OPTIMAL CONTROL STRATEGY OF PLUG-IN HYBRID ELECTRIC VEHICLES

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ABSTRACT
Development of eco-friendly vehicles is in progress in order to reduce emissions of greenhouse gas and oil usage. Among the eco-friendly vehicles, plug-in hybrid electric vehicles (plug-in HEV) have attracted much attention. Unlike the existing hybrid vehicle, the control method of the plug-in hybrid vehicle is different, because the distance that can be driven only by the motor increases now. In this paper, we'll describe the equivalent consumption minimization strategy (ECMS) that has been used in hybrid vehicles. However, this control strategy is difficult to be applied for to an actual vehicle because parameters are changed according to the driving cycle. Thus, this paper suggests a novel ECMS control strategy to overcome these limitations. As a result, compared with other control strategies, the novel ECMS control strategy can appear the best result of improving the fuel economy, and it is less sensitive to changes in the driving cycle.

Keywords: Plug-in hybrid electric vehicle, Equivalent Consumption Minimization Strategy, Energy management control, Parallel hybrid vehicle system

1. INTRODUCTION

Currently, the automotive industry′s fuel economy regulation has been continued to be strengthened for reducing green house gas emissions due to the destruction of the natural environment, such as air pollution. A variety of eco-friendly vehicles are released to correspond these regulations and the eco-friendly vehicles such as the HEV, plug-in HEV, Electric vehicle are getting the attention. Also, the conventional vehicle has used only the engine as a power, but otherwise in the HEV, the motor is added. Thus, various control strategies have been studied for power distribution of the engine and the motor (Al-Alawi, et al. 2013, Shaik, et al. 2010).

Due to the limitations in the battery capacity, the conventional HEV supports to assist the power of the engine. If the battery capacity is increased slightly, it supports the EV function at low speed. However, in the case of plug-in HEV, the power of the battery capacity and the motor is greatly increased, so that the distance that can be driven motor is dramatically increased. A range of driving using only the electric motor is called a CD (Charging-Depletion) and in the case of that the battery reaches a threshold, a driving range in the normal hybrid drive mode is called CS (Charging-Sustaining). Unlike the hybrid vehicle, plug-in HEV control method is classified into two types due to the CD-CS mode. The first is the CDCS control strategy, and the second is a Blended mode control strategy (Sharer, et al. 2012, Gonder, et al. 2007, Torres, et al. 2014, Zhang, et al. 2011).

In the CDCS control strategy, the vehicle initially uses the motor only, and when the SOC has reached the limit value, it uses the motor and engine. On the other hand, Blended-mode is a control strategy that distributes the entire driving range into motor and the engine properly. Assuming that the total trip distance is longer than the distance which can be driven by a motor, when the battery reaches a threshold, the CD stage ends and CS stage that frequently uses the engine at low speed begins, so that it takes an adverse effect on fuel economy. Blended mode control Strategy can overcome this disadvantage according to the distribution of the torque. In this regard, various studies have been proceeding.

There have been a lot of studies for distributing power of HEV and plug-in HEV. There is a way that minimize the fuel consumption by optimizing the parameters using the Genetic Algorithm, which is one of the way to find a optimal solution and simulate the process of evolution (Salisa, et al. 2009, Piccolo, et al. 2001, Chen, et al. 2014). Also, by using the road traffic information such as GPS and GIS, if the starting point and destination are determined by reflecting the traffic information, modelling the optimized driving cycle has been conducted as to the global optimization with Dynamic Programming method (Gong, et al, 2007, Karbowski, et al, 2013, Gong, et al, 2009, Zhang, et al, 2010). And it is in progress to use a Utility Factor, which is one of methods for calculating the fuel consumption of the plug-in HEV to improve the fuel economy based on the driving statistical data of the vehicle (SAE J2841 2010, SAE J1711 2010, Wang, et al. 2013, Hou, et al. 2014). In addition, there are many studies of the control strategy to distribute the torque of the engine and the motor so as to minimize the objective function with the battery power and the fuel consumption by the equivalent (Pourabdollag, et al 2012, Geng, et al. 2011, Paganelli, et al. 2010, Sciarretta, et al. 2004, Musardo, et al. 2005, Tulpule, et al. 2009, Paganelli, et al. 2002). Assuming that drivers entry the distance into the vehicle, optimal control as the Pontryagin's Mimimum Principle using the optimal solution of Euler-Lagrange equation is also studied (Kim, et al. 2012, Kim, et al. 2011, Hou, et al, 2014, Yuan, et al. 2013).

This paper will point out the limitations of previous ECMS (P-ECMS) control depending on the parameters according to the driving cycle. Next, for solving the problems, we will suggest a novel ECMS control (N-ECMS) strategy that is adaptive to changes in the driving cycle. Also, the simulation will be carried out in two aspects. First, CDCS and N-ECMS control strategy will be compared in terms of fuel consumption. Second, P-ECMS and N-ECMS control strategies will be analyzed in respect of the fuel economy with the driving cycle of the NEDC and UDDS. Overview of the paper will be described in the model of the vehicle and then will present N-ECMS control strategy in comparison with other strategies. The proposed algorithm will be simulated by the driving cycles such as the NEDC and UDDS cycle.

