

A Study on How to Utilize Hilly Road Information in Equivalent Consumption Minimization Strategy of FCHEVs

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ABSTRACT

This paper presents an adaptation method of equivalent factor in equivalent consumption minimization strategy (ECMS) of fuel cell hybrid electric vehicle (FCHEV) using hilly road information. Instantaneous optimization approach such as ECMS is one of real-time controllers. Furthermore, it is widely accepted that ECMS achieves near-optimum results with the selection of the appropriate equivalent factor. However, a lack of hilly road information no longer guarantees near-optimum results as well as charge-sustaining of ECMS under hilly road conditions. In this paper, first, an optimal control problem is formulated to derive ECMS analytical solution based on simplified models. Then, we proposed updating method of equivalent factor based on sensitivity analysis. The proposed method tries to mimic the globally optimal equivalent factor trajectory extracted from dynamic programming solutions. Finally, simulations for various hilly roads are carried out for validation of the proposed adaptation method of equivalent factor. Results show that the proposed method generates similar equivalent factor trajectory with globally optimal equivalent factor trajectory in the specific drive condition. In conclusion, if future vehicle velocity can be assumed as average velocity such as highway driving mode, the proposed method using hilly road information is very effective in near-optimum results as well as charge-sustaining.

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INTRODUCTION

Fuel cell technology is one of the promising long-term solutions for future transportation energy sources because it can completely eliminate CO₂ emissions as well as harmful emissions, and at the same meet the customer expectations for range, fueling time, etc. Generally, fuel cell powered vehicles are equipped with an energy storage system, often called fuel cell hybrid electric vehicle (FCHEV). An addition of energy storage system adds an additional degree of freedom in power flow. Power coordination between two energy sources (Fuel Cell and Battery), known as energy management strategy or supervisory control, plays very important role in harnessing the full potential of the FCHEV. Several research studies regarding optimal energy management strategy have been widely carried out over the past decade.

Existing energy management strategies for FCHEV can be classified into three types; rule-based approach, horizon (global) optimization approach, and instantaneous (real-time) optimization approach. Rule-based approach uses a deterministic rule or a fuzzy set of the rules based on the efficiency of each power source [1, 2]. Horizon optimization

approach such as dynamic programming (DP) is generally used to obtain globally optimal solutions [3, 4]. DP is generally used to evaluate quality of sub-optimal real-time controller or to tune the rules for satisfying near-optimum results for rule-based method [5, 6]. However, DP cannot be implemented to real-time controller because it requires a prior disturbance over the entire time period, and causes heavy computational burden. On the other hand, instantaneous optimization approach such as equivalent consumption minimization strategy (ECMS) is easy to be implemented [7]. Namely, equivalent factor of ECMS is only one variable to be updated for near-optimum results and charge sustaining. Therefore, with selection of appropriate equivalent factor was chosen, it leads to near-optimum results; otherwise, near-optimum results are not guaranteed. This appropriate equivalent factor can be extracted by offline iterative search because it depends on future drive condition [8]. The future drive conditions include drive cycle and altitude profile, etc. Except for drive cycle, altitude variation is also important for optimal energy management strategy [9]. There is a substantial potential to improve control performance when hilly road information is utilized. Among a few research studies using hilly road information, one research generated the desired battery state

of charge and then ECMS tried to follow this desired battery state of charge for recuperation of maximum braking energy in admissible range of battery state of charge [10]. Another one only used minimum altitude information to guarantee charge-sustaining [11].

In contrast to the past research studies, the main purpose of this paper is to introduce new adaptation law using future hilly road information. Therefore, we derived input constrained optimal solution of ECMS and designed adaptation law of equivalent factor based on sensitivity analysis. Finally, globally optimal equivalent factor trajectory extracted DP solutions [12] is used as a reference to validate the proposed adaptation law.

Section 2 describes system configuration of FCHEV. Section 3 introduces ECMS concept and explains derivation procedure of input constrained optimal solution of ECMS. And then adaptation law is proposed through sensitivity analysis. Section 4 shows the simulation results. Finally, in Section 5, summary and conclusions from results are addressed.

