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Research on Control Strategy of Plug-in Hybrid Electric Vehicle Based on Improved Dynamic Programming

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Abstract

Because of the long driving range and good power performance, plug-in hybrid electric vehicles (PHEV) have drawn much attention. And the current fuel-saving effect of PHEV still has a lot of room for improvement. The complex powertrain structure of PHEV makes the requirements for control strategy be increasing. Therefore, it is crucial to develop an efficient control strategy to ensure that the PHEV operates at optimal performance with an improved driving range. This paper establishes a mathematical model for fuel economy control of PHEV, by treating the torque distribution problem as a multi-stage decision optimization problem, and establishes a global energy management strategy based on a dynamic programming (DP) algorithm. Based on the actual physical model, this paper creatively solves the correction range of battery SOC value according to the charge and discharge power of the motor, which greatly reduces the calculation time of the DP algorithm. Through further simulation study, it is found that the energy management strategy based on the improved DP algorithm can significantly improve the fuel economy of the whole vehicle compared with the rule-based energy management strategy. By comparing the working interval diagrams of the motor and the engine under the two strategies, it can be concluded that the higher the frequency of the engine working in the high efficiency zone, the more likely to get better fuel economy. This study provides the theoretical basis and essential guidance for the establishment and optimization of online energy management strategy.

Introduction

To solve the increasingly serious energy shortage and environmental pollution problems, new energy vehicles have received widespread attention and rapid development because of their good economy, low emissions and long driving range [1]. Hybrid electric vehicle (HEV) is the main new energy vehicle in the current market. Usually, the power system of HEV is a coupling system composed of internal combustion engine and electric motor, which overcomes some of the disadvantages of pure electric and traditional vehicles by the cooperation of two power sources [2]. Therefore, HEV is an effective technical route in the current technical context [3].

Plug-in hybrid electric vehicle (PHEV) is a kind of HEV that can be charged using an external grid [4]. By using an electric motor as an auxiliary drive device, it allows the engine to be controlled to operate in an efficient and low-pollution region, improving fuel economy and reducing emissions [5]. Efficient internal combustion engine and battery can operate coordinately and efficiently under different driving conditions through the appropriate power allocation scheme provided by the energy management strategy. The proper design of energy management strategy is critical to fully exploit the performance potential of PHEVs. However, the powertrain of a PHEV is a highly nonlinear and complex system, making it a challenging task to investigate an effective energy management strategy with optimal performance and real-time execution capability [6].

In recent years, control algorithms have been continuously optimized, and many new algorithms have emerged. Hu et al. [7] used a mapping strategy-based control algorithm combined with a dynamic programming (DP) algorithm to allocate power between the engine and battery and determine the minimum fuel consumption. Yang et al. [8] proposed an approximate optimal rapid DP method, which effectively reduces the decision time. Combined with particle swarm optimization (PSO), a multi-mode configuration with optimal component parameters was established to achieve the most fuel-efficient operation. Based on the Q-learning algorithm, Xu et al. [9] parametrized the key elements of a parallel HEV energy management system to achieve torque distribution between the engine and the motor.

In terms of improving fuel economy, globally optimized energy management strategies can improve the control effect indeed, but it is necessary to know the driving conditions in advance, on the other hand, the computation volume and time of the global optimization method increase significantly as the mileage of the working conditions increases. The information processing ability of current vehicle control processors cannot be used for real-time scenarios. Wang et al. [10] trained pattern recognition neural networks based on the best results of DP and used common state corrections and relaxation constraints, to build a control framework for online model prediction based on velocity prediction. Chen et al. [11] used an online sequence extreme learning machine for short-term power prediction to improve the accuracy under irregular road conditions through online learning capability, and designed a predictive adaptive equivalent consumption minimization strategy. The equivalence factor was optimized on a rolling basis over the prediction range to maintain the battery state of charge and ensure fuel economy.

Due to the poor dynamic characteristics of the rule-based energy management, the fuel economy has already been close to its limits. Since the DP approach does not impose many restrictions on the system state equations and performance index functions, the system model can be a numerical model based on experimental data. In addition, the fuel consumption problem under the specified path of the HEV has no posterior or overlapping subproblems and satisfies the optimization principle of the DP method. Therefore, the DP energy management strategy is used to explore the limits of the fuel economy of PHEV.

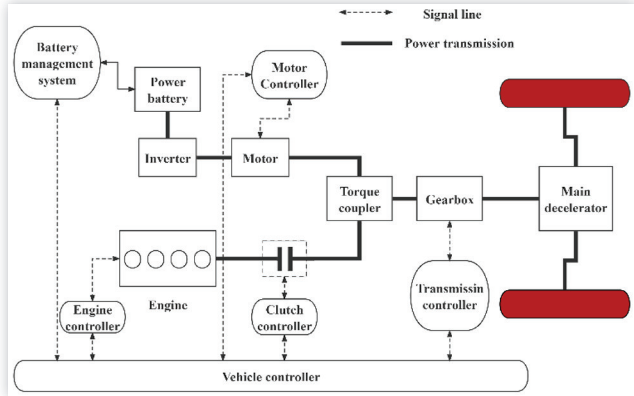
In this paper, an energy management strategy based on improved DP algorithm is proposed, which not only has a better optimization effect, but also can be well adapted to real-time scenarios. The method treats the torque allocation problem as a multi-stage decision optimization problem and establishes a global energy management strategy based on the DP algorithm. For the problem of long calculation time of DP algorithm, this paper creatively solves the correction range of the battery SOC value according to the charging and discharging power of the electric motor, which greatly reduces the calculation time. A high-efficiency energy management strategy for parallel PHEV is developed.

