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Optimizing the Powertrain Configuration of a Heavy-Duty Series-Type HEV to Improve the Fuel Economy

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Abstract

In recent years, many HEVs and EVs have been produced commercially and used on real roads. Among the various types of HEVs, the series-type HEV has several advantages, including the fact that the engine can operate its optimal point and, recover more vehicle kinetic energy through regenerative braking. However, the many energy-converting processes occurring in a series-type HEV can cause a lower energy transfer efficiency from the tank to the wheel compared with other types of HEVs. To overcome these disadvantages, the generation system can be operated in the highest efficiency region of both the engine and the generator. By matching the operating region of the engine and generator, the fuel economy can be improved by 2 %. In addition, fuel economy can be improved by placing motors in the front and in the rear. If motors are located in the front and in the rear, the regenerative energy is increased because regenerating braking is occurring in both locations. Moreover, the operating points of the motor can be shifted into the high-efficiency region by varying the front and rear motor sizes. Finally, the use of a transmission should be considered. Because conventional series-type HEVs or EVs do not use a transmission, the motor size should be large enough to provide the required hill-climbing ability. However, by applying a transmission to a series-type HEV or to an EV, the hill-climbing ability can be satisfied with a small motor. Moreover, because it is possible to use the motor in the high-efficiency region, the fuel economy should be improved by approximately 3 %. Through this optimization process for the powertrain system, a series-type HEV can achieve the highest fuel economy. In this study, the suggested optimization effects are simulated based on Dynamic Programming.

Keywords: series-type HEV, Regenerative braking, transmission, optimization

1 Introduction

In recent years, various technologies for solving problems such as global warming, the exhaustion of the global petroleum resource and strict regulations have been executed. Among these technologies, the HEV is considered a realistic alternative, so many studies have been conducted. The main subject of HEV research is the control strategy because it is the most important for determine how to control the powertrain system to improve fuel economy in an HEV [1-7]. For example, DP (Dynamic Programming) is a representative optimizing method [4]. DP is based on the optimal theory proposed by Bellmaan and is identified as a global optimization method. Thus, the fuel economy obtained by DP is considered to be the theoretical maximum value at a specific configuration and test cycle. The ECMS (Equivalent Consumption Minimize Strategy) is also an optimal control strategy that minimizes the equivalent fuel consumption [2]. Compared with DP, ECMS can be applied in real-time environments. However, the optimal design of the powertrain is important because the basic fuel economy of an HEV is determined by the configuration of the HEV. This means that the optimal control strategy simply determines the operation of the powertrain, which is fixed in the design process. Thus, the HEV configuration should be optimized in the powertrain design process. The optimal design of a parallel HEV based on DIRECT (Divided RECTangles), simulation annealing, and genetic algorithms has been conducted, and optimal component sizes for items such as the engine, the motor and the battery have been proposed [8-10]. The battery size is the main factor when designing a Plug-in HEV because the All-Electric Range is the most important performance parameter. Thus, studies to determine the appropriate size of the battery and other components according to various AERs have been executed [11-13]. In addition, the characteristics of the clutch location and motor type in a parallel HEV has been investigated [14]. Extended-range electric vehicles based on 2-mode transmission have been designed by considering fuel type, engine size, battery size and electric motor size and type [15].

However, previous studies have focused on the optimal control strategy or on optimal design to determine the components size. In other words, the optimal design for the configuration of a series-type HEV has not been studied. In this study, the optimal design for the configuration of a series-type HEV is determined to improve the fuel economy based on DP. To achieve this, the generation system and the arrangement and size of the traction motors have been optimized. In addition, the use of a transmission is considered to analyze the effect of a transmission in a series-type HEV.

2 Basic configuration of the target series-type HEV system

2.1 Target series-type HEV system

The schematic diagram of the target HEV system is shown in Figure 1.