2. THE MODELING OF THE PARALLEL HEV

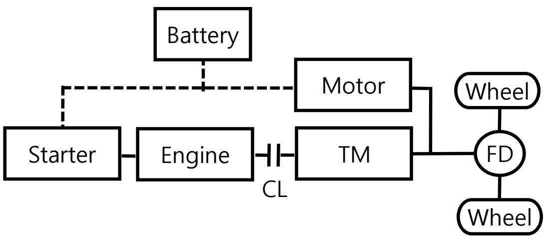

Figure 1: Reference Vehicle

Fig.1 is a model of the vehicle, which was constructed based on the Autonomie developed by the Argonne Institute testing the performance and fuel economy of the various vehicle. Starter represents the start Engine, TM is the transmission, CL is the clutch, FD is the final drive. The Structure of the system is a parallel type hybrid vehicle architecture. The engine is connected to the transmission via the clutch. Then, the sum of the engine and motor power is delivered to the final drive. Information from the main components of the vehicle is in the table 1 and the parameters of the vehicle are in the table 2.

Table 1: The main components of Plug-in hybrid electric vehicle

Engine	75kW 1.8L diesel engine
Motor	50kW PM motor
Battery	240V, 41Ah lithium-ion battery

Table 2: Vehicle Parameters

Curb Weight (kg)	1680
Frontal Area (m^2)	1.23
Rolling Coefficient	0.008
Aerodynamic Coefficient	0.3
Air density (kg/m^3)	1.23
Final drive ratio	3.63

2.1. Power distribution model

The variable u(t) distributes the torque of the engine and the motor. The torque of the engine and the motor is composed of a combination of the demand wheel torque and u(t) represented by the following formula. :

$$u(t) = \frac{T_{mot}}{T_{whl.dmd}} \quad where \;\; 0 < u < 1 \qquad (1)$$

where T_{mot} is the motor torque, $T_{whl.mot}$ is the demand wheel torque, u(t) is the control variable for distribution the engine and motor power.

$$T_{mot} = u(t) \cdot \frac{T_{whl.dmd}}{R_{fd}}$$
$$T_{eng} = (1 - u(t)) \cdot \frac{T_{whl.dmd}}{R_{fd}} \cdot \frac{1}{R_{gb}} \qquad (2)$$

where T_{eng} is the engine torque, R_{fd} is the Final drive ratio, R_{gd} is the Gear ratio

2.2. Fuel and Battery power consumption model

The fuel consumption of the engine consists of a lookup table of the engine map with torque and speed of engine. Battery power is also configured with a motor map receiving the motor torque and speed. The formula is expressed as follows :

$$\dot{m}_{eng} = f_{eng}(T_{eng}(t), w_{eng}(t))$$
$$P_b = f_b(T_{mot}(t), w_{mot}(t)) \qquad (3)$$

where $w_{eng}(t)$ is the engine speed, $\dot{m}_{eng}$ is the fuel rate. $w_{mot}(t)$ is the motor speed, $P_b(t)$ is the battery power.

2.3. Battery model

The battery model is to be applied for the actual real-time due to the complex chemical model. Therefore, the simplified internal resistance model (Rint model) is used for use in the control strategy. The relationship between the parameters of the battery is represented by the following formula:

$$\frac{dSOC}{dt} = -\frac{i_b(t)}{Q_b}$$
$$i_b(t) = \frac{V_{oc} - \sqrt{V_{oc}^2 - 4R * P_b}}{2R} \qquad (4)$$

where SOC is the battery state of charge, $i_b(t)$ is the battery current, Q_b is the nominal capacity of the battery, V_{oc} is the open circuit voltage, R is the constant battery resistance.

2.4. Vehicle model

A longitudinal dynamic model is applied to the vehicle and losses, such as air resistance, gravity, degree are considered. The traction force at the wheel is computed as follow :

$$F_{veh}(t) = F_r + F_w + F_g + F_a + F_{brk}$$
$$= \frac{1}{2}\rho C_D A_f v(t)^2 + mg\sin\theta + mg \cdot f_r \cos\theta + m\frac{dv}{dt} + F_{brk}(t)$$
(5)

where F_r, F_w, F_g, F_a, m, g, ρ, f_r, A_f, C_D, θ, v and F_{brk} is the rolling resistance, the aerodynamic drag, the grade, the acceleration force, the vehicle mass, the gravitational acceleration, the air density, the rolling resistance, the front area, the air drag coefficient, the road angle, the vehicle speed and the braking force.

3. CONTROL STRATEGY

Fig.2 is a graph referred to (Sharer, et al. 2012). The first graph represents a case of using the CDCS control. In CD stage, the engine is off and the motor is only driven. The CS stage is operating in the hybrid mode, and it gives an adverse effect on fuel economy because the engine is operating in the low speed range at low efficiency. The second graph represents a case of using a Blended mode control (Hou, et al. 2014). In the low-speed range, for the efficiency of the engine is low, the vehicle is driven by the motor. On the other hand, in high-speed range, the vehicle is driven by the engine for the efficiency of engine is high. As a result, the overall fuel economy is improved. Fig.3 is a graph of the SOC of the CDCS and Blended strategy based on the NEDC cycle. CDCS is clearly divided into two sections, as a CD and CS stage, and the SOC is quickly exhausted, whereas Blended mode falls slowly and steadily the SOC. Consequently, this process brings the more efficient distribution of the engine and the motor torque in the high and low speed, and SOC is used to the last. Also, time to reach the limit SOC and the end time of trip are almost similar. That is, blended mode uses the engine and the motor more efficiently. After that, CDCS, P-ECMS and N-ECMS control strategies will be described.