Modeling of Parallel Hybrid Power System

Structure of the Powertrain

The schematic diagram of the hybrid power system structure is shown in Figure 1. A single-axis parallel structure is used for the study. The engine and the electric motor in the figure can drive the vehicle separately or cooperatively through the coupler. The output torques of the engine and motor are transmitted to the wheels through the torque coupling device, gearbox and main reducer. The real-time communication between the component controller and the vehicle controller is controlled by the vehicle controller.

FIGURE 1 Structure diagram of hybrid system.



In hybrid electric vehicles, components such as the engine, motor and transmission have complex dynamic characteristics, and it is difficult to describe the entire dynamic process mathematically. Therefore, in order to simplify and facilitate the design of component models and control rules while ensuring that the model reflects the basic dynamic characteristics of the actual hybrid electric vehicle, the secondary factors affecting the system are ignored in this study.

Design and Matching of Dynamic Parameters The design goal of the powertrain is to improve fuel economy as much as possible while meeting the power conditions. The design of hybrid vehicle parameters includes the selection and matching of engine, motor and battery parameters, as well as the design of transmission and main gear ratio in the drive train [12]. Here are the basic parameters of the vehicle as shown in Table 1:

Based on the PHEV powertrain shown above, a longitudinal dynamics model of the PHEV energy management strategy was developed, which focuses more on vehicle dynamics and fuel economy, while ignoring vehicle vibration and operational stability. Among the vehicle driving resistance include rolling resistance, ramp resistance, acceleration resistance, wind resistance and other types of resistance. The electric motor and engine provide the driving force to overcome the resistance during vehicle travel and maintain the vehicle in normal operation. The longitudinal vehicle dynamics model is given by the following equation [13].

TABLE 1 Parameters of the vehicle.

Parameter name	Parameter value
m_0,Vehicle mass (kg)	1400
m_a,Full load mass of car (kg)	1750
c_d,Coefficient of air resistance	0.3
A,Windward area (m2)	1.99
f,Rolling resistance coefficient	0.013
Rotational mass coefficient	0.014
η_T,Average Transmission efficiency	0.9025
L,Wheelbase (m)	3.079

$$F_t = F_f + F_w + F_i + F_j = mgfcos\alpha + \frac{C_D A V^2}{21.15} + mgsin\alpha + \delta_m m \frac{dv}{dt} \quad (1)$$

where F_t is the driving force; F_f is the rolling resistance; F_i is the ramp resistance; F_j is the acceleration resistance; m is the full-load mass of the whole vehicle; f is the rolling resistance coefficient; C_D is the wind resistance coefficient; A is the windward area; $\frac{dv}{dt}$ is the acceleration; δ_m is the rotating mass conversion factor.

After calculating the whole vehicle demand power under different dynamics indexes by the longitudinal vehicle dynamics model, the parameter matching of detailed components can be carried out. The parameters of the power system components are shown in Table 2:

Engine Model

The engine, as the main drive unit of the vehicle, needs to drive the vehicle independently, providing power to meet the maximum speed and climbing performance of the vehicle. And the engine and motor should work together to meet the acceleration requirements. Fuel consumption and torque map diagrams for an electronically controlled injected gasoline engine can be obtained from a test stand to describe the external characteristics of the engine.

The mathematical model of the engine mainly focuses on the fuel consumption calculation module, so there is no need to consider the complex dynamic characteristics of the engine. The engine fuel consumption is written as [14]:

$$Q = \frac{T_e \cdot n_e \cdot g_e \cdot \Delta t}{9550 * 3600} \quad (2)$$

where T_e is the actual output torque of the engine; n_e is the current engine speed and g_e is the fuel consumption rate of the engine, which can be obtained from the iso-fuel consumption rate diagram of the engine.

The iso-fuel consumption rate diagram of the engine is shown in Figure 2.

