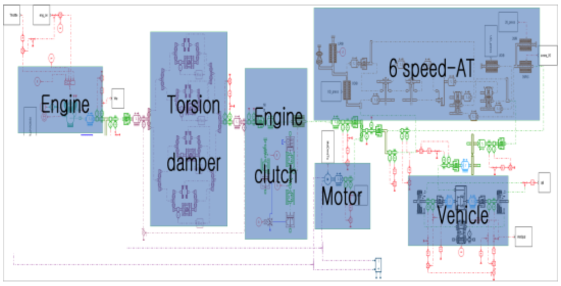


Figure7:HEV performance simulator

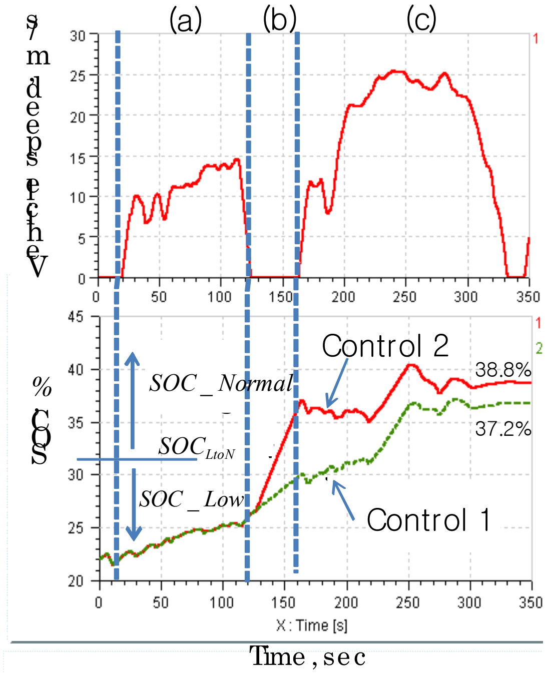


Figure8:Battery charging during FTP-72 mode travel

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($SOC > SOC_{LtoN}$) 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.

Acknowledgments

This work was supported by the Technology Innovation Program funded by the Ministry of Knowledge Economy(MKE, Korea).

References

[1] The Boston Consulting Group "The come back of the electric car, how real, how soon, and what must happen next", *BCG report*, 2009.

[2] S. Kim et al., "A study on control strategy for hybrid electric vehicle during mode change", KSAE 2008 Annual Conference, 2008

[3] M. Song et al., "Motor control of a parallel hybrid electric vehicle during mode change without an integrated starter generator", Journal of Electrical Engineering & Technology, Vol.6, No.22, 742-749, 2013

[4] B. Min et al., "Development of fuel economy improvement technique for hybrid electric vehicle by using driving condition prediction", KSAE annual conference, 2011

[5] J. Motosugi et al., "Development of a slip control system for RWD hybrid vehicle using integrated motor-clutch control", SAE 2011-010945, 2011

[6] F. Renken et al., "Power electronics for hybrid-drive systems" Power Electronics and Applications, 2007 European Conference

[7] I. Soliman et al., "Control of electric to parallel hybrid drive transition in a dual-drive hybrid powertrain", SAE paper 2010-01-0819, 2010.

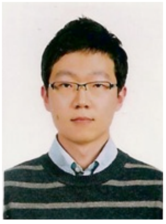
Authors

Minseok Song

He received B.S and M.S in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2009 and 2011, where he has been working toward Ph. D. degree. His research interests include modeling and control of powertrain system for hybrid electric vehicle and plug-in hybrid electric vehicle

Seokhwan Choi

He received B.S in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2012 where he has been working toward M.S. degree. His research interests include modeling powertrain system for hybrid electric vehicle



Gyeonghwi Min

He studies for a master's degree in mechanical engineering from Sungkyunkwan University, Korea. His research interests modeling and control of hybrid vehicle.

Jonghyun Kim

He received a B.S. in mechanical engineering from Sungkyunkwan University, Suwon, Korea, in 2002. Since 2006, he has worked as an engineer at Hybrid Transmission part of HEV system engineering team in Hyundai Motor Company. He is in charge of developing oil pump of hybrid transmission including electric oil pump.

Hyunsoo Kim

He received a B.S. in mechanical engineering from Seoul National University, Seoul, Korea, in 1977, a M.S. degree in mechanical engineering from the Korea Advanced Institute of Science and Technology (KAIST), Seoul, Korea, in 1979, and 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, Chairman, and Dean of the College of Engineering at Sungkyunkwan University. His main research interests include Hybrid Electric Vehicle (HEV) transmission system design, regenerative braking, and optimal power-distribution algorithms for HEV and vehicle stability control for HEV and In-wheel Electric Vehicles. He has authored numerous journal papers and patents.

Prof. Kim served as a President of Electric Drive Vehicle Division of the Korea Society of Automotive Engineers and an editor of the International Journal of Automotive Technology from 2005 to 2012. He has served the society as a leader in next-generation automotive technology in Korea.