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Optimal adaptation of equivalent factor of equivalent consumption minimization strategy for fuel cell hybrid electric vehicles under active state inequality constraints

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HIGHLIGHTS

- We discuss DP, PMP, and ECMS in presence of state inequality constraints.
- We use DP solution for extracting optimal equivalent factor trajectory.
- Equivalent factor must be adjusted drastically if state constraints are active.
- Equivalent factor adaptation prevents loss of recuperation energy under downhill road.

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ABSTRACT

Among existing energy management strategies (EMSs) for fuel cell hybrid electric vehicles (FCHEV), the equivalent consumption minimization strategy (ECMS) is often considered as a practical approach because it can be implemented in real-time, while achieving near-optimal performance. However, under real-world driving conditions with uncertainties such as hilly roads, both near-optimality and charge-sustenance of ECMS are not guaranteed unless the equivalent factor (EF) is optimally adjusted in real-time. In this paper, a methodology of extracting the globally optimal EF trajectory from dynamic programming (DP) solution is proposed for the design of EF adaptation strategies. In order to illustrate the performance and process of the extraction method, a FCHEV energy management problem under hilly road conditions is investigated as a case study. The main goal is to learn how EF should be adjusted and the impact of EF adaptation on fuel economy under several hilly road cases. Using the extraction method, the DP-based EF is computed, and its performance is compared with those of Pontryagin's minimum principle (PMP) and conventional ECMS. The results show that the optimal EF adaptation significantly improves fuel economy when the battery SoC constraint becomes active, and thus EF must be properly adjusted under severely hilly road conditions.

1. Introduction

Fuel cell technology is one of the promising long-term energy solutions for future transportation systems because it can eliminate tail-pipe CO_2 emissions as well as other harmful emissions. Generally, fuel cell-powered vehicles are equipped with an energy storage system and are often called fuel cell hybrid electric vehicle (FCHEV) because the addition of an energy storage system creates an additional degree of freedom in power flow. This allows the fuel cell system to operate more reliably and efficiently. For harnessing the full potential of FCHEVs, power coordination between the two energy sources, known as energy management strategy (EMS), is very important, and the optimal EMS has been studied widely over the past decade.

Existing EMSs can be classified into three types: rule-based approach, horizon optimization approach, and instantaneous (real-time) optimization approach. Rule-based approaches use a deterministic rule or a fuzzy set of rules, designed heuristically

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Nomenclature

BT	battery
DP	dynamic programming
ECMS	equivalent consumption minimization strategy
EF	equivalent factor
EMS	energy management strategy
FC	fuel cell
FCHEV	fuel cell hybrid electric vehicle
GPS	global positioning system
HEV	hybrid electric vehicle
HJB	Hamiltonian Jacobi Bellman
PMP	Pontryagin's minimum principle
SoC	state of charge in battery system

based on the efficiency of each power source [1,2]. Other recent studies attempt to optimize the performance of rule-based controllers by calibrating control parameters and thresholds that determine operation mode switching [3,4], but the optimization of multiple control parameters under real-world driving conditions with many uncertainties are challenging and their optimality are not guaranteed. In order to ensure the optimality, horizon optimization method such as Dynamic Programming (DP) is widely used [5,6]. However, DP cannot be implemented as a real-time controller because it requires complete driving cycle information a priori and imposes a heavy computational burden [7,8]. In contrast, instantaneous optimization methods such as equivalent consumption minimization strategy (ECMS) are easy to implement, but their global optimality over the horizon is not guaranteed [9]. However, it is widely accepted that ECMS achieves near-optimal performance with the selection of an appropriate equivalent factor (EF) [10–12]. A few studies have proposed a method for determining the EF using a pattern recognition algorithm for achieving near-optimal performance under real-world driving conditions [13].

The near-optimality of ECMS, however, no longer holds when state inequality constraints become active. For instance, when uncertainties such as a hilly road section are present, constant EFs cannot guarantee the charge-sustenance and near-optimality. For solving this problem, many studies have proposed adaptive-ECMS, wherein the EF is adjusted based on the battery state-of-charge (SoC) [14,15]. While these online adaptive ECMSs yield practical benefits in terms of charge sustenance, they do not guarantee near-optimality and even charge-sustenance under active state inequality constraints. In Ref. [16], a predictive reference signal generator was proposed for generating the desired battery SoC trajectory, which helps maximize energy recuperation under state inequality constraints. Although this approach helps recuperating a greater amount of braking energy while maintaining SoC within the admissible range as compared with the conventional ECMS, it cannot be considered as benchmark that guarantees global optimality.