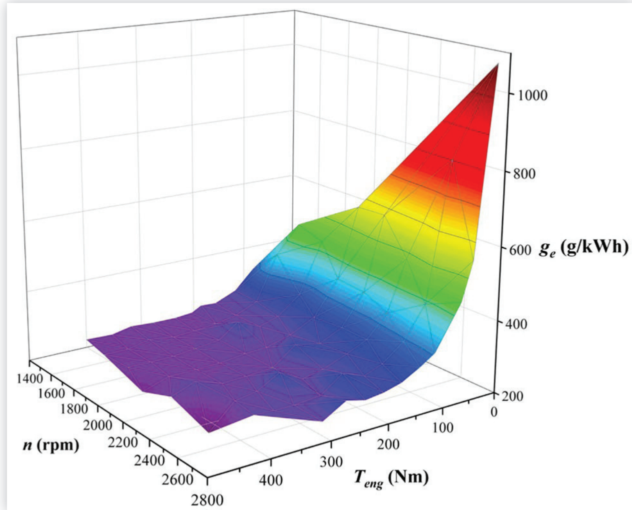
Motor Model

In the power system of parallel hybrid vehicles, the motor, although it is an auxiliary power drive, also needs to meet the maximum speed requirement and climbing degree requirement when driving independently. At the same time, according to the working conditions, the motor and the engine need to complete the cooperation, and sometimes the motor needs to act as a generator to charge the battery. The above two states can be described by the equation as follows [13]:

TABLE 2 Parameters of power system

Parameter name	Parameter value
Engine displacement	2.0T
Number of cylinders	4
Maximum power / speed	78KW/5500rpm
Maximum torque / speed	325N.M/2800rpm

FIGURE 2 Engine fuel consumption map [15].

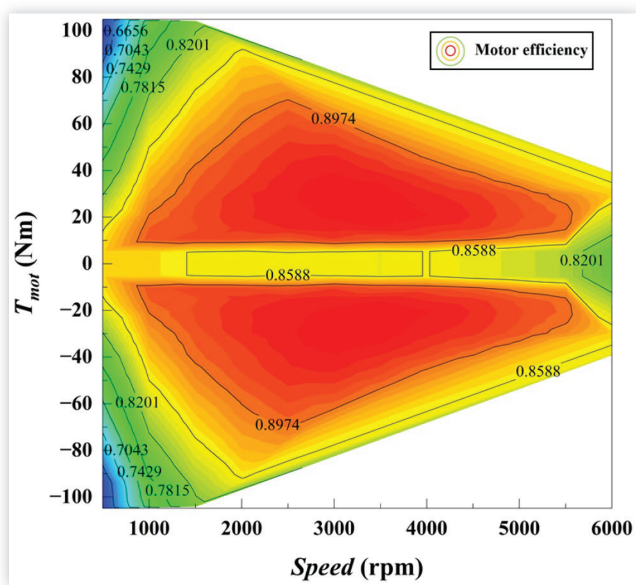


$$\begin{cases} P_m = \dfrac{T_m \cdot n_m}{9550 \cdot \eta_m}, motor \\ P_m = \dfrac{T_m \cdot n_m \cdot \eta_m}{9550}, generator \end{cases} \quad (3)$$

where P_m is the output power of the motor; T_m is the output torque of the motor; n_m is the current motor speed; η_m is the motor efficiency, and the function of the motor torque and speed, which is shown in Figure 3.

At the same time, the output torque of the motor should meet the following relationship, the output torque of the motor

FIGURE 3 Motor efficiency map [16].



diagram, it can be found that there is a significant distinction between the working points of different strategies. The engine working point based on dynamic planning is concentrated in the efficient engine interval of low to medium speed and high torque, while the engine working interval of the regular type is distributed on a curve in the medium to high torque area, which is not less efficient but cannot adjust the specific position of the working point. Therefore, compared with the regular and dynamic programming energy management strategy, there will still be a large gap in the dynamic characteristics, but also shows that the energy management strategy makes the engine work in the high efficiency zone more frequently, the more likely to get better fuel economy, which provides some ideas for further improvement of the energy management strategy later on. From the motor working interval diagram, it can be seen that the difference between the motor working points of the two strategies is not much mainly because the efficiency characteristics of the motor are relatively average, so the motor is often used as an auxiliary power source for hybrid vehicles.

Conclusion

In this paper, an energy management strategy for PHEV based on an improved DP algorithm is proposed. The key components model and controller model of the hybrid vehicle were established in MATLAB environment. The control strategy is designed according to the working mode of the hybrid vehicle. In order to solve the problem of long calculation time of DP method, this paper creatively improves the DP algorithm by eliminating the unreasonable SOC values in advance, thus reducing the searching range of SOC values and saving computing resources. And it also has positive effect on the design of future automotive electronic control systems. The DP-based energy management strategy can also distribute the torque between the motor and engine more reasonably, to effectively improve the fuel economy of PHEV. The optimized fuel consumption rate is 6.82L/km, which is 14.8% lower than that of the rule-based energy management (8.004L/km). This control strategy can also decrease the shift times and improve the shift quality. This study provides an essential guidance to the development of energy management strategy of PHEV.

Deficiencies and Prospect

Based on the existing vehicle dynamics model, an energy management strategy for PHEV based on an improved DP algorithm is proposed. However, the vehicle dynamics model used in many energy management optimization studies does not capture the actual conditions of vehicle movement like the on-board measurement system, and actually the vehicle controller manages energy consumption by the feedback from the measurement system, in addition, the application of this method does not take into account the increase of energy consumption caused by the development of OBD [20], so it is necessary to perform identification experiments on more vehicles and vehicles under changing environmental conditions to improve this algorithm.

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