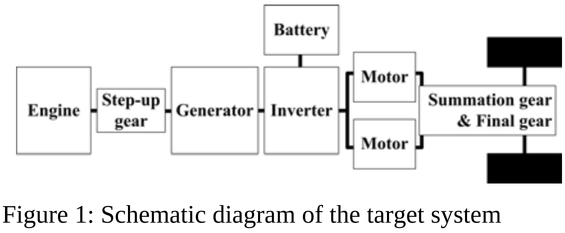

Figure 1: Schematic diagram of the target system

The basic configuration of the target system has just two induction-type traction motors in the rear, and the motors are connected by a summation gear. The reason why the dual motor is used in this system is that a dual-motor system can reduce the volume of the motors and can handle urgent situations when one motor fails. The generation system consists of a CNG engine and a PM-type generator, and they are coupled by a step-up gear for which the ratio is 1 to match each shaft. To determine the traction motor's power size, the requirements of the vehicle manufacturers should be satisfied. Because the target system is used in Seoul, Republic of Korea, the geographical features of the city and drivers' demands are considered to determine the requirement. The basic specifications and requirements are described in Table 1 and Table 2, respectively.

Table 1: Basic specification of the target vehicle

Engine	CNG SI 8 L, 130 kW
Dynamic tire radius	0.508 m
Vehicle mass(GVW)	15,500 kg
Battery	NiMH 60 Ah
Final gear efficiency	90 %

Table 2: Requirements for vehicle performance

Maximum speed	100 km/h
Acceleration [0-80 km/h]	Under 30 sec
Hill-climbing ability	Start at 30 %
	Driving at 15 %, 30 km/h

The maximum speed of the traction motor is defined as 10,000 rpm by the manufacturer. Based on this data, the maximum total gear ratio is assumed to be 19. To determine the required minimum motor power, the maximum speed and hill-climbing ability during driving condition are considered. From these two requirements, the minimum power of the motor is calculated as 232 kW. However, for the hill-climbing ability—when starting up a road with a slope of 30 %—much higher torque is needed than in the previous two cases. Because there is no transmission, to provide the necessary hill-climbing ability, the minimum required total motor power is determined to be 400 kW. Thus, it is assumed that the traction system of the target vehicle consists of two 200 kW induction-type motors.

A generator should cover the engine operation range because the high-efficiency region of an engine is located at the full-load condition. Because the target system has a series-type configuration, the engine can operate at the most efficient operating points and, by doing so, the fuel economy can be improved. The most efficient operating point of the target engine is at the full-load condition. Thus, the generator's maximum torque should be greater than the engine's full load. To satisfy this condition, the generator power is determined to be 260 kW for the basic system.

2.2 Test mode for fuel economy

In this study, the test mode that represents the driving pattern of a city bus is used to estimate the fuel economy. This test mode is developed by using a statistical method based on the real driving data of the Number 150 city bus of Seoul. The specifications of the test mode are described in Table 3, and the profile is shown in Figure 2. In the test mode, the start condition is assumed to be the fully warmed-up state.

Table 3: Specifications of the test mode

Time	1719 sec
Distance	6.95 km
Average Speed	14.5 km/h
Maximum Speed	74.7 km/h

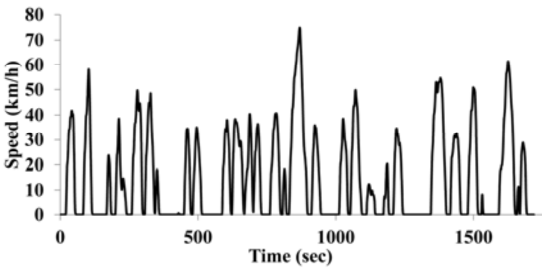

Figure 2: Profile of the test mode

3 Simulation method

There are many simulation methods available to determine the optimal control in deterministic problems. Among them, DP has become known as a global optimization method, and it has shown high reliability in many previous studies. The optimal control problem is defined as:

$$J_k^*(x_k) = \min_{u_k}\{ g_k(x_k, u_k) + J_{k+1}^*(a(x_k, u_k))\} \quad (1)$$

where

$$x_{k+1} = a(x_k, u_k) \quad (2)$$

In Equation (1), the control u_k means battery power and the state x_k means SOC. The optimal cost-to-go J_k^* means the minimum fuel consumption to arrive at the state x_k at time k. At each time point, the optimal battery power that minimizes the fuel consumption is calculated. Consequently, the optimal fuel consumption trajectory can be determined based on the calculated optimal results [16]. Thus, it is certain that the fuel economy calculated by DP is the global optimal result for the specific configuration and driving cycle. Using DP to optimize the configuration or power size of each component, it is clear that the result of each case is the theoretical optimal fuel consumption under the revised configuration.

