EVS26
Los Angeles, California, May 6-9, 2012

Development of Backward Simulator based on Dynamic Programming for the Multiple Power Sources of Series Hybrid Electric Vehicle

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Abstract

There are many studies about how to control and distribute the power sources of hybrid electric vehicles which consists of engine and battery. However studies about to control the three power sources of HEV system is not studied enough. In this study a backward simulator which could calculate the optimal distribution of multiple power sources, engine, battery and ultra capacitor, of series HEV was developed. The method of the backward simulator to calculate the optimal solution is based on the dynamic programming which is one of the optimization theories. For the verification and the comparison of the backward simulator two series HEV system of which one only consists of engine and battery of which the other one consists of engine, battery and ultra capacitor were applied to the backward simulator. As a result, the latter system which includes ultra capacitor is more efficient than the other one because of low resistance of ultra capacitor. However it spent tremendous time to calculate the system of three power sources because each two state variables and two control variables make simulation much more complicated and plenty of calculation quantity. To develop the simulator more reasonably it needs further study how to decrease the calculation amount of simulation.

Keywords: Energy source, Optimization, Series HEV, Simulation, Vehicle performance

1 Introduction

Hybrid electric vehicle (HEV) is an alternative transportation which harnesses the combination of mechanical and electric power for the vehicle's traction. As many countries start to restrict the vehicle's fuel economy and emission of gases, many studies about HEV have been conducted. Although there are many studies about optimization of HEV which has two power sources (engine and battery), study about optimization of HEV which has three power sources such as engine, battery and ultra capacitor is still needed.

In this study, a backward simulator which can simulate the system of one, two or three power sources is developed. The simulation is conducted based on the dynamic programming theory which could find the optimal solution of the problem efficiently. For example, the series HEV which has three power sources composed of engine, battery and ultra capacitor shown in Fig. 1 applied. Using

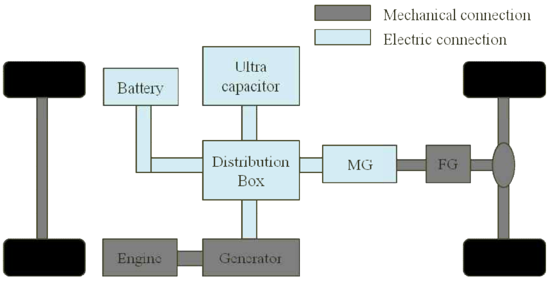

Figure 1: configuration of example HEV system

simulator it is possible to calculate the fuel economy, optimal power distribution and output power of motors of the system when it drives on a specified driving cycle.

2 Series HEV System

2.1 Series HEV System and Specifications

In this paper simulator which could simulate series HEV system of which energy sources are engine, battery and ultra capacitor is developed. Basically series HEV only utilizes electric energy for the propulsion of the vehicle. Engine can only produce the output power when it is utilized to generate electric energy.
The series HEV system as in Fig. 1 is explained and compared for the example of simulator usage. The specifications of the vehicle are shown in Table 1.

Table1: Simulation data of the vehicle

Vehicle specifications and calculation factors	
Weight	5000 kg
Frontal area	4.2 m^2
Tire radius	0.4 m
Final gear efficiency	95 %
Rolling resistance coefficient	0.009
Air drag coefficient	0.6
Air density	1.24 km/m^3
Vehicle power source's capacities	
Engine	6500cc / 120kW
Battery	28 Ah
Ultra capacitor	0.6 Ah

