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Review article

Model predictive control power management strategies for HEVs: A review

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HIGHLIGHTS

- A brief study on power management strategies used in HEVs is conducted.
- MPC-based strategies are emphasized and elaborated in several aspects.
- The current issues existing in MPC-based strategies are identified and analyzed.
- The future trends and active research topics of MPC-based strategies are discussed.

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ABSTRACT

This paper presents a comprehensive review of power management strategy (PMS) utilized in hybrid electric vehicles (HEVs) with an emphasis on model predictive control (MPC) based strategies for the first time. Research on MPC-based power management systems for HEVs has intensified recently due to its many inherent merits. The categories of the existing PMSs are identified from the latest literature, and a brief study of each type is conducted. Then, the MPC approach is introduced and its advantages are discussed. Based on the acquisition method of driver behavior used for state prediction and the dynamic model used, the MPC is classified and elaborated. Factors that affect the performance of the MPC are put forward, including prediction accuracy, design parameters, and solvers. Finally, several important issues in the application of MPC-based power management strategies and latest developing trends are discussed. This paper not only provides a comprehensive analysis of MPC-based power management strategies for HEVs but also puts forward the future and emphasis of future study, which will promote the development of energy management controller with high performance and low cost for HEVs.

1. Introduction

Environmental crisis and economic awareness have called for a substantial reduction of the fuel consumption and emission of all vehicles [1,2]. Conventional vehicles propelled by internal combustion engines (ICEs) profit from the very high energy density of diesel fuel or gasoline, but suffer from low efficiency. To overcome these issues, new regulations have been introduced by governments and researchers worldwide, including enacting strict emission standards, limiting transportation activity, improving the fuel economy of conventional vehicles, and developing green vehicles [3]. Among all the current solutions, HEVs represent one of the most promising approaches to considerably reduce fuel consumption and emissions [4].

A typical HEV employs an internal combustion engine (ICE), an energy storage source (ESS), electric machine(s), and inverter(s). Several kinds of HEVs have been conceived and developed. They are: 1) series HEV, where the engine drives a generator whose electric power is added to the power from the ESS, and then transmitted to the electric motors driving the vehicle. Coaster light duty bus, Fisher Karma, Orion bus Renault Kangoo, Opel Flextreme, and Swiss auto REX VW polo belong to the series configuration; 2) parallel HEV, where the mechanical instead of the electrical power is merged: the engine and the electric machines are connected by a gear set, a chain, or a belt, such that their torque is merged and then

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transmitted to the wheels via a conventional driveshaft [5]. Honda's Insight, Civic, Accord, General Motors Parallel Hybrid Trucks, Chevrolet Mali, BAS Hybrid such as Saturn VAU and Aura Green line by hybrids utilize parallel configuration; 3) Power-split HEV, where two electric machines are able to either subtract or add torque at the engine shaft; thus, the vehicle can perform as a series or parallel hybrid; Chevrolet volt, Lexus RX400h, Toyota Prius, Lexus HS250h, Toyota Camry and Highlander, Lexus GS450h, and Lexus LS600h use the split configuration.

In a series HEV, the main power source devices are associated only with the electrical connections; thus, each component can be independently placed to simplify vehicle packaging and design. Also, the fact that the engine is completely disconnected from the wheels provides great freedoms in choosing its speed according to the load, thus the engine can operate at its highest possible efficiency. Whereas, in parallel HEVs, both the engine and the motor can power the vehicle since they are connected to the transmission either separately or in combination. The power-split HEV can perform either as a series or a parallel HEV, taking the advantages of both. In addition, based on the degree of hybridization, the HEVs can be also classified as 1) micro HEVs, 2) mild HEVs, or 3) full HEVs [2]. Furthermore, according to the ability of having access to the grid power, HEVs can be categorized into plug-in HEVs or traditional HEV.

The main advantages of HEVs are mainly attributed to the following: 1) downsizing the engine to reduce friction losses and compensating for the lacking power by the electric motor; 2) recuperating kinetic and potential energy during braking phases by using the electric path instead of the conventional brakes [6,7]; 3) shutting off the engine during standstill to avoid idling losses, and 4) avoiding part-load operation of the engine by shifting these operating points to higher torques or shutting off the engine and driving in the electric-only mode.