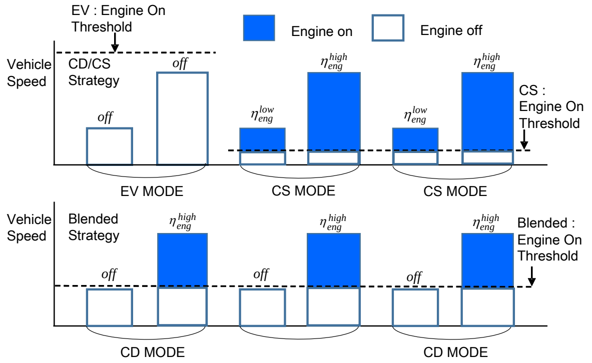

Figure 2: CDCS strategy and Blended Strategy

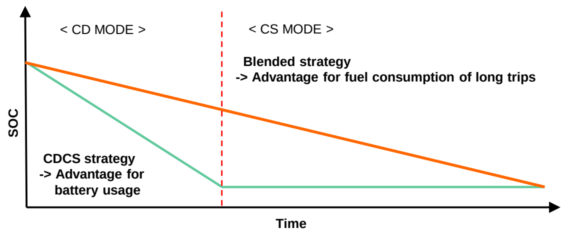

Figure 3: SOC of the CDCS and Blended Strategy

3.1. CDCS Control Strategy

The CDCS control strategy is divided into a total of two steps. The first step is a CD (Charging-Depletion) stage. In this case, the formula is represented as (6). The value is divided into the gear ratio by the demand torque of the wheel of the motor torque. Only the vehicle is driven by battery power and the engine is turned off. The second is the CS (Charging-Sustaining) stage. The vehicle is operating in hybrid mode and the engine is switched on to maintain the SOC. It can be shown that (7). The torque of the engine and the motor is calculated by a method using the maximum torque of the engine and vehicle model. The advantage of the CDCS is what uses the battery to the maximum. If the distance is shorter than the total trip to drive only a motor, it is possible that the vehicle is driven by electric without the fuel consumption at all. However, when the total distance is longer than the trip to drive only a motor, it will increase the stage of the hybrid mode. Therefore, the fuel consumption drastically increases. For this reason, the optimal strategy such as blended mode will be required for optimal distributing the torque of the engine and motor over the entire trip.

CD stage :

$$T_{mot} = \frac{T_{whl.dmd}}{R_{fd}} \qquad (6)$$

CS stage:

$$\begin{cases} T_{eng} = \min\left(T_{eng.\max}, \left(\frac{T_{whl.dmd}}{R_{fd}} - T_{mot}\right)\cdot\frac{1}{R_{gb}}\right) \\ T_{mot} = \frac{T_{whl.dmd}}{R_{fd}} - \min\left(T_{eng.\max}, \frac{P_{whl}}{w_{eng}}\right)\cdot R_{gb} \end{cases} \qquad (7)$$

Where $T_{eng.\max}$ is defined as the maximum torque of the engine, P_{whl} is the power of wheel.

3.2. ECMS Control Strategy

3.2.1. The Basic Idea of Control

In this paper, to compensate for the weaknesses of the CDCS control strategy, the ECMS control strategy that has been studied in a hybrid system is proposed in consideration of the plug-in hybrid system. The real-time control of ECMS control strategy first obtains the fuel consumption for the demand power of the engine and the equivalent of the demand power of the battery. Then, it distributes the torque to the engine and the motor so as to minimize the sum of the fuel consumption and equivalent fuel. The objective function of ECMS is

$$\min J(t) = E_f(t) + s(t) \cdot E_e(t) \quad (8)$$

$$\begin{aligned} E_f(t) &= \dot{m}_f(T_{eng}(t), w_{eng}(t)) \cdot H_{LHV} \\ E_e(t) &= V_{bat.oc}(t) \cdot I_{bat}(t) \end{aligned} \quad (9)$$

$E_f(t)$ represents energy of the fuel consumption for the demand power of the engine. $E_e(t)$ is the energy for the demand power of the battery. H_{LHV} is low heating value of fuel. Energy per unit time of the engine is calculated by a product with fuel consumption and H_{LHV}. The variable s(t) is an equivalent factor between the fuel energy and electric energy. That is, s(t) is a factor that adjusts the cost between energies. If equivalent factor is large, the electric energy usage is penalized and the fuel energy is used more. On the other hand, if the equivalent factor is small, the electric energy is used more and the fuel energy is saved, but the battery is exhausted before the entire trip. In other words, the equivalent factor directly affects the fuel consumption by determining remained capacity of the battery. Therefore, it is necessary to select the appropriate equivalent factor.