4 Optimization of the generation system

In a series-type HEV, a generation system supplies electrical energy to drive the vehicle or charge the battery. This means that the mechanical energy of the engine is not used directly to drive the vehicle. Thus, the tank-to-wheel efficiency decreases because of the frequent energy conversion process [17]. However because the engine can operate in the most efficient operating region, the disadvantage of the frequent energy conversion process can be compensated for. Moreover, the generator should operate at its optimal point to increase the efficiency of the generation system. Thus, the optimization of a generation system focuses on matching the optimal operation point of the engine and the generator. In addition, the optimization process considers the generator power size. For testing generators of various sizes, a scaling method is applied to the reference data that is obtained from PSAT [18]. Because the generator's maximum torque is higher than the engine's maximum torque and the operating point of an engine and a generator should be located in the most efficient region of both components, the ratio of the step-up gear is changed from 1. However, the maximum speed of the generator and the engine are fixed, and, thus, the ratio of the step-up gear is limited. The maximum speed of the engine is 2300 rpm, and the most efficient point is approximately 1100-1350 rpm. The maximum speed of the generator is limited at 3500 rpm. Thus, the ratio of the step-up gear cannot be over 2.18. Moreover, the most efficient point of the generator is approximately 2400 rpm. Thus, the ratio of the step-up gear is determined as 2.04. Then, the generator's maximum torque at 2400 rpm should be greater than the engine operating torque. To satisfy this condition, the generator power size is determined to be 180 kW. The total fuel consumption and the electrical energy generated from the generation system of each case are shown in Table 4.

Table 4: Total fuel consumption and generated electrical energy of each case

	Total fuel consumption [g]	Generated electrical energy [kJ]
Basic system	2248	41.32
Optimized system	2207	41.36

By optimizing the generation system, the operating point of the generator is changed as shown in Figure 3 and 4. The optimized generation system shows a 2 % higher fuel economy than the basic generation system.

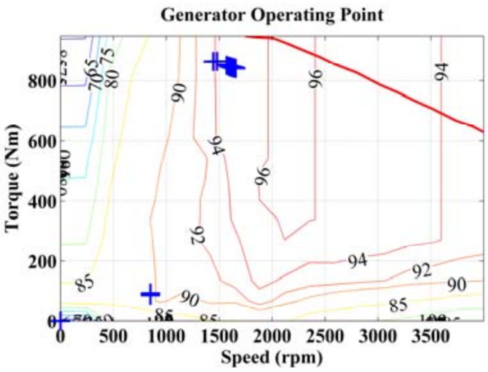

Figure 3: Generator operating point before optimizing

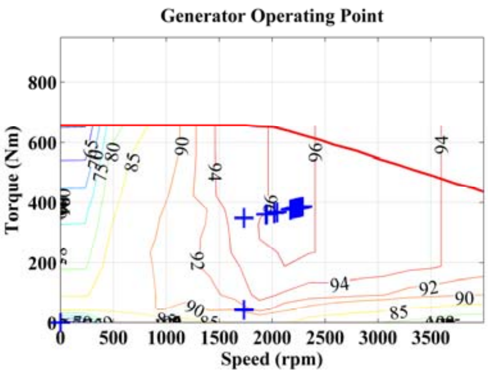

Figure 4: Generator operating point after optimizing

5 Optimization of the traction system

5.1 Arrangement of traction motors

In the general configuration of series-type HEVs, the traction motors are located only in the rear or in the front. The target system has dual motors in the rear. This means that the motor is connected by the rear wheels and that regenerative braking is possible at the rear wheels. However, the braking force is applied in both the front and the rear simultaneously during the braking period. Thus, the kinetic energy of the front wheel is not recovered by regenerative braking and is lost because of friction. The braking force at each wheel can be determined from the optimal braking line [19]. As shown in Figure 5, the required front braking force is not smaller than the rear braking force. In other words, if the kinetic energy of the front wheel is recovered by the regenerative braking, an additional improvement in the fuel economy should be achieved.