HEVs are sophisticated electro-mechanical-chemical systems. The complex power flow, the potential of fuel economy improvement and emission reduction for HEVs rely on the configuration and power distribution within the hybrid powertrain. Strategies that control this power distribution are often referred to as PMSs [8]. The PMSs in HEVs decides how to divide the power demanded between different energy sources to sustain battery charge, optimize drivetrain efficiency, and reduce fuel consumption and emission. In recent decades, large amount of efforts have been put to design PMSs, which has become one of most extensive and active research topics in HEVs in present [3].

A large number of literature surveys on PMSs of HEVs have appeared, but the existing review articles emphasize on discussing the development of PMSs and comparing several of them qualitatively [2–4,9,10]. As one of the most promising control strategies, the MPC has been extensively studied theoretically and applied in different fields. The same thing happens in the MPC-based PMSs development for HEVs. However, there has been no scholar presenting a comprehensive review of all classes of MPC-based PMSs used in HEVs, thus this study intends to fill this gap. In addition, the factors affecting the performance of the MPC are put forward and several important issues should be treated for the application of MPC strategies, and future trends of the PMSs, especially the MPC-based strategies, are discussed.

The paper is organized as follows: In Section 2, the categories of the existing PMSs for HEVs are identified from the latest literature, and a brief study of each type is conducted; the MPC strategies with their advantages are briefly studied in Section 3; the formulation of the MPC is presented, and factors that affect the performance of the MPC are put forward in Section 6; finally, several significant issues for application of MPC strategies and future trends of the PMSs, especially MPC based strategies, are discussed.

2. Review of PMSs in HEVs

The existing PMSs of HEVs can be generally classified into heuristic strategies and optimization-based strategies. The most common PMSs employed in HEVs are shown in Fig. 1.

2.1. Heuristic strategies

Heuristic strategies depend on a set of rules to determine the control action at each time instant. The rules are designed in accordance with intuition, human expertise, and/or mathematical models and, usually, without knowing driving information *a priori*. Deterministic rule-based and fuzzy logic approaches are two parts of this category. The latter has become considerable popularity in recent years as artificial intelligence (AI) related technologies develop [9,11].

2.1.1. Deterministic rule-based strategies

Rule-based PMSs can be further classified into thermostat (on/off) strategy, power follower strategy, modified power follower strategy, and state machine-based strategy [10]. Thermostat (on/off) control strategy is robust, simple and easy to realize. Due to the fixed rules, it lacks the ability to deal with uncertainties brought by model inaccuracy and then the flexibility for different drive cycles [9]. Accordingly, both drive cycle recognition [12] and prediction [13] are proposed to enhance the rule-based PMSs. Power follower control strategy is popular and has been successfully applied in commercial HEVs such as the Honda Insight and Toyota Prius [14]. However, the major disadvantage is that the overall efficiency of the powertrain is not optimal, and the emission control is not directly considered. The modified power follower strategy, however, integrates the energy usage and emissions into the cost function, as proposed by Johnson et al. [15]. The state machine-based approach was proposed by Phillips et al. [16]. In this strategy, the transition between operating modes, such as ENGINE, BOOST, CHARGING, etc., is decided by a state machine that is based on vehicle operating conditions, change in driver demand, and any system fault [10].

2.1.2. Fuzzy logic approach

The main advantages of the fuzzy logical approach are its robustness to measurement noises and component variability

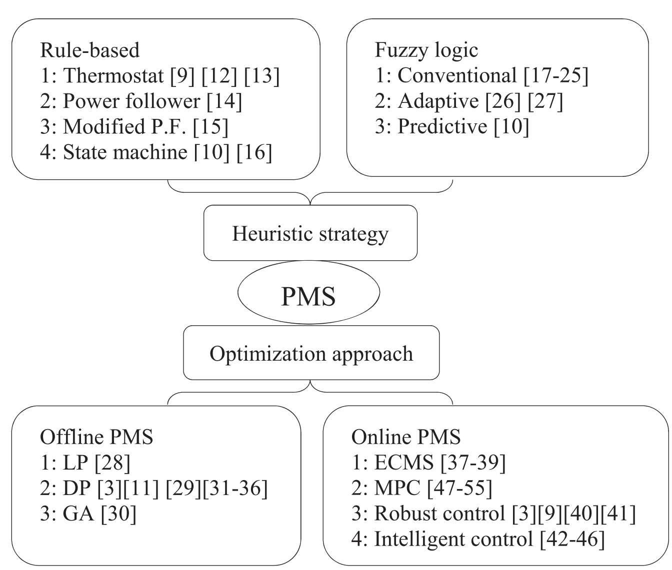

Fig. 1. Classification of PMSs for HEVs.