3.2.2. P-ECMS control strategy

The typical ECMS control strategy is to use the Self-sustaining in the electrical path (Pourabdollah , et al. 2012, Sciarretta, et al. 2004, Musardo, et al. 2005). Sciarretta suggests method of calculating the equivalent factor to use two constant factors of s_{dis} , s_{chg} . It is related with energy route for the equivalent fuel flow consumption of electric path (Paganelli, et al. 2002).

3.2.2.1. Calculation of the ECMS parameters

In order to obtain the equivalent factor, control system is calculating the parameters. Equation of (1), u is control variable to determine ratio of the engine and motor torque. In the case of plug-in HEV, the maximum of SOC is 90% and minimum of SOC is 20%. The goal here is to analysis the tendency of the charge and discharge rate. Thus, the SOC initial is setting 60%. u_r of the maximum value of u is the value that it is reached the maximum SOC and u_l of the minimum value of u is the value that it is reached the minimum SOC. Also, U_o represents point of the battery of first turning to negative energy. On the basis of the point U_o , the slope of the points with the positive energy is defined as s_{chg} and the slope of the point with the negative energy is s_{dis} . Simulation with respect to the input value between 0 and 1 can be obtained the total fuel energy and battery energy, such as Fig.4. The elements relate with the efficiency of mechanical and electrical power-train connection. Two elements will depend on the driving cycle, thus, the values will be calculated in advance.

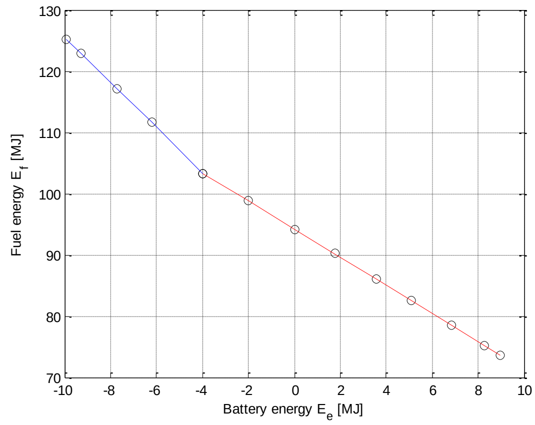

Figure 4: Relation of Fuel and Battery energy

3.2.2.2. Equivalent Factor

$$\begin{aligned} s(t) &= p(t)s_{dis} + (1 - p(t))s_{chg} \\ p(t) &= \frac{E_e^+(t)}{E_e^+(t) - E_e^-(t)} \end{aligned} \quad (10)$$

The probability factors are represented in the equation (10) and the probability of the fuel energy consumption during the remaining distance from the current point is estimated. If p(t) is 1, s(t) is the s_{dis} . Then, the battery will be charged and fuel consumption will increase. On the contrary, if p(t) is 0, s(t) is the s_{chg} . In this case, the battery will be discharged and the fuel is to be saved. That is, p(t) is a factor for calculating a probability charge and discharge. $E_e^+(t)$ and $E_e^-(t)$ is the estimating value of the maximum positive and negative energy during the remaining trip, considering the current value of $E_e(t)$.

$$\begin{aligned} E_e^+(t) &= E_e(t) + E_{\max}^+(t) - E_{rebrake}(t) \\ E_e^-(t) &= E_e(t) - E_{\max}^-(t) - E_{rebrake}(t) \end{aligned} \quad (11)$$

Equation of (11), The $E_e(t)$ represents a difference in initial battery energy and the current battery energy. The $E^{+}_{\max}(t)$ means the maximum electrical energy used to propel the vehicle when u_r reaching the 20% of the SOC for the rest of the trip is entered into the input. The $E_{brake}(t)$ is a braking energy capable of regenerative braking energy for the rest of the trip. The $E^{-}_{\max}(t)$ is the maximum electrical energy to be charged when $-u_l$ reaching the 90% of the SOC for the rest of the trip is entered into the input. The detailed description of the individual equation is the following paper (Sciarretta, et al. 2004). Here, the second and third elements are calculated as parameters obtained through the driving cycle.

In this process, p(t) is calculated. In addition, equivalent factor is determined through s_{dis}, s_{chg}. p(t) in the graph is obtained by the driving cycle in advance. As a result, equation (8) is applied to s(t) and finds the minimize control value u(t) to the cost function. ECMS control instantaneously selects the control variable u(t) to distributes the optimal torque of the engine and motor.

3.2.3. N-ECMS control strategy

P-ECMS control strategy has the advantage to allocate the optimal torque of the engine and motor but the disadvantage to depend on the driving cycle determining the equivalent factor. Figure.5 shows a flow chart for selecting the equivalent factor to P-ECMS control strategy.