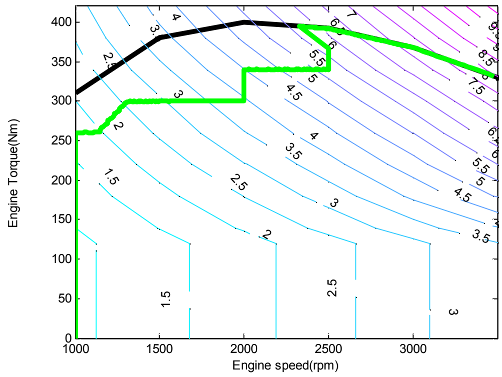

Figure 2: Model of engine fuel consumption

2.2 Models of the simulator

Because the objective could have many components such as engine, battery, ultra capacitor and motor/generators, each components of the system is modelled individually and assembled according to the flow of energy to make the simulator easy to change according to the system configuration.
Engine model is composed of operating map as in Fig. 2 of which input factors are engine operating speed and torque and output factor is fuel consumption rate of engine.
In battery and ultra capacitor model, the important factor of battery and ultra capacitor is state of charge (SoC) because it could be explained energy storage state and flow of energy. The model of SoC is as

$$S\dot{O}C = -\frac{1}{Q}\cdot\frac{V-\sqrt{V^2-4RP}}{2R} \qquad (1)$$

In (1), SOC means state of charge of battery or ultra capacitor. Q is capacity, V is voltage, R is resistance and P is output power of battery or ultracapacitor [1]. V and R are determined by each SoC from the maps of models as in Fig. 3.

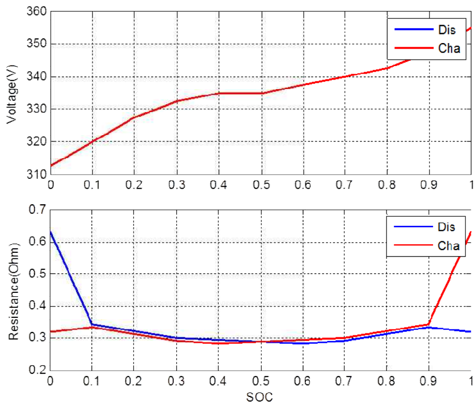

Figure 3: Example model of battery or ultra capacitor

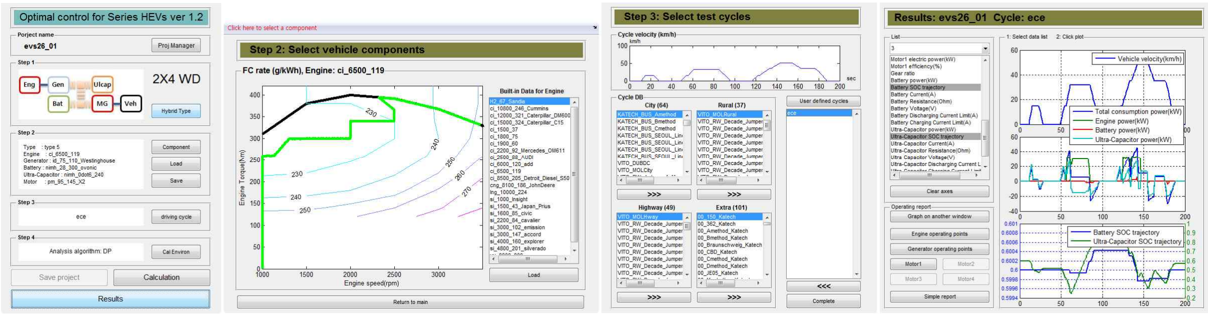

Figure 4: Series HEV Backward simulator

3 Backward Simulator based on Dynamic Programming

Since the system utilizes multiple power sources, it is important to distribute each power sources appropriately. In this study dynamic programming (DP) which is one of global optimization theories is applied to the study to find the optimal power distribution of engine, battery and ultra capacitor.

3.1 Dynamic Programming

Dynamic programming (DP) is based on the Bellman's principle of optimality. According to the theory it is possible to search all possible solutions which can be the optimum of the problem and to apply to the step wise problem.

As in (2) the goal of the DP is to find the minimum of total cost J where the cost of each step L depends on state variable x and control variable u of which step size N.

$$J = \min \sum_{1}^{N} L(x(k), u(k)) \qquad (2)$$

If the cost from $k+1$ to N $J^*_{k+1,N}(x(k+1))$ is known only the step cost from k to $k+1$ should be calculated to know the total optimal cost of k to N as

$$J^*_{k,N}(x(k)) = \min\left\{L(x(k), u(k)) + J^*_{k+1,N}(x(k+1))\right\}$$

(3)

By this method, optimal cost of $J^*_{1,N}$ is calculated from the final step N to initial step backwardly [2]. Using this calculation method it is less time consuming work than normal optimization method which searches every solution from the first step to the final step [3-6].