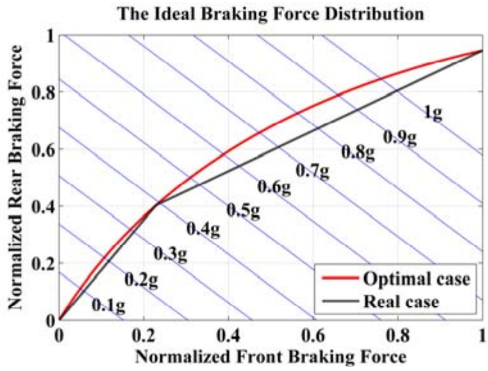

Figure 5: Optimal braking line

Thus, in this study, one motor is connected with the rear drive shaft, and another motor is connected with the front drive shaft, as shown in Figure 6.

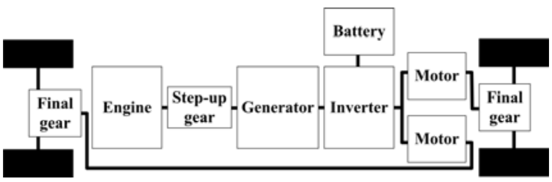

Figure 6: Revised configuration for maximizing regenerative braking

The power distributed to each traction torque is assumed to be equal. However, the braking force is calculated based on the optimal braking line, so the required torque to each motor during the braking period is different. In addition, it is assumed that if the minimum motor torque is greater than the braking torque, then the minimum motor torque is selected as the regenerative braking torque, and the rest of the required braking force is supplied by the friction braking system. The generation system optimized in the previous section is used in this comparison. The total gear ratio between the motor and the drive shaft is 19 for each side. The summation of each traction motor torque is shown in Figure 7.

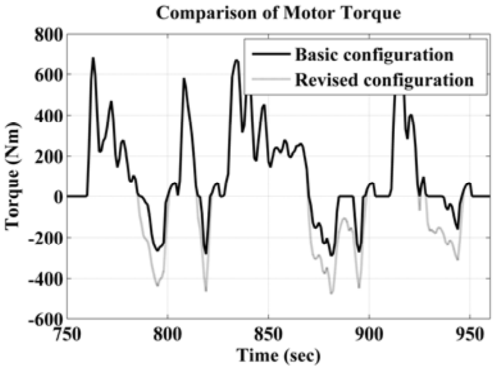

Figure 7: Comparison of motor torque

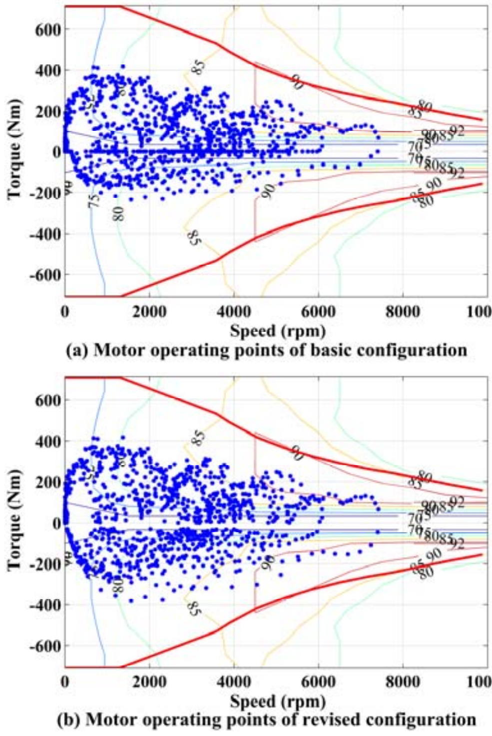

Figure 8: Comparison of motor operating points

It is certain that more vehicle kinetic energy is recovered in the revised configuration case because the regenerative braking torque is greater than that of the basic configuration case. In addition, the motor operates at a more efficient operating point when regenerative braking occurs. In the basic configuration case, the required rear braking force is divided into each motor, and this causes the motors to operate at a relatively low torque point. However, in the optimal motor arrangement case, the required front and rear braking force is covered by each motor. Thus, the torque that the motor should absorb is higher than in the basic configuration case, as shown in Figure 8. The total energy recovered by the regenerative brake in each system is given in Table 5.

