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

Comparison of ECMS and Optimal Control in FCHVs

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Abstract

A fuel cell hybrid vehicle (FCHV) which combines a fuel cell system (FCS) and a battery is the target system in this research. The fuel economy of the FCHV depends on its power management strategy, which determines the power split between the FCS and the battery. In this paper, the equivalent consumption minimization strategy (ECMS) for FCHVs is compared to the optimal control strategy based on Pontryagin's Minimum Principle (PMP) and Dynamic Programming (DP) for FCHVs. The ECMS is originally based on the heuristic concept that the usage of the electric energy can be exchanged to equivalent fuel consumption. Both the PMP and DP are based on the optimal control theory, they minimize the fuel consumption and optimize the power distribution between the FCS and the battery. The PMP gives the optimal solution by providing the necessary optimality conditions, and the DP provides the global optimal solution. The ECMS is based on the heuristic concept, though it is also related to the optimal concept because the solution of the ECMS is obtained by minimizing the total equivalent fuel consumption. To verify the relationship between the ECMS and the optimal control strategy, the solution obtained from the ECMS is compared to the solutions derived from the PMP-based optimal control strategy and the DP.

Keywords: fuel cell, power management, optimization, simulation

1 Introduction

FCHVs have gradually become a major issue among academia and in the automotive industry because of the energy supply problem and environmental problem. The fuel economy of an FCHV depends on its power management strategy, which determines the power split between power sources. Several types of power management strategies for FCHVs have been developed, including optimal control strategies based on the optimal control theory [1, 2], rule-based algorithms [3], and ECMS [4].

The ECMS is originally based on the heuristic concept that the usage of the electric energy can be exchanged to the equivalent fuel consumption [4]. It is assumed in the ECMS that the current battery usage would be compensated in the future by the fuel usage [5]. The task of the optimal control is to determine a control function that minimizes the fuel consumption while satisfying the system constraints. The optimal control theory to accomplishing minimization includes PMP and DP. The PMP-based optimal control strategy minimizes the fuel consumption and optimizes the power distribution between the FCS and the battery by providing the necessary optimality conditions [6]. The DP examines all possible control inputs at every state, thus it provides the global optimal solution.

The ECMS is based on the heuristic concept, though it is also related to the optimal concept because the solution of the ECMS is obtained by minimizing the total equivalent fuel consumption. To find out the relationship between the ECMS and the optimal control strategy in FCHVs, the solution obtained from the ECMS is compared to the solutions derived from the PMP-based optimal control strategy and the DP.

2 The Vehicle Model

The target FCHV in this research combines an FCS and a battery. Fig. 1 [7] illustrates the power flows in the FCHV. The arrows indicate the power flow directions. The motor receives electric power from both the FCS and the battery, and the battery can recover the braking energy through the motor.

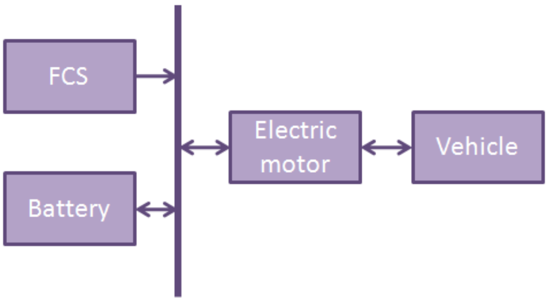

Figure1: Power flows of the FCHV

The vehicle parameters used here are listed in Table 1. These data were sourced from available literature [8]. Table 2 summarizes the powertrain components selected in this paper.

Table1: Vehicle parameters

Item	Value
Vehicle total mass (kg)	1500
Final drive gear efficiency (%)	95
Tire radius (m)	0.29
Aerodynamic drag coefficient	0.37
Vehicle frontal area (m^2)	2.59
Air density (kg/m^3)	1.21
Rolling resistance coefficient	0.014

Table2: Powertrain components of the FCHV

Component	Value
Electric motor	75 kW
FCS	45 kW
Battery	1.5 kWh

A steady-state model is used for the FCS. In this model, there exists a relationship between the FCS net power and the fuel consumption rate. Fig. 2 shows the relationship for the FCS used in this research.