For development of backward simulator cost J in (3) is defined total fuel consumption from the engine and state variable $x(k)$ is determined as SoC of battery and/or ultra capacitor. Control variable $u(k)$ is defined as SoC rate of battery and/or ultra capacitor which is equivalent with output power of battery and/or ultra capacitor [6-9].

3.2 Backward Simulator

Based on DP a backward simulator as in Fig. 4 was developed. It is possible to show the optimal operating points of engine and optimal trajectories of battery and ultra capacitor based on DP when the vehicle follow the given driving cycle. To do a simulation data of vehicle such as engine fuel consumption map, battery and ultra capacitor voltage and resistance maps and other vehicle components data explained in 2.2.

4 Simulation Results

Two backward simulations were conducted with developed backward simulator and the data of the vehicle mentioned in 2.1. One simulation is about normal HEV which only consists of engine and battery. The other simulation is for the HEV which consists of the same engine and battery of the former HEV including ultra capacitor. In other words ultra capacitor is added to the former HEV system.

Driving cycle 'ECE' as in Fig. 5 was applied for the simulations.

Table 2 is the fuel economy results of the simulation.

Table2: Fuel economy of simulation results

	HEV 1 (E/B)	HEV 2 (E/B/UC)
Fuel economy	7.39 km/L	7.84 km/L

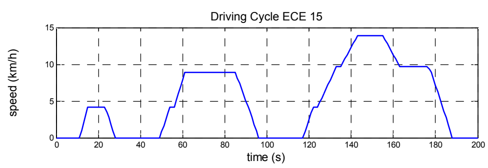

Figure 5: 'ECE' driving cycle

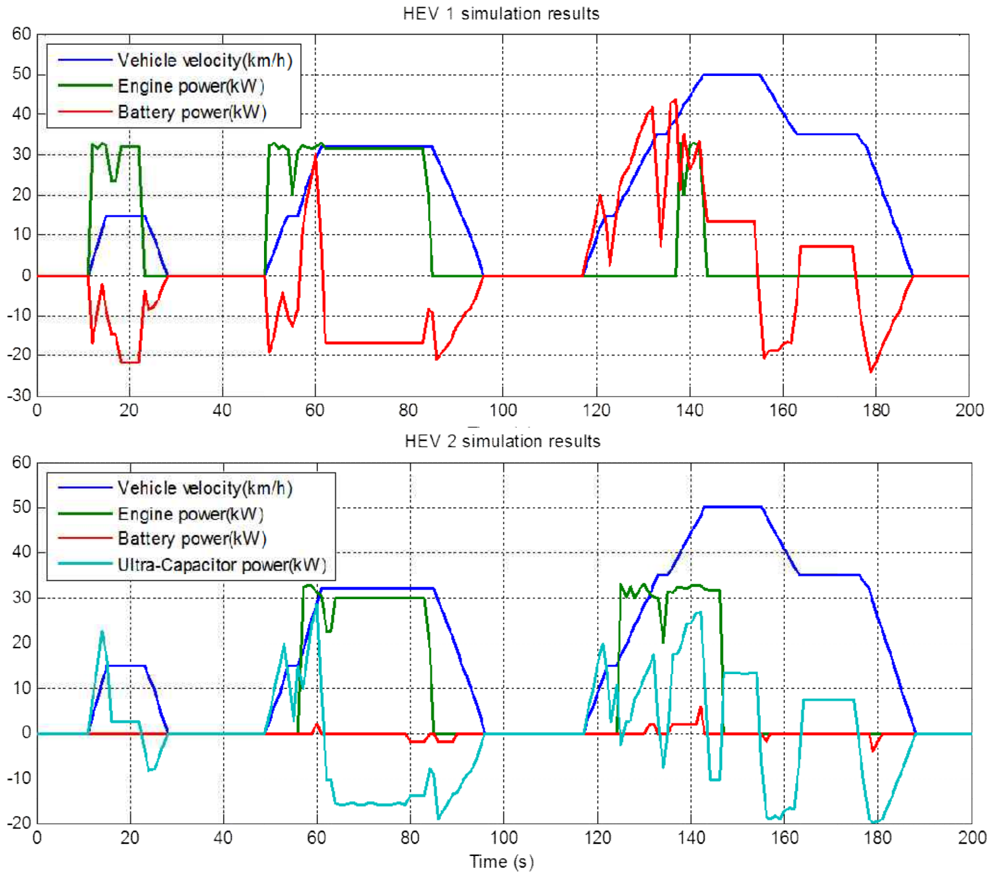

Figure 6: Output power of HEV simulation results

It is seen that the fuel economy of HEV with three power sources (HEV 2) is better than HEV with two power sources (HEV 1). It is very similar with each fuel economy results because every specifications and components of the vehicle are the same except ultra capacitor. Because the resistance of ultra capacitor is very low than battery HEV 2 is relatively more efficient than HEV 1.

Fig. 6 shows the output power of engine, battery and ultra capacitor of the vehicle. In HEV 1 battery is frequently used for the traction or regeneration of the vehicle. On the other hand in HEV 2 battery is less used than HEV 1 but ultra capacitor is relatively used for the traction and regeneration of the vehicle because the resistance of the battery is about 200 times larger than ultra capacitor. Fig. 7 shows the SoC trajectories of battery and ultra capacitor according to the time. It is also identified that use of ultra capacitor is more frequent than battery.