Table 5: Energy recovered by regenerative braking according to the arrangement of the motor

	Basic	Revised
Energy recovered by regenerative braking (MJ)	9.9	24.6

The optimal arrangement case can recover two times more energy than the basic configuration case. Consequently, by arranging a motor in both the front and the rear, the fuel economy can be improved by 41 % compared with the basic configuration case without the optimized generation system.

5.2 Optimization of the motor size

In this study, the traction motor has been arranged at the front and the rear of the vehicle to recover more kinetic energy. However, the quantities of the braking force in each location are different. Thus, it is certain that the combination of different traction motor sizes affects the fuel economy. Therefore, it is necessary to determine the optimal combination of the motor size to further improve the fuel economy. The combinations of motors that are considered in this study to identify the optimal case are described in Table 6.

Table 6: Combinations of motor power sizes

Case no.	Front	Rear
1	100 kW	300 kW
2	200 kW	200 kW
3	300 kW	100 kW

The power distribution ratio that determines the torque quantity of each motor is assumed to be proportional to the motor size. For example, in case 1, if the required power is 100 kW, the front motor produces 25 kW and the rear motor produces 75 kW.

Table 7: Consumed and recovered energy of the motors

Case no.	Consumed Energy (MJ)	Recovered Energy (MJ)
1	42.8	24.6
2	42.8	24.7
3	42.8	24.0

In table 6, the electrical energy consumed and recovered for each motor combination is shown. With respect to the fuel economy, case 1 and case 2 yielded almost the same value. However, case 3 shows a lower fuel economy than case 1 and case 2. The fuel economy of case 3 is lower by 3-4 % than that of cases 1 and 2. This occurred because the recovered energy is smaller than in the other cases. As shown in the results, the effect of the motor power size for the same total power is very small. The reason why the fuel economy yields almost the same value is that when the total motor power is the same, the operating points of the downsized motor move into a more efficient region, while the operating points of the upsized motor move into a less efficient region. However, case 3 should be avoided to prevent a decrease in the fuel economy. It is noted that the power distribution ratio is assumed to be proportional to the power size of each motor in this study. If the optimal power distribution is considered, the fuel economy can be improved by combining various motor power sizes.

5.3 Analysis of the transmission effect

The basic target system has large traction motors to provide the required hill-climbing ability. However, the hill-climbing ability can be provided if the total power is higher than 240 kW. The problem is that the traction system for 240 kW of torque is much lower than the required torque when starting up a road with a 30 % slope. Thus, by adopting a two-stage transmission, the total power of the traction system can be decreased to 240 kW from 400 kW while maintaining the hill-climbing ability. Hence, in this study, a two-stage transmission is applied to the system to downsize the traction system. The first and the second stage gear ratios are assumed to be 2 and 1, respectively. Figure 9 shows the effect of the transmission. The total power of the vehicle is less than 240 kW when the vehicle is driven at 30 km/h on a road with a 15 % slope. However, to start up a road with a 30 % slope, the vehicle motor requires approximately 1360 N m. The total maximum torque of a dual 400 kW traction system that consists of two 200 kW motors is 1422 N m. In contrast, even though the total maximum torque of the dual 240 kW traction system that consists of two 120 kW motors is 860 N m, the torque transmitted to the wheel through the transmission is 1720 N m if the first stage gear ratio is 2. Thus, it is possible to downsize the traction motor while still providing the required hill-climbing ability. By downsizing the traction motor, reductions of the cost and the vehicle mass can be achieved. In addition, more space in the engine compartment can be created. However, the more important fact is that the fuel consumption can be reduced. The reason for this can be explained by the motor operating points. The operating points of each case are shown in Figure 10.