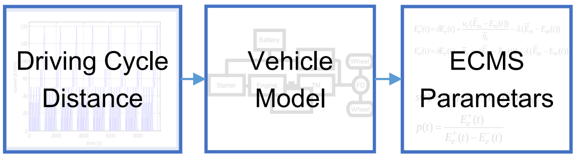

Figure 5: Flow chart to determine the equivalent factor

Determining the equivalent factor can be accomplished in three steps. First, the simulation corresponding the driving cycle is repeatedly performed. Then, the values $E_e(t)$, $E_f(t)$ are collected while the vehicle model applied in the equation (2) according to the input u which distributes the torque of engine and motor. The relationship between the two values is represented by a graph as shown in Fig.4. And parameter like slope is substituted in the equation (11). As a result, the corresponding parameters are fixed according the driving cycle. It is difficult to use in real time. Also, the plug-in HEV is added to the concept of driving distance to the motor. If the distance is changed, the parameters also vary as well. That is, the previous control method is dependent on these parameters in two aspects, such as the driving cycle and distance. Thus, the control does not work properly with this difficulty. Therefore, even if there are no the knowledge about driving and distance, a new control way should be adopt to get the best fuel economy effects.

3.2.3.1. The Relation between the energy at the wheel and distance

Fig.4-1 represents the energy at the wheel about the NEDC driving cycle repeated 8 times.

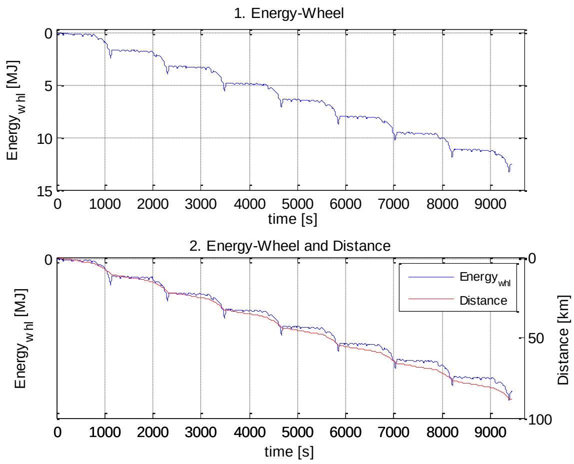

Figure 6: The energy in the wheel and Distance

The wheel at the energy is computed by first term of equation (12). The t_{final} represents the final time of the driving cycle. If the current time is the t_{final}, the total wheel energy has the maximum value. In case that the battery is used to decrease the wheel at the energy and the battery SOC with the same slope, the SOC reaches the $SOC_{\min}$ at the end of the trip. In other words, when s(t) is chosen, the criterion about decreasing the any slope is needed and s(t) has to be selected by that criterion.

$$E_{whl}(t) = \int_0^{t_{final}} T_{whl}(t) \cdot w_{whl}(t)\,dt$$
$$D(t) = \int_0^{t_{final}} Chas_{spd}(t)\,dt \qquad (12)$$

where E_{whl} represents the energy at the wheel, D(t) is the current distance, $Chas_{spd}(t)$ is the vehicle speed.

Fig.4-2 is a plot concerning the energy in the wheel and distance. The distance of the vehicle is computed by second term of equation (12). If the current time is t_{final}, the trip is finished and then it means that the total trip is completed. The energy of the wheel and distance is similarly dropped. Namely, SOC_{ref}, the reference decreasing the battery SOC, has to been chosen via the data of the trip distance. Then, s(t) is determined by tracking the SOC and this is the most important algorithm in the paper.

3.2.3.2. Determination of the equivalent factor

Next, SOC_{ref} and s(t) is defined as (13).

$$SOC_{ref}(t) = SOC_{init} - \frac{D(t)}{D_{tot.d}} \cdot (SOC_{init} - SOC_{end})$$
$$s(t) = K \cdot (SOC_{ref}(t) - SOC(t)) \quad (13)$$

where SOC_{init} is the initial value of the battery SOC, SOC_{end} is the final value of the SOC, SOC_{ref} is the reference value of the SOC, $D_{tot.d}$ is the total distance.

The method of calculating SOC_{ref} is referred to the [18]. If the total distance is known in advance, SOC_{ref} represents the equation of decreasing the SOC according to trip range. The variable s(t) is to reduce the difference between the SOC_{ref} and SOC to be feedback. The factor of K is feedback gain to reduce them. Fig.7 is a graph about SOC and equivalent factor over the NEDC cycle repeated 1 times.

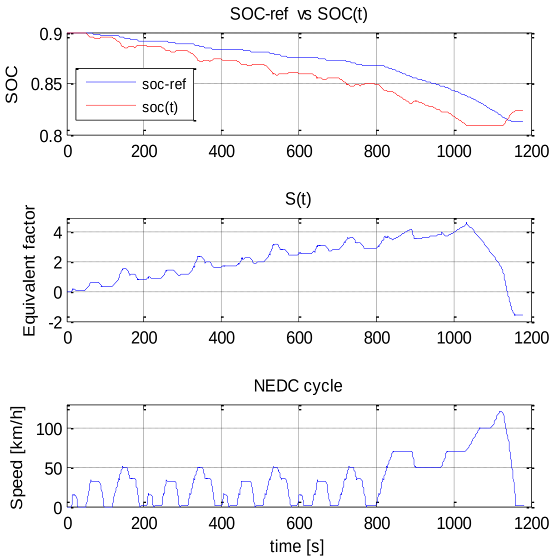

Figure 6: Relations between SOC and s(t)

When the driving cycle becomes the end time, the battery SOC is able to track the SOC_{ref} in order to coincide them. Then, s(t) is changed by depending the difference between the current SOC and SOC_{ref}. If equivalent factor is small, the motor is frequently used. In contrast, if it is large, the engine is mainly operated. SOC_{ref} is suddenly decreased after 800 second, It is because that the distance is increased according to high speed. Thus, s(t) is increased and then the equivalent factor is determined to use the engine primarily.