From the simulation results it can be thought that by applying ultra capacitor to the conventional HEV which consists of engine and battery could make HEV more efficient and also powerful.

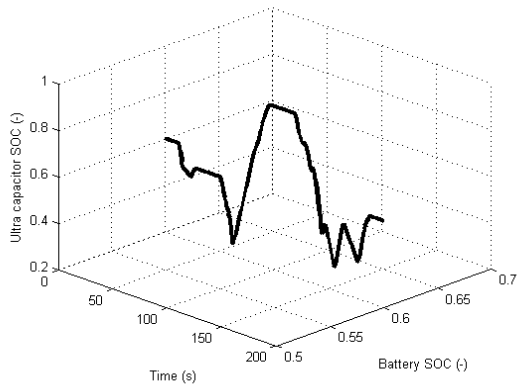

Figure 7: SoC trajectories of battery and ultra capacitor

However for the backward simulation of three power sources it needs lots of calculations because of its two state variables. In 3.2 it is mentioned that the state variable and control variable are battery and/or ultra capacitor. With three power sources there are two state variables and two control variables for each step optimization. If we set the resolution of battery state 5000 and resolution of ultra capacitor 5000, the number of calculation will be squared compared to the only two power source system optimization. For this reason it needs lots of time to calculate all optimization output power of battery and ultra capacitor. The driving cycle 'ECE' is only 200 seconds long cycle so that it needs less time than other long time driving cycles. More studies should be done to make the simulation time reasonably.

5 Conclusions

In this study backward simulator based on dynamic programming was developed. The backward simulator could calculate the fuel economy, optimal distribution of power sources and gear ratio when the vehicle drive on the specified driving cycle. For the verification of the simulator two HEV system of 5000kg vehicle were applied to the simulator. The one system only consists of engine and battery similar with well known series HEV and the other system consists of engine, battery and ultra capacitor. All of specifications and components are the same but ultra capacitor only added to the system. Because resistance of ultra capacitor is much lower than battery the fuel economy of the latter system is better than the former. In the system which consists of engine, battery and ultra capacitor, the use of ultra capacitor is much more frequent than battery because of its resistances. However because there are three power sources and two state variables and two control variables it spent much more time to calculate optimal solution of the problem than the other system. To solve the time consuming problem, a new concept of problem solving method should be developed.

Acknowledgments

This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MEST) (No.2011-0001276)

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