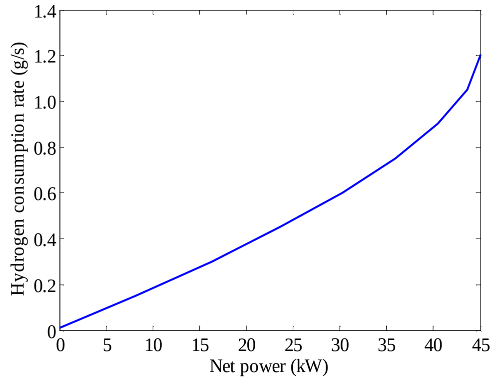

Figure2: The relationship between the FCS net power and the fuel consumption rate

The internal resistance model is utilized for the battery. In this model, the parameters of the battery are related according to the following equation:

$$\dot{SOC} = -\frac{I}{Q_{bat}}$$
$$I = \frac{V(SOC) - \sqrt{V(SOC)^2 - 4R(SOC)P_{bat}}}{2R(SOC)} \quad (1)$$

Here, Q_{bat} is the battery capacity, P_{bat} is the battery power, and I is the battery current. V represents the open circuit voltage (OCV) of the battery and R represents the internal resistance of the battery. Both V and R are functions of the battery SOC in this model. Fig. 3 and Fig. 4 illustrate the OCV and the internal resistance for the battery used in this research. The internal resistance for charging and discharging is different here.

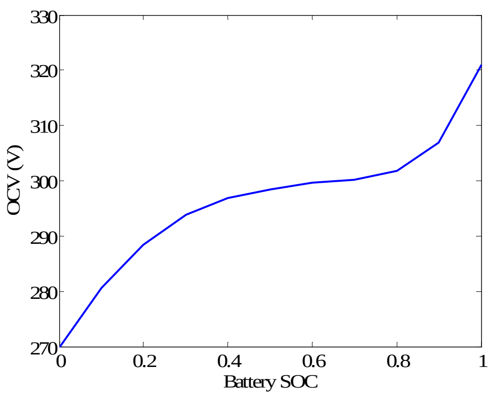

Figure3: OCV of the battery

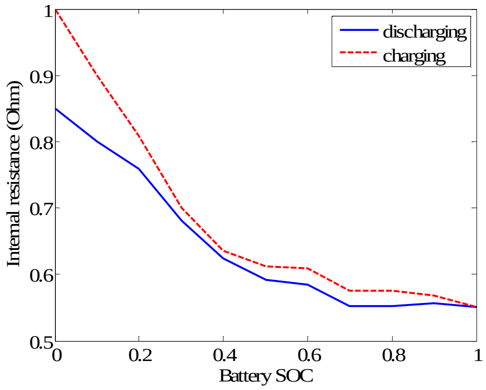

Figure4: Internal resistance of the battery

3 The ECMS

As stated previously, the ECMS is based on the heuristic concept that the electric usage can be exchanged to the fuel usage. In the ECMS, the total equivalent fuel consumption rate consists of the actual fuel consumption rate of the FCS and the equivalent fuel consumption rate of the battery [4], as follows:

$$C = C_{fcs} + k \cdot C_{bat} \tag{2}$$

Here, C is the total equivalent fuel consumption rate, C_{fcs} is the actual fuel consumption rate of the FCS illustrated in Fig. 2, and C_{bat} is the equivalent fuel consumption rate of the battery. k is a linear penalty coefficient which is used to accomplish the charge-sustaining operation of the battery [4].

If it is assumed that the battery provides the same amount of power as the FCS, the fuel consumption rate of the FCS illustrated in Fig. 2 will be the equivalent fuel consumption rate of the battery. Considering the battery efficiency caused by the internal resistance R, C_{bat} can be expressed as follows:

$$C_{bat} = \frac{C_{fcs,avg}}{P_{fcs,avg}} \cdot \left(P_{bat} + I^2 R\right) \tag{3}$$

Here, $C_{fcs,avg}$ is the average fuel consumption rate of the FCS, and $P_{fcs,avg}$ is the average net power of the FCS. The motor receives electric power from both the FCS and the battery as follows:

$$P_{req} = P_{fcs} + P_{bat} \tag{4}$$

Here, P_{req} represents the power required for the motor and P_{fcs} represents the FCS net power. $C_{fcs,avg}$ and $P_{fcs,avg}$ are given for the FCS used in this research. P_{req} is also given when a driving cycle is selected for the FCHV. I is related to the FCS net power and the battery SOC based on equation (1) and equation (4). R is a function of the battery SOC as illustrated in Fig. 4. By summing up the above explanation, equation (2) can be expressed as follows:

$$C = C_{fcs}\left(P_{fcs}\right) + k \cdot C_{bat}(P_{fcs}, SOC) \tag{5}$$

In equation (5), the first term is from Fig. 2. At every simulation time step, the solution of the ECMS can be obtained by determining the FCS net power that minimizes the total equivalent fuel consumption rate C in equation (5).