4. SIMULATION RESULTS

The data of reference vehicle is applied by Autonomie software. The simulation is performed by the NEDC and UDDS cycle in the Fig 7-8. The NEDC cycle reflects the circumstance of the urban and highway. It is repeated 8 times and the driving distance is about 89km. The UDDS is the urban driving cycle. It is repeated 7 times and the total trip is about 83km. With these data, the algorithm will be analyzed in aspect of fuel consumption. First, the ECMS control is compared to the CDCS control in terms of fuel economy using the Matlab/Simulink. Second, using the two driving cycle, P-ECMS control strategy utilizing the parameters optimized in the NEDC cycle will be compared and analyzed with N-ECMS control strategy. Control logic used in the simulation parameters are as follows.

Table 3: Simulation Parameters

Type of Data	Parameters	Values
Equivalent Factor	s_{dis}	3.63
	s_{chg}	2.31
SOC	SOC_{init}	0.9
	SOC_{final}	0.2
Distance	$D_{nedc\cdot 8cycle}$	88.1km
	$D_{nedc\cdot 7cycle}$	83.9 km
K factor	K	1000

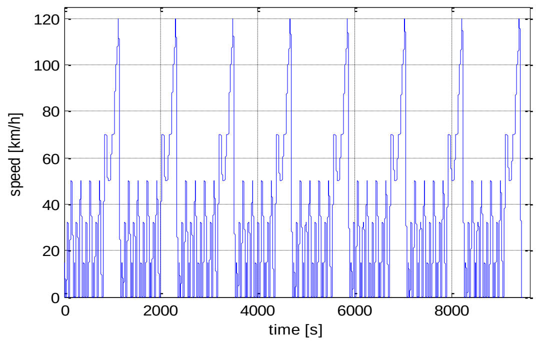

Figure 7: NEDC repeated 8cycle

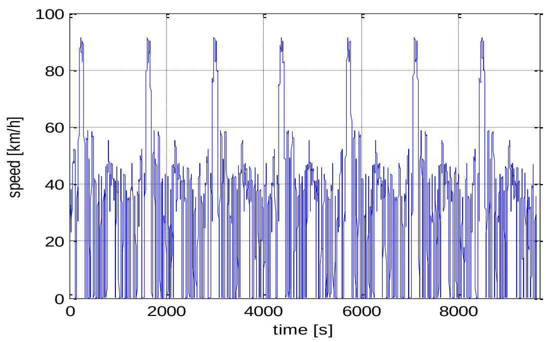

Figure 8: UDDS repeated 7cycle

4.1. Comparison with CDCS and ECMS control strategy

In this section, the simulation is performed about the CDCS and N-ECMS control strategies. Each control strategies to the power of the engine and motor are shown in Fig 9-10. The power of the engine has not been changed in the CDCS before the battery SOC drops below 0.2 and the engine is operated since 4500s. Also, in the CS stage, the vehicle is to be operated in the hybrid mode and the engine is frequently worked. Fig.10 is the plot of the ECMS control and the engine evenly works over a total trip. Because the equivalent factor is selected by tracking the SOC_{ref}, time to reach the limit SOC and trip end time become similar. In result, the torque of the motor and engine is efficiently distributed. In other words, ECMS control little uses the engine in terms of fuel consumption to minimize the fuel consumption by the objective function in comparison to the CDCS control. Also, in the Fig.11, ECMS control uses the motor to track SOC_{ref} and SOC is used up to $SOC_{\min}$. Thus, N-ECMS can distribute the torque to the engine and motor optimally than CDCS.

