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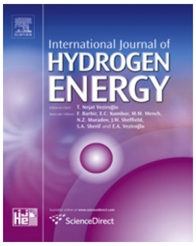

The effect of battery temperature on total fuel consumption of fuel cell hybrid vehicles

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ABSTRACT

In order to consider the effect of battery temperature on the total fuel consumption when a Pontryagin's Minimum Principle (PMP)-based power management strategy is applied to a fuel cell hybrid vehicle (FCHV), this paper designates the battery temperature as a second-state variable other than the battery state of charge (SOC) and defines a new costate for the battery temperature in the control problem. The PMP-based power management strategy is implemented in a computer simulation and the relationship among the final values of the two state variables and the total fuel consumption is illustrated based on the simulation results. This relationship is defined as an optimal surface in this research. Using the optimal surface, it can be concluded that considering the battery temperature effect in the PMP-based power management strategy improves the fuel economy of the FCHV. Potential fuel economy gains attributed to consideration of the battery temperature effect are also determined based on the optimal surfaces.

1. Introduction

Hybrid vehicles have become a major area of interest in academia and in the automotive industry recently owing to the energy supply problem and environmental problems. The power management strategy of hybrid vehicles is one of the most important and popular research topics in this area, as it determines the power split between power sources and because it is related to the fuel economy of the vehicle. Several types of power management strategies for hybrid vehicles have been developed during last few decades. These power management strategies can be divided into two major groups: those based on the heuristic concept and those based on the optimal control theory. The former mainly includes rule-based algorithms and fuzzy logic algorithms [1–3]. Earlier in the development of hybrid vehicles, power management strategies were dominated by these types of strategies owing to their simplicity when actually realizing them. These types

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of strategies, however, cannot guarantee the optimal power distribution and the optimal fuel economy as well. To remedy this problem, the optimal control theory was introduced as part of the power management strategy of hybrid vehicles, including both Dynamic Programming (DP) as developed by R. E. Bellman [4,5] and Pontryagin's Minimum Principle [4,6]. The DP approach examines all admissible control inputs at every state, thus guaranteeing global optimality if the driving cycle information is given in advance. However, the DP approach cannot be used directly for the real-time control of hybrid vehicles due to the backward-looking calculation process and the long calculation time. The PMP-based power management strategy optimizes the power distribution and minimizes the performance measure by instantaneously providing the necessary optimality conditions. One of the major advantages of the PMP-based strategy is that there is only one parameter to be tuned in this strategy in order to obtain optimal results over a specific driving cycle [7]. Moreover, the core of this strategy is implementable in a real-time controller, even if the driving cycle information is not known in advance [8].

The PMP-based power management strategy is applied to an FCHV in this research. Some researchers have studied this type of optimal control strategy for FCHVs and for engine/battery powered hybrid vehicles as well [9–12]. In earlier research on FCHVs, the performance measure to be minimized is the total fuel consumption, the system state variable is the battery *SOC*, and the system control variable is the battery power or the fuel cell system (*FCS*) power. In this research, the system state variable is expanded to two which are the battery *SOC* and the battery temperature.

A proton-exchange-membrane (PEM) fuel cell is usually used in vehicular applications, and the temperature of the PEM fuel cell is controlled properly within a certain small range by its thermal management system when it is operating. However, the battery temperature increases during its operation. This affects the total fuel consumption, as the battery temperature is related to the battery efficiency and is further related to the efficiency of the entire vehicle system. Good battery thermal management is necessary for better fuel economy. In order to consider the influence of the battery temperature on the total fuel consumption, the battery temperature is designated as a second-state variable and a new costate is defined for the battery temperature in the control problem of the FCHV in this research. Effects of the battery *SOC* and temperature on the total fuel consumption are assessed by presenting the relationship among the final battery *SOC*, the final battery temperature, and the total fuel consumption based on simulation results. An optimal surface is defined based on the simulation results of the PMP-based power management strategy, and the fuel consumption differences are also given for the case with consideration of the battery temperature effect and for the case without consideration of the temperature effect.

2. Control-oriented vehicle model

In order to evaluate the power management strategy proposed in this research, a quasi-static vehicle model is used. A quasi-static model is sufficient to calculate energy flows in the powertrain and is suitable for fuel economy optimization problems [13]. Fig. 1 illustrates energy flows in an FCHV. The motor receives power from both the *FCS* and the battery through the DC–DC converter and the DC–AC inverter. The battery can recover braking energy through the motor. The arrows in Fig. 1 indicate the energy flow directions. In this research, the motor uses a map to express its efficiency, and the converters are considered to be ideal power converters with a constant efficiency of 95%. The final drive gear efficiency is assumed to be a constant. The vehicle parameters used in this research are shown in Table 1. Parts of these data are sourced from available literature [14]. A 62 kW *FCS* and a battery with the energy capacity of 1.9 kWh at 25 °C are selected as the power sources of the FCHV. A 75 kW motor is also selected.

2.1. *FCS*

The *FCS* is the primary power source in the FCHV. In this research, the main losses of a single cell, including activation loss, ohmic loss, and concentration loss, are considered by physical and empirical equations [15,16]. These losses are caused by various physical or chemical factors. The parameters used to calculate the *FCS* net power are listed in Table 2. Some of these data are sourced from the literature [15]. The power loss caused by an air compressor is modeled by a map which is obtained from the compressor model [15,16]. The part of power loss caused by other auxiliary components is modeled by a constant.

Fig. 2(a) illustrates the stack-provided power, auxiliary power, and *FCS* net power of the *FCS* used in this research. The relationship between the *FCS* net power P_{fcs} and the stack-provided power P_{stack} is as follows:

$$P_{fcs} = P_{stack} - P_{aux} \tag{1}$$

Here, P_{aux} represents the power consumption of the auxiliary components.

For the fuel cell stack, the fuel consumption rate $\dot{m}_{h_2}$ is related to the stack current according to the following equation:

$$\dot{m}_{h_2} = \frac{N_{cell} \cdot M_{h_2}}{n \cdot F} \cdot I_{stack} \cdot \lambda \tag{2}$$

In Eq. (2) [9], N_{cell} represents the cell number, M_{h_2} represents the molar mass of hydrogen, n represents the number of electrons acting in the reaction, F is the Faraday constant, I_{stack} is the stack current, and λ is the hydrogen excess ratio. The *FCS* net power and the fuel consumption rate have a specific relationship, as both of them are related to the fuel cell stack current according to Fig. 2(a) and Eq. (2). Fig. 2(b) illustrates the relationship between the *FCS* net power and the fuel consumption rate of the *FCS* used in this research.

The *FCS* efficiency η_{fcs} is defined as

$$\eta_{fcs} = \frac{P_{fcs}}{\dot{m}_{h_2} \cdot LHV} \tag{3}$$

In Eq. (3) [17], $LHV = 120{,}000$ kJ/kg is the lower heating value of hydrogen. Fig. 2(c) illustrates the *FCS* efficiency for the *FCS* used in this research.