4 Optimal Control Strategy

The task of the optimal control is to determine a control function that minimizes the fuel consumption while satisfying the system constraints. The optimal control theory to accomplishing minimization includes PMP and DP. The PMP-based optimal control strategy minimizes the fuel consumption and optimizes the power distribution between the FCS and the battery by providing the necessary optimality conditions [6]. The performance measure to be minimized is the total fuel consumption. Considering the optimal control theory based on the Calculus of Variation, and equation (1), which is the constraint of the system, the necessary conditions of the optimal control are as follows [9]:

$$\begin{aligned} &\frac{\partial H}{\partial p} = S\dot{O}C \\ &\frac{\partial H}{\partial SOC} = -\dot{p} \\ &H(P_{fcs}^*, SOC^*, p^*, t) \le H(P_{fcs}, SOC^*, p^*, t) \end{aligned} \tag{6}$$

Here, p is called the costate, H is the Hamiltonian, which is defined as follows:

$$H = \dot{m}_{h_2}(P_{fcs}) + p \cdot S\dot{O}C(P_{fcs}, SOC) \tag{7}$$

The FCS net power P_{fcs} is considered as the control variable in the PMP. The third necessary condition in (6) instantaneously determines the optimal control variable P_{fcs}.

DP is a numerical method of the Hamilton-Jacobi-Bellman (HJB) equation, and it examines all available control inputs at every state, thus it provides the global optimal solution. In this research, the battery power P_{bat} is regarded as the control variable in the DP, whereas the FCS net power P_{fcs} is considered as the control variable in the PMP.

5 Comparison of the ECMS and the Optimal Control

As stated before, the ECMS is based on the heuristic concept, though it is also related to the optimal concept because the instantaneous solution of the ECMS in equation (5) is obtained by minimizing the total equivalent fuel consumption rate C. To find out the relationship between the ECMS and the optimal control strategy in FCHVs, the solution obtained from the ECMS is compared to the solutions derived from the PMP-based optimal control strategy and the DP in this section.

As we can see, equations (5) and (7) have similar formats. The costate p in the PMP can be considered as a constant, and there exists an approximately proportional relationship between the final battery SOC and the fuel consumption while changing the constant p in the PMP [10]. The relationship between the final battery SOC and the fuel consumption for the ECMS is also assessed while altering the linear penalty coefficient k in order to compare the ECMS and the PMP. Fig. 5, Fig. 6, and Fig. 7 show the comparison results of the ECMS and the PMP for the relationship on the FTP75 urban, NEDC 2000, and Japan 1015 driving cycles. It is clear that the relationship for the two strategies is nearly identical for the three driving cycles. The discrepancy between the two strategies is within plus/minus 0.02%.

The simulation results of the ECMS are also compared to that of the DP. Fig. 8 and Fig. 9 illustrate the comparisons of the simulation results on the FTP75 urban driving cycle. Fig. 8 shows the FCS net power trajectories and Fig. 9 illustrates the battery power trajectories. It can be seen that the simulation results of the ECMS and the DP overlap each other most of the time.

Previous research [6] proved that the optimal control strategy based on the PMP can serve as a global optimal solution (DP) under the assumption that the internal resistance and OCV of a battery are independent of the battery SOC. This assumption is reasonable for non-plug-in hybrid vehicle applications. Therefore, it can be assumed that the PMP and DP have the same solution in this research.