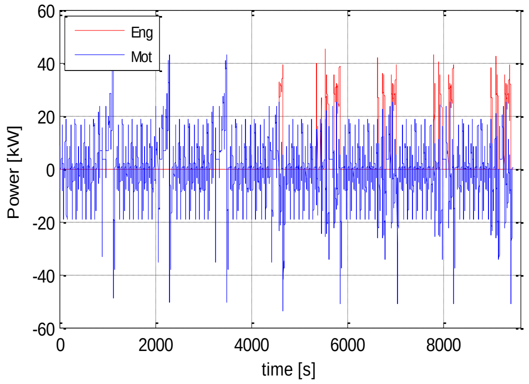

Figure 9: CDCS control the power of Engine and Motor

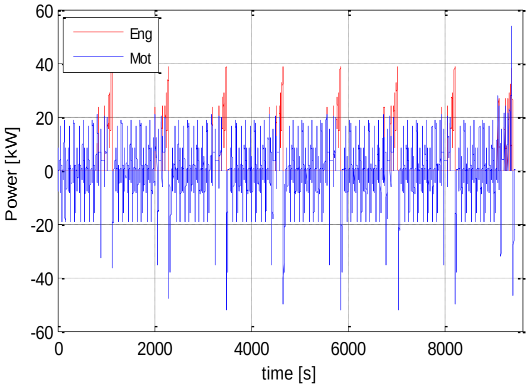

Figure 10: ECMS control of the power of Engine and Motor

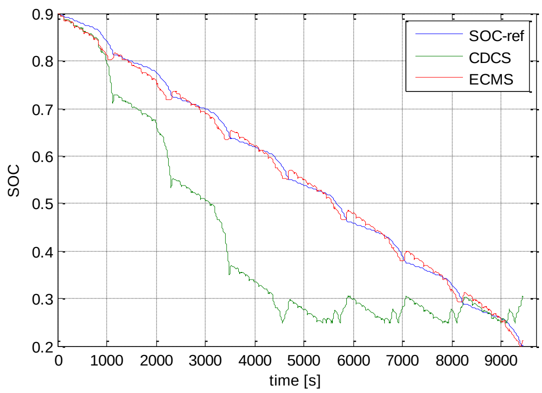

Figure 11: The SOC of the CDCS and ECMS

Fig.12 is a graph in the Fuel consumption. The ECMS control strategy has better fuel economy compared with other control strategies. Total fuel consumption of each control is represented in the Table.4 and ECMS control improves fuel economy approximately 13.1%, compared the CDCS control.

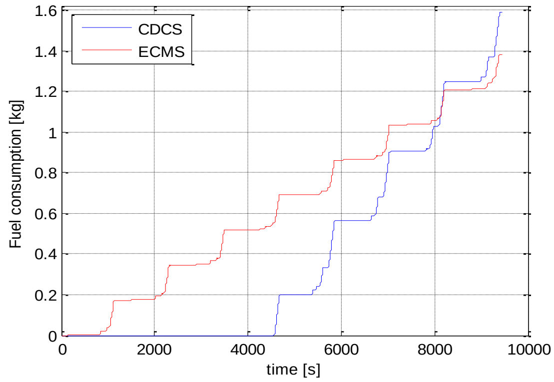

Figure 12: Fuel consumption of CDCS and ECMS control

Table 4: Fuel consumption and SOC over NEDC cycle

Parameters	Control strategy	
	CDCS	ECMS
Fuel (kg)	1.5892	1.3814
Fuel (km/l)	30.86	35.51
$SOC_{\min}$ time	6730.4	9383.1

4.2. Comparison with P-ECMS and N-ECMS control strategy

In P-ECMS control, the control parameters that are specific to NEDC cycle are set. It was simulated in NEDC and UDDS two cycles to compare N-ECMS control unrelated to the driving cycle and P-ECMS control depending the cycle.

Fig.13 is a simulation result by repeating the NEDC driving cycle 8 times. In terms of the battery SOC, the P-ECMS and N-ECMS follow the SOC reference well. However, from the point of view of fuel consumption, N-ECMS will have better fuel economy than P-ECMS. The reason for this is that while controlling SOC along the SOC reference, P-ECMS determines in advance the equivalent factor to the optimal power distribution over the driving cycle. Therefore, it is possible to have little more optimal control. In the table 5, P-ECMS improved about 3% fuel economy than N-ECMS and this difference is very minor.

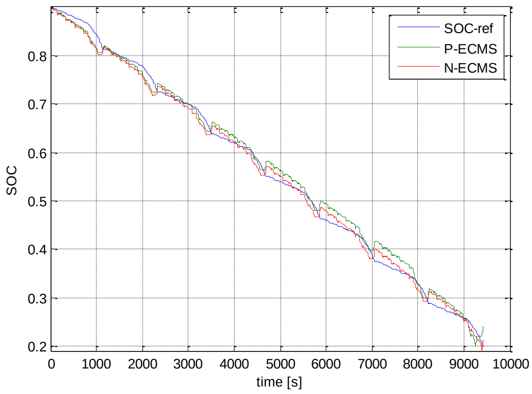

Figure 13: SOC of P-ECMS and N-ECMS in the NEDC cycle

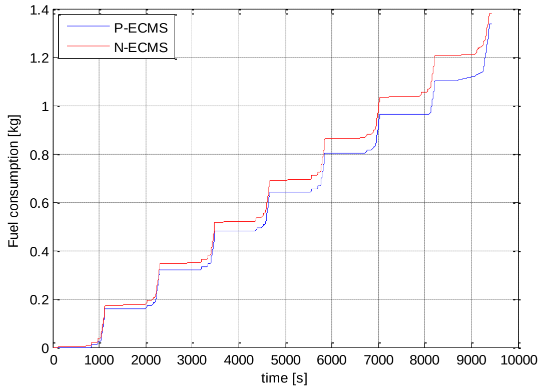

Figure 14: Fuel consumption of P-ECMS and N-ECMS in the NEDC cycle

Table 5: Fuel consumption and SOC over NEDC cycle

Parameters	Control strategy	
	P-ECMS	N-ECMS
Fuel (kg)	1.3377	1.3814
Fuel (km/l)	36.6649	35.51
SOC_{min} time	9254.6	9383.1

Fig.15 is simulated by UDDS cycle repeated 7 times. P-ECMS has a simulation with optimized parameters in the NEDC cycle. Characteristics of the NEDC cycle very differ considerably from UDDS. A comparison of detailed parameters is in Table 6.

