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Mode shift map design and integrated energy management control of a multi-mode hybrid electric vehicle

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HIGHLIGHTS

- Dynamic programming is used to optimize the energy management of multi-mode HEV.
- Mode shift frequency and energy losses during mode transition are considered.
- Working points of each mode for multi-mode HEV are extracted.
- Mode shift map of the charge-sustained mode is designed through the support vector machine.
- Combine the optimized mode shift map with equivalent consumption minimization strategy.

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ABSTRACT

Multi-mode hybrid electric vehicles (HEVs) have become popular in recent years because of their high efficiency and excellent overall performance. However, the introduction of multiple operating modes has led to some issues, e.g., mode shift problems, which are not observed in conventional HEVs with a single mode. Similar to a gear shift map in conventional vehicles, the mode shift map in multi-mode HEVs needs to be properly designed. In this study, the energy management algorithm of a multi-mode HEV is optimized using dynamic programming (DP) considering the mode shift frequency and energy losses. A mode shift map is then extracted from the operating points of the DP results using the support vector machine (SVM). By combining the derived mode shift map and the equivalent consumption minimization strategy (ECMS), a real-time control strategy is proposed for the online energy management of the multi-mode HEV. The results of a case study show the effectiveness of the proposed mode shift map and energy management strategy.

1. Introduction

Fuel economy and carbon emission standards for automobiles have become much tighter worldwide in recent years [1]. Hybrid electric vehicles (HEVs) or plug-in HEVs, which are one of the most viable and promising solutions to reach the fuel economy goals, have achieved success in both two wheel [2] and four wheel drive [3,4] applications.

In HEVs, an internal combustion engine (ICE) is generally used as the primary power source and a battery pack as the secondary power source. Electric motor/generators (MGs) are used to complement the engine load so that it operates more efficiently and effectively [5]. By having more than one power source in the powertrain, various system architectures can be obtained by changing the combinations and sequences between the powertrain components (ICE and MGs). Based on the mechanical connection between the powertrain components, the HEVs are generally divided into four categories: series, parallel, power split, and multi-mode.

Among the four categories, the power-split HEV is the most popular type of HEV available in the market, wherein one or more planetary gear (PG) sets are used to couple the engine, two MGs, and output shaft of the vehicle [6,7]. The engine speed in power-split HEVs is decoupled from the vehicle speeds when MGs are well controlled [8]. Hence, the engine operates efficiently in a wide range of vehicle speeds. This characteristic is also referred to as electronic continuously variable transmission (ECVT) in some studies [9].

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Nomenclature

A_f	frontal area of the vehicle
C_D	aerodynamic drag coefficient
F_*	internal force of PGs acting between gears
$\overline{FC}$	estimated fuel consumption conversion factor
FR	gear ratio of final drive
$f(SOC)$	SOC related penalty factor
g	gravitational acceleration
$g_{fuel}(k)$	fuel consumption at time k
I_*	inertia of powertrain components
$K(*)$	kernel function
m	vehicle mass
$\dot{m_{f_{batt}}}(\cdot)$	equivalent fuel consumption rate of the battery energy
m_{fuel}	fuel consumption of the engine
$Mode_{available}$	available modes
$Mode$	mode state
$P_{shift}(k)$	mode shift penalty
P_{batt}	battery power
Q_{batt}	maximum capacity of the battery
R_*	radius of the ring gear
R_{tire}	tire radius
R_{int}	internal resistance of the battery
R_t	terminal resistance of the battery
S_*	radius of the sun gear
SOC_{des}	desired battery SOC
SOC_f	terminal battery SOC
T_*	torques of powertrain components
T_{load}	vehicle resistance from the road
T_{req}	vehicle torque demand
$v_{vehicle}$	vehicle speed
V_{oc}	open circuit voltage of the battery
$\vec{\boldsymbol{x}}_*$	input vector of the training data
$\boldsymbol{y}_*$	class type of the training data
α_*	weighting factors of the mode shift penalty
α	road slope
β_*	Lagrange multiplier
μ_*	weighting factors of two penalties
ω_*	rotational speed of powertrain components
$\vec{\omega}$	normal vector to the hyperplane
ρ_{air}	density of air
δ	mode state related factor