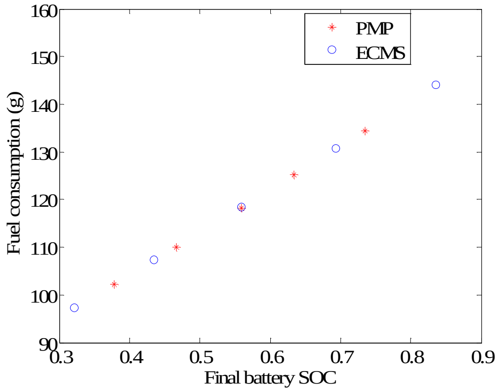

Figure5: Comparison between the ECMS and the PMP-based optimal control (FTP75 urban driving cycle)

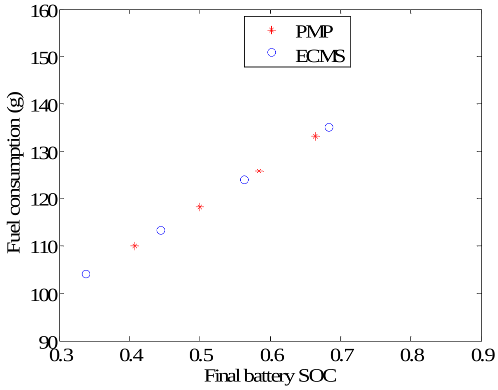

Figure6: Comparison between the ECMS and the PMP-based optimal control (NEDC 2000)

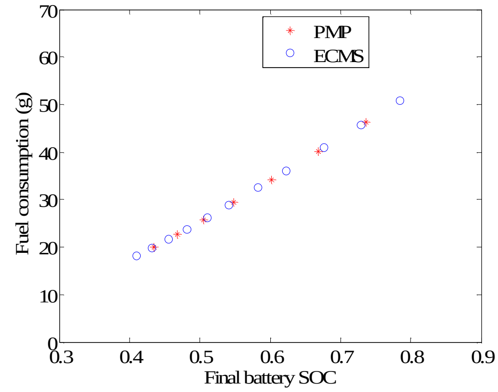

Figure7: Comparison between the ECMS and the PMP-based optimal control (Japan 1015 driving cycle)

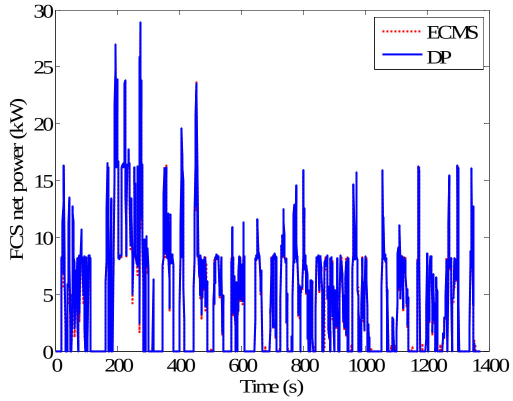

Figure8: FCS net power trajectory comparison of the ECMS and the DP

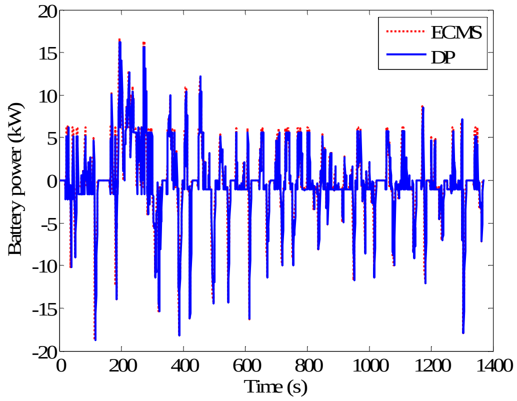

Figure9: Battery power trajectory comparison of the ECMS and the DP

It can be concluded from the contents in this section that the ECMS provides the same solution with the PMP and DP for FCHVs. The same conclusion can be drawn for engine/battery powered non-plug-in hybrid vehicles.

6 Conclusion

The ECMS is originally based on the heuristic concept of equivalent fuel consumption, though it is also related to the optimal concept duo to the minimization of the total equivalent fuel consumption. The PMP and DP are based on the optimal control theory. The ECMS for FCHVs is introduced and the simulation results of the ECMS are compared to that of the PMP and DP in this research. As a conclusion, the ECMS provides the same solution with the PMP and DP for FCHVs. This conclusion is also effective to engine/battery powered non-plug-in hybrid vehicles.

Acknowledgments

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (No.2011-0001276).

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