Energy 123 (2017) 89–107

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Particle swarm optimization of driving torque demand decision based on fuel economy for plug-in hybrid electric vehicle

Peihong Shen, Zhiguo Zhao*, Xiaowen Zhan, Jingwei Li

National Engineering Laboratory for Clean Energy Automotives and Powertrain Systems, School of Automotive Studies, Tongji University, No. 4800, Cao'an Road, Shanghai 201804, China

ARTICLE INFO

Article history:
Received 3 September 2016
Received in revised form
20 December 2016
Accepted 22 January 2017
Available online 25 January 2017

Keywords:
PHEV
Fuel economy
Driving torque demand decision
DCWPSO algorithm
Optimization

ABSTRACT

In this paper, an energy management strategy based on logic threshold is proposed for a plug-in hybrid electric vehicle. The plug-in hybrid electric vehicle powertrain model is established using MATLAB/Simulink based on experimental tests of the power components, which is validated by the comparison with the verified simulation model which is built in the AVL Cruise. The influence of the driving torque demand decision on the fuel economy of plug-in hybrid electric vehicle is studied using a simulation. The optimization method for the driving torque demand decision, which refers to the relationship between the accelerator pedal opening and driving torque demand, from the perspective of fuel economy is formulated. The dynamically changing inertia weight particle swarm optimization is used to optimize the decision parameters. The simulation results show that the optimized driving torque demand decision can improve the PHEV fuel economy by 15.8% and 14.5% in the fuel economy test driving cycle of new European driving cycle and worldwide harmonized light vehicles test respectively, using the same rule-based energy management strategy. The proposed optimization method provides a theoretical guide for calibrating the parameters of driving torque demand decision to improve the fuel economy of the real plug-in hybrid electric vehicle.

1. Introduction

A plug-in hybrid electric vehicle (PHEV) is a vehicle with a battery that can be charged by an external power grid [1]. PHEV combines the advantages of pure electric vehicle and hybrid electric vehicle [2]. Compared with the traditional hybrid electric vehicle, the PHEV has a larger battery capacity, longer driving range, as well as better fuel economy and emission performance [3]. As is the reason, PHEV has attracted a lot of attention from researchers and engineers recently [4]. As the PHEV is equipped with two power sources—a traditional internal combustion engine and driving motor—it is very important to optimize the control strategy in order to improve the fuel economy [5].

1.1. Review of existing optimization approaches

Many scholars are studying the control strategy of the PHEV, aiming to improve its fuel economy. In Ref. [6], an instantaneous optimal energy management strategy for the PHEV is established based on the simulated annealing and Pontryagin's minimum principle. Dynamic programming is used to globally optimize the energy management strategy for a parallel PHEV at various driving mileages [7]. The energy management which combined offline stochastic dynamic programming part and the online equivalent consumption minimization strategy is performed on the plug-in hybrid electric bus [8]. Quadratic programming and simulated annealing algorithm are applied to optimize the best power allocation between the engine and driving motor in order to improve the fuel economy [9].

However, owing to a relatively high computational burden for the controller of the aforementioned control strategies, the majority of real PHEVs are currently adopting the rule-based control strategy that is simple, practical, and robust [10]. The rule-based control strategy involves many parameter threshold values. These parameters are usually determined by trial and error based on the engineers' experience in real vehicle debugging. However, there are still many scholars who are doing some optimization studies for the parameters of the rule-based energy management strategy for the PHEV, such as the opening ranges of accelerator and braking pedal,

* Corresponding author.
E-mail addresses: shenpeihong@tongji.edu.cn (P. Shen), zhiguozhao@tongji.edu.cn (Z. Zhao), xiaowenzhan1@163.com (X. Zhan), wojiaodoubao@outlook.com (J. Li).

http://dx.doi.org/10.1016/j.energy.2017.01.120
0360-5442/

state of charge (SOC) limits for battery charging and discharging, and engine working range. The parameter optimization model for PHEV components with variables that include the engine power, motor power, and bus voltage of the battery is formulated. The DIRECT algorithm is used to solve the model and obtain the optimization results [11]. In Ref. [12], a genetic algorithm is applied for defining the optimal set of decision variables for powertrain design and energy flows management. Furthermore, a hybrid genetic algorithm which combines an enhanced genetic algorithm with simulated annealing is proposed to optimize the powertrain and control parameters of plug-in hybrid electric bus [13]. Ref. [14] presents Pontryagin's Minimum Principle based Selective Hamiltonian Minimization to optimize the energy management strategy as well as the sizing parameters of various powertrain components for hybrid electric vehicle. In Ref. [15], the improved non-dominated sorting genetic algorithm which has better convergence is used to optimize the rule-based control strategy parameters, with the target of minimizing the equivalent fuel consumption. Moreover, the simulated annealing particle swarm optimization (PSO) algorithm is implemented to optimize the parameters of the PHEV rule-based control strategy for improving the fuel economy and emission performance [16]. In Ref. [17], four parameters of the PHEV rule-based control strategy are optimized by PSO to improve the fuel economy.