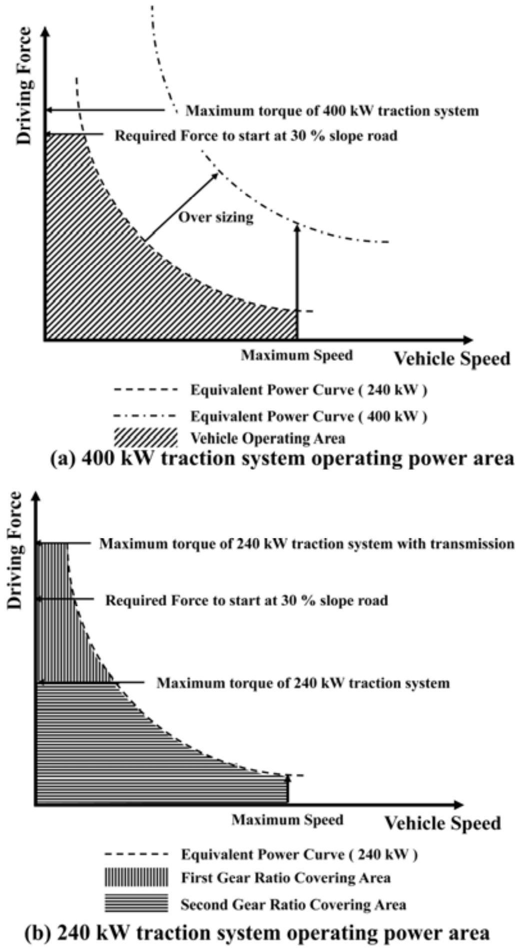

Figure 9: Operating area of each traction system

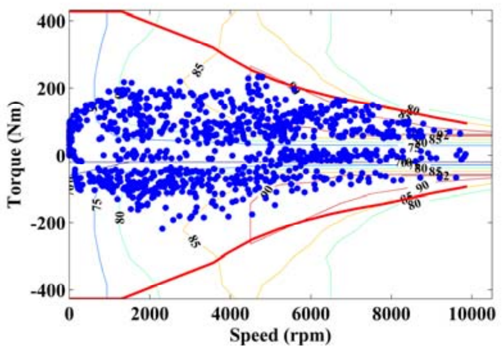

Figure 10: Motor operating point when applying a transmission

As shown in Figure 10, motors operate in the more efficient points when a transmission is applied. Thus, incorporating a transmission not only satisfies the required hill-climbing ability but also achieves better fuel economy because it causes the motors to operate in a more efficient region. The fuel economy of the rear dual 240 kW traction system is improved by 25 % compared with the rear dual 400 kW traction system.

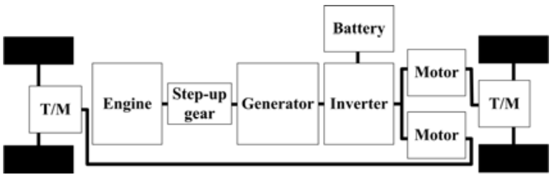

Figure 11: Optimal configuration of a series-type HEV

It is difficult to incorporate two transmissions in the front and the rear simultaneously. However, in the simulation, it is possible to implement this system and to evaluate the improvement in the fuel economy when all of the optimization methods are applied to the series-type HEV. The optimal configuration proposed in this study is described in Figure 11. Compared with the basic configuration, the revised configuration—which has the optimized generation system, the revised motor arrangement and a transmission—produces a 47 % improvement in the fuel economy.

6 Conclusions

In this study, various optimizations are considered to improve the fuel economy of a series-type HEV. In the series-type HEV, a generation system and a traction system have been considered. The basic configuration and each component size are determined based on the requirements of the manufacturers. To determine a basic component, such as the motor size, the generator size and the total gear ratio, the requirements of the manufacturer are used as criteria. After determining each component size and gear ratio, optimization is executed. Optimizing the generation system by changing the step-up gear ratio and the generator size results in a fuel economy improvement of 2 %. In addition, re-arranging the traction motors yields a 43 % improvement in the fuel economy compared with the basic configuration. By adopting a 2-state transmission, it is possible to downsize the traction motor, and the fuel economy is improved by 25 %. Consequently, the fuel economy can be improved by 47 % when all optimization cases are applied to a series-type HEV.

Acknowledgments

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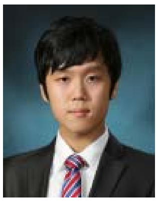

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