Acronyms

AHS	Allison Hybrid System
B_1	Grounding Clutch
BSFC	Brake Specific Fuel Consumption
CD	Charge Depletion
CS	Charge Sustained
DP	Dynamic Programming
ECMS	Equivalent Consumption Minimization Strategy
ECVT	Electronic Continuously Variable Transmission
FUDS	EPA Federal Urban Driving Schedule
GM	General Motor
HEV	Hybrid Electric Vehicle
HWFET	EPA Highway Fuel Economy Driving Schedule
ICE	Internal Combustion Engine
J1015	Japan 10–15 Mode Cycle
MG	Motor/Generator
MPC	Model Predictive Control
NVH	Noise Vibration and Harshness
NEDC	New European Driving Cycle
OWC	One Way Clutch
PG	Planetary Gear
PMP	Pontryagin's Minimum Principle
SUV	Sport Utility Vehicle
SVM	Support Vector Machine
SOC	State of Charge
US06	EPA high acceleration driving schedule
UC	California Unified Cycle
WLTP	Worldwide Harmonized Light Vehicles Test Procedures

Recently, the multi-mode HEVs, realized by adding clutches, have become increasingly popular because of their potential in improving the fuel economy [10–18]. A series-parallel configuration is employed in a typical multi-mode HEV, wherein a clutch is used to disengage the connection between the ICE and the output shaft, thereby realizing the following three operating modes: electric vehicle (EV) mode, series mode, and parallel mode.

Another type of multi-mode hybrid powertrain is realized by introducing clutches between the PG nodes of the power-split configuration [11,12]. By switching the clutch states, multiple operating modes can be realized in a single powertrain. For example, the Allison hybrid system (AHS) manufactured by General Motors (GM), is a typical multi-mode hybrid powertrain with double PGs and two clutches, enabling two ECVT modes [13]. An input-split mode is used in a low speed range whereas a compound-split mode is more beneficial for high-speed cruising. The combination of different operating modes helps the powertrain in maintaining superior efficiency under different working conditions.

In addition to the operating efficiency, a better acceleration performance can be obtained if the parallel mode or pure electric mode with a high gear ratio is introduced in the multi-mode hybrid powertrain [14]. The two-mode hybrid powertrain, developed by GM, is another popular multi-mode hybrid powertrain, which has been applied to pick-up trucks, SUVs, and buses [15]. It has six operating modes, which are realized using four clutches. The two ECVT modes ensure efficient engine operation, and the parallel mode with a high gear ratio fulfills high torque demand while accelerating, climbing, and towing [16]. Because the multi-mode HEVs have many advantages, optimal designs have been identified with varies approaches, such as exhaustive search [17] and mode combination [18].

The multi-mode configuration is generally more complex than series and parallel configurations because of the additional PGs or clutches. In particular, controlling the multi-mode HEVs involves two aspects: one is the energy management system, which decides the power demands for each power source in the system; another is the mode shift control-related issues due to the introduction of multiple modes.

The energy management can be solved using dynamic programming (DP) [19,20], equivalent consumption minimization strategy (ECMS) [21,22], the Pontryagin's minimum principle (PMP) [23–25], convex optimization [26], and model predictive control (MPC) [27,28]. The DP is a global optimal approach but the computation burden makes it impractical for real-time control. The ECMS is an instantaneous optimization method that requires tuning of the equivalent fuel consumption factor. A numerical-convergence issue is frequently observed in the PMP for nonlinear two-point boundary-value problems. The computation time required by the convex optimization is less; however, the control of power-split and multi-mode HEVs cannot be optimized because of the convexity requirement. With the advancements in machine learning methods, recently, adaptive control strategies have been proposed