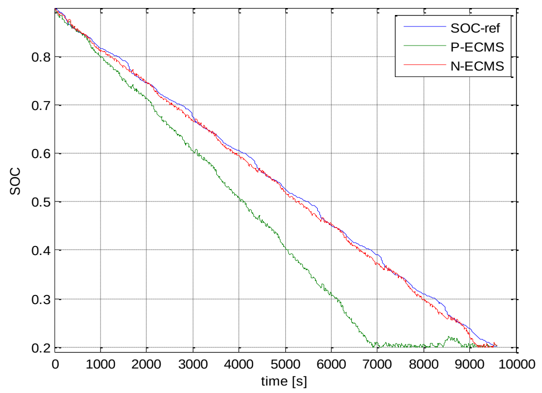

Figure 15: SOC of P-ECMS and N-ECMS in the UDDS cycle

UDDS cycle has much rapid acceleration and deceleration and the figures are higher approximately 1.4 times than NEDC cycles. In other words, it reflects the rapidly changing road conditions in the urban. On the other hand, NEDC cycle is smoothly accelerated and decelerated. NEDC cycle is divided into two stages of the urban and highway. Acceleration and deceleration are repeated slowly in the urban. In the highway, Acceleration, constant speed, and deceleration time are smooth in progress. When viewed in numerically, the values of acceleration and deceleration are very low compared to the value of UDDS cycle.

Table 6: Statistical features of Driving cycles

Features	Driving Cycle	
	NEDC 8 cycle	UDDS 7 cycle
Total time (s)	9449	9590
Average Speed (km/h)	33.57	31.51
Maximum Speed (km/h)	120.06	91.25
Average Acceleration (m/s^2)	0.12	0.20
Average Deceleration(m/s^2)	-0.12	-0.20
Maximum Acceleration (m/s^2)	1.08	1.48
Maximum Deceleration(m/s^2)	-1.43	-1.48
Idling Percentage (%)	24.90	18.91

In terms of the battery, the SOC of P-ECMS reaches the lowest value at 7000s. The reason is that it could not reflect the properties of parameters of UDDS which are repeated acceleration and deceleration unlike the NEDC. On the other hand, in the N-ECMS control, the battery reaches a minimum SOC at 9000s nearly finishing the driving cycle, because it is to track the SOC_{ref} .

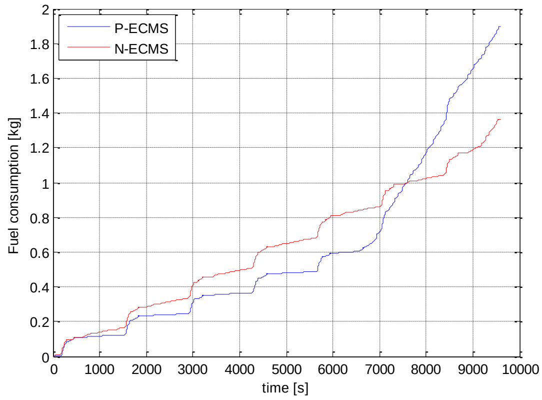

Figure 16: Fuel consumption of P-ECMS and N-ECMS in the UDDS cycle

With regard to the fuel consumption, there are many differences. N-ECMS improves approximately 72% in fuel economy compared P-ECMS. The reason for this is that the engine is mainly operated in the CS stage and the fuel consumption is suddenly increased. The CS stage starts after 7000s and the fuel consumption is twice compared before 7000s according to repeat of acceleration and deceleration. On the other hands, the fuel consumption is a steady increase in the N-ECMS control, without the case suddenly increasing it because the torque of the engine and the motor is evenly distributed.

Table 7: Fuel consumption and SOC over UDDS cycle

Parameters	Control strategy	
	P-ECMS	N-ECMS
Fuel (kg)	1.8972	1.3646
Fuel (km/l)	25.8525	35.9428
SOC_{min} time	7306.9	9383.1

5. CONCLUSIONS

This describes the result which reflects the property of the plug-in HEV according to increasing driving distance by using only the motor in aspect of the fuel consumption. Unlike previous HEV, plug-in HEV increases the driving distance using only the motor, therefore a novel control strategy is needed.

1. A control strategy of plug-in HEV is divided into CDCS and blended mode control strategies. In this paper, ECMS control used in previous hybrid system is applied with the property of the plug-in HEV.
2. A previous ECMS control can distribute torque properly into the engine and the motor. However, it has the disadvantage which the parameters depend on the driving cycle and the distance. Therefore, to overcome this disadvantage, N-ECMS control is proposed. While P-ECMS control requires the complex process calculating the parameters, N-ECMS control has simple and easy applied control algorithms, which in assumption that the total driving distance is known.
3. CDCS, ECMS control system is simulated in aspect of fuel consumption, and ECMS control has the improved fuel consumption than CDCS by 14%. Also, P-ECMS and N-ECMS are simulated with NEDC 8 cycle and UDDS 7 cycles. P- ECMS represents the improved fuel consumption than N-ECMS by 2% in NEDC, because it is composed of proper parameters. In contrast, N-ECMS has improved fuel consumption by 72% in UDDS driving cycle that acceleration and deceleration are repeated frequently. As a result, N-ECMS shows the efficient fuel consumption regardless of driving cycle.

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