A practical method of guaranteeing near-optimality would be to adjust EF using the horizon optimization approach. A means of obtaining a good reference EF trajectory is the use of Pontryagin's minimum principle (PMP) approach because the PMP necessary condition includes costate dynamics, which essentially represents the optimal EF trajectory [17,18]. In particular, for HEV applications, it is widely accepted that the PMP solution is unique and globally optimal [19]. However, under active state inequality constraints, PMP problem formulation is not trivial, and the solutions are no longer unique. There have been attempts to formulate and solve PMP problems with state inequality constraints. For instance, Kim et al. used an optimal control theory that converts the state inequality constraint into a new single equality constraint as a part of the necessary condition [19,21]. In addition, Kim et al. proposed the use of a jump condition, which allows discontinuity of the costate dynamics for plug-in HEV energy management problems [20]. However, these approaches lead to multiple local minimum solutions, and these solutions do not guarantee optimality unless many iterations are carried out for determining the globally optimal solution. Therefore, a methodology for extracting the globally optimal EF trajectory from the DP solution is proposed, including extreme case of active state inequality constraints. This method can potentially be used for designing an adaptive ECMS, the EF of which tries to mimic the EF extracted from DP solutions.

The main contributions of this paper are as follows: 1) The strengths and limitations of three EMSs (DP, PMP, and ECMS) under state inequality constraints are discussed. 2) A simple but effective method is proposed for extracting the globally optimal EF trajectory that preserves the state inequality constraints from DP solution. This method can provide valuable insights into how to adjust EF for achieving global optimal performance as a benchmark for online ECMS adaptation. 3) A case study is carried out for checking the DP-based EF trajectory corresponding to conditions in which hilly road conditions activates SoC constraints or not. The results show that when hilly road conditions activate SoC constraints, the loss of optimality of ECMS is significant, and thus the EF must be adjusted appropriately for achieving both near-optimal fuel economy and charge sustenance.

The remainder of this paper is organized as follows: Section 2 includes an introduction to the FCHEV system configuration and system modeling. Section 3 explains the horizon optimization approach under state inequality constraints. In Section 4, ECMS is addressed as one of the instantaneous optimization approaches. In the presence of state inequality constraints, the EF role of ECMS is emphasized for achieving charge sustenance and near-optimality. Therefore, the method to extract the optimal EF trajectory from the DP solution is introduced. Section 5 discusses a case study in which ECMS with DP-based EF is applied to a real-world driving condition. The results of the case study show that the DP-based EF trajectory provides a reference and valuable insights into how EF should be adjusted under hilly road conditions. Finally, in Section 6, the summary and conclusions of this study are presented.

2. FCHEV system configuration

In this section, a system-level FCHEV model is introduced for energy management studies. Fig. 1 shows a block diagram of the FCHEV model, which consists of a fuel cell system, battery system, and vehicle. The fuel cell system acts as the main electrical power source for the system bus, and the electrical power supplied by the battery is determined as follows.

$$P_{\mathrm{demand}} = P_{\mathrm{BT\cdot req}} + P_{\mathrm{FC\cdot req}} \quad (1)$$

This power bus relationship is based on the fact that the two energy sources put together must provide the power required by a driving cycle.

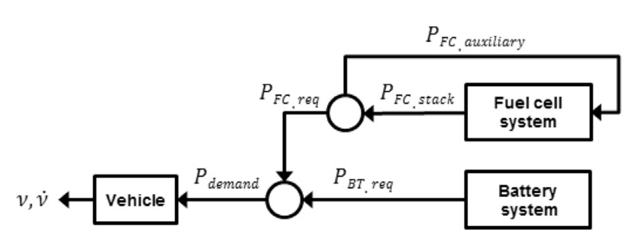

Fig. 1. Block diagram of FCHEV model.