The studies mentioned above show that the optimization of logic threshold parameters for PHEVs has a big potential for improving the fuel economy. However, the abovementioned optimal parameters do not reflect the influence of the driving torque demand decision on the PHEV performance. As a matter of fact, the driving torque demand decision should be determined initially, then comes the rule-based control implementation, seen in Fig. 2. Thus, the driving torque demand decision has an influence on the PHEV performance. Whereas, there are only a few studies that focus on optimizing the PHEV driving torque demand decisions to improve its performance, especially fuel economy. In Ref. [18], the driving torque demand decision of PHEV is optimized by adaptive fuzzy proportion integration differentiation (PID) control to improve the PHEV harshness. In Ref. [19], the radial basis function neural network is applied to fit the driving torque demand decision of PHEV according the tested data, which contributes to decreasing the driving cycle tracking error and improving the fuel economy.

1.2. Contribution of the paper

As mentioned above, rule-based control strategy is most commonly used in real PHEV. And most studies focus on the optimization of the rule-based control strategy parameters and the powertrain parameters for PHEV to improve the fuel economy. Only a few research work has been found to optimize the driving torque demand of PHEV. Whereas, the driving torque demand decision of PHEV has not been comprehensively analyzed and optimized from the perspective of fuel economy in these studies. Actually, the driving torque demand decision of PHEV has a great influence on the fuel economy. The optimization of driving torque demand decision of PHEV thoroughly from the perspective of fuel economy makes sense. The main purpose of this study is to specifically analyze the influence of driving torque demand decision of PHEV on fuel economy and comprehensively optimize the driving torque demand decision from the perspective of PHEV fuel economy. This study aims at providing a theoretical guide for calibrating the parameters of driving torque demand decision of real PHEV.

1.3. Organization of the paper

This study is organized as follows. In Section 2, the feedback control strategy of PHEV aimed at making the engine work within the high-efficiency area and keeping the battery SOC within a particular range, is presented. In Section 3, the mathematical model of the PHEV powertrain is prepared using MATLAB/Simulink based on experimental test data of the power components. Besides, the accuracy of the simulation model and validity of the proposed logic threshold energy management strategy are validated by the comparison with the verified simulation model which is built in the AVL Cruise. In Section 4, the influence of the PHEV driving torque demand decision on its fuel economy is studied. Based on this, the optimization model of the PHEV driving torque demand decision is proposed. The dynamically changing inertia weight PSO, which has better convergence and faster computing speed, is used to optimize the PHEV driving torque demand decision. The validation of the proposed driving torque demand decision optimization method to improve the PHEV fuel economy is verified by simulation in the fuel economy test driving cycle of new European driving cycle (NEDC) and worldwide harmonized light vehicles test (WLTP). Section 5 presents the optimized results and discussion. Finally, the conclusions are drawn in Section 6.

2. PHEV control strategy

This study critically concerns about the fuel economy of PHEV. In the braking cycle, the braking energy is regenerated by the driving motor. As the fuel economy is mainly related with the control strategy in the driving cycle, the control strategy of driving cycle is considered in this paper. In this study, a feedback control scheme for PHEV in driving is proposed, which is shown in Fig. 1. The driver controls the accelerator pedal opening according to the difference of target velocity and actual velocity. Then the driving torque demand is decided based on the driving torque demand decision, which is the focus of this paper. The commonly used rule-based control strategy, which is simple, practical, and robust, is selected in this paper. Afterwards, the torque and speed demand of engine and driving motor transmit to the PHEV powertrain model, which feedbacks the actual velocity to the driver. This study mainly analyzes and optimizes the driving torque demand decision from the perspective of PHEV fuel economy.

2.1. Driver model

The function of the driver model is to simulate the real driver's controllability. And the driver model diagram is shown in Fig. 2. The driver controls the accelerator or the braking pedal opening based on the difference between the real velocity and driving cycle velocity. The proportional–integral (PI) controller is selected for the driver model [20].

The driver model can be described as the following equations:

$$\begin{cases} \alpha = K_p e(t) + K_i \int e(t)dt \\ e(t) = v_{cyc} - v \end{cases} \tag{1}$$

where α is the pedal opening, with positive and negative values representing the accelerator pedal and braking pedal opening, respectively; v_{cyc} is the target driving cycle velocity; v refers to the actual speed; K_p and K_i are the proportional and integral coefficients of the PI controller, respectively.

2.2. Driving torque demand decision

When the vehicle is running, the driver's torque demand can be divided into driving torque and braking torque demands, which can be identified by the accelerator and braking pedal opening,