FCHEV SYSTEM CONFIGURATION

This paper considers fuel cell powered vehicle with the battery. Fuel cell system provides electrical power through a DC/DC converter to a system bus, and the battery is considered as another power source. Simplified FCHEV model consists of three components; Fuel cell system, battery, and vehicle.

The fuel cell system is modelled as steady-state model. We used experimental polarization curve, which has a static dependency between cell voltage and current density. Balance of plant is also taken into account by using an experimental auxiliary power map. The battery is assumed as equivalent internal resistance model. In battery circuit model, open circuit voltage and internal resistance depends on the battery state of charge.

ECMS

One of the real-time optimization strategies is ECMS. The main idea of real-time optimization approach is to reduce the global fuel economy minimization to an instantaneous minimization problem.

Concept of ECMS

The cost function of ECMS represents equivalent fuel consumption. For the FCHEV, ECMS considers the battery as virtual fuel cell system, thereby, cost function can be expressed as equivalent hydrogen consumption with equivalent factor, as expressed below:

$$\dot{m}_{eqv.} = \dot{m}_{H_2} + \dot{m}_{eqv.H_2.by.BT} = \dot{m}_{H_2} + \frac{s}{LHV_{H_2}} P_{eBT}$$

where $\dot{m}_{eqv.}$ denotes equivalent fuel consumption, $\dot{m}_{H_2}$ denotes hydrogen mass flow rate, $\dot{m}_{eqv.H_2.by.BT}$ denotes virtual hydrogen mass flow rate by the battery, s denotes equivalent factor, LHV_{H_2} denotes lower heating value of hydrogen, and P_{eBT} denotes electric battery power flow.

DP-Based ECMS

In this section, DP-based ECMS is introduced as benchmark for designing how to adjust equivalent factor over hilly roads. DP-based ECMS is a methodology to extract globally optimal equivalent factor trajectory from DP solutions [12]. ECMS algorithm with globally optimal equivalent factor trajectory generates same results as DP. Therefore, DP-based ECMS will act as a guideline designing equivalent factor adaptation laws that can achieve near-optimum results which satisfying charge-sustaining.

Input Constrained Optimal Solution of ECMS

Under real-world drive conditions many uncertainties such as varying altitude affect power demand. Then, it leads to loss of near-optimum results unless equivalent factor is adjusted. Therefore, it is necessary to analyze how the uncertainties affect ECMS optimal control solution. In this section, ECMS optimal control problem is formulated to derive analytical optimal solution; this problem is valid only for positive power demand because negative power demand generated from braking directly charges the battery. For simplicity of derivation, simplified sub-component models are used.

In a fuel cell system, the polarization curve can be approximated as linear function of fuel cell current with the exclusion of very low current. In hydrogen system, the hydrogen mass can be simply calculated by fuel cell current. Under the assumption of linear polarization and no auxiliary power, we can express fuel cell current I_{FC} as function of required fuel cell power $P_{FC.req}$. Then, it can be approximated using Taylor's series around $P_{FC.req}=0$ as follows:

$$\dot{m}_{H_2} = N_{FC} \frac{M_{H_2}}{n_e F} I_{FC} \approx N_{FC} \frac{M_{H_2}}{n_e F} \left\{ \frac{1}{V_{FC.OC}} P_{FC.req} + \frac{R_{FC}}{V_{FC.OC}^3} P_{FC.req}^2 \right\}$$

where N_{FC} denotes the number of cells in the fuel cell stack, M_{H_2} denotes the molar mass of the hydrogen, n_e denotes the number of electrons, F denotes Faraday's constant. $V_{FC.OC}$ denotes the voltage at $I_{FC}=0$ (no-current state) and R_{FC} denotes overall resistance of fuel cell.

Electric battery power flow can be expressed as the sum of required battery power $P_{BT.req}$ and its loss $P_{BT.loss}$. The battery power loss can be derived based on an equivalent internal resistance model. Then, it can be approximated using Taylor's series equation in the same way above.