A review of hybrid electric vehicle energy management strategy based on road condition information

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Abstract. Energy management strategy (EMS) plays a vital role in energy saving for hybrid electric vehicle (HEV), which incorporates the advantages of both fuel vehicles and pure electric vehicles. A desirable EMS can not only help the vehicle meet the power demand, but also effectively reduce fuel consumption and realize long-distance driving. At present, most of existing EMSs are optimized based on specific driving conditions, which makes these strategies not adaptive to the dynamic real-world driving conditions. This paper analyses some traditional EMSs of HEV based on fixed road conditions, and points out their shortcomings and future development trends.

1. Introduction
With the all-round development of economy and society and the deepening of urbanization process, the transportation industry is developing rapidly, which leads to the expansion of energy demand, and the contradiction between resources and environmental problems is becoming more and more prominent. According to the report released by the International Renewable Energy Agency, the energy consumption of road transportation sector accounts for more than one third of the global total energy consumption in 2021, of which 95% is non-renewable energy. In the face of severe energy shortage, many countries have issued macro policies to actively develop energy-saving and new energy vehicles (NEVs) so as to promote the sustainable development of the transportation industry. As one of the important forms of energy-saving vehicles, hybrid electric vehicle (HEV) has become one of the key directions of the future automotive industry. China's "energy saving and new energy vehicle technology roadmap 2.0" points out that "in the field of energy-saving vehicles, the proportion of fuel vehicles will gradually decline. By 2025 and 2030, the proportion of HEVs will reach more than 50% and 75% respectively. In 2035, all traditional vehicles must realize hybridization". It can be predicted that China's energy-saving vehicle industry will vigorously develop HEVs in the future.

For the research on how to improve the working efficiency and realize emission reduction of HEV, the common solution is to design suitable hybrid system (including parameters and configuration optimization) to match the power demand of the whole vehicle, or formulate the energy-saving oriented energy management strategy (EMS) [1]. HEV has a nonlinear power system with dual power sources of engine and motor. EMS is the main way to improve the fuel economy of HEV on the premise of given vehicle topology configuration. In the real vehicle application, rule-based EMS based on the expert experience is widely used due to its characteristics of fast calculation speed and easy implementation. In theory, optimization-based strategies are commonly investigated. Dynamic programming (DP), quadratic programming (QP), Pontryagin's minimum principle (PMP) and equivalent consumption minimization strategy (ECMS) are widely used algorithms in this field. Although the optimization
performance is good, the heavy computational burden makes it difficult for the actual vehicle controller to realize real-time application [2].

At present, EMS for HEV can achieve good control effect and fuel economy under simulation conditions. However, the actual operational conditions and road conditions of vehicles are constantly changing, which leads to the failure of optimal control effect in real-world application. By studying how to predict road condition information and combining it with EMS, the energy-saving performance of EMS can be greatly improved. Therefore, EMS based on road condition information is the main development trend for HEVs in the future.

2. HEV energy management strategy under fixed traffic information
At present, HEV EMSs based on fixed traffic information can be summarized into three categories: rule-based, global optimization based and instantaneous optimization based.

2.1. Rule-based energy management strategy
Rule-based EMS is based on certain engineering experience to develop logical rules for energy allocation between multiple power resources. For example, Banvait h et al. [3] divided the driving modes of vehicles into charge depleting (CD) and charge sustaining (CS). If the driving mileage exceeds the pure electric driving mileage, the remaining mileage needs engine power, and the longer the driving mileage, the worse the fuel economy. Zhang et al. [4] made an improvement on the basis of CD-CS EMS. For CD mode, the electric auxiliary strategy was designed. For CS mode, the control parameters were optimized based on the multi-objective genetic algorithm (GA) [5]. At the same time, the engine and generator will work together in the whole working condition. Cheng Fei [6] and others introduced the reference SOC and proposed a fuzzy rule-based control strategy aiming at the optimal fuel consumption and emission performance. Results show that the fuel consumption of this strategy can be reduced by 12% on average compared with the electric auxiliary control strategy under standard conditions, and the emission performance is also improved. In [7], an EMS based on fuzzy control is proposed, which mainly considers the urban road conditions. In order to further improve fuel economy and maintain SOC balance, DP algorithm is used to get the optimal energy distribution scheme under multiple driving conditions.

In order to make the rule-based EMS more robust against the change of the actual working conditions or other uncontrollable factors, many researchers use intelligent algorithms to find the relative optimal solution of the parameters related to the mode switching in rule-based strategy. For example, in [8], considering braking energy recovery, a double-layer fuzzy EMS is designed. The rules of the fuzzy controller are optimized by GA. Finally, the optimal energy distribution scheme is calculated by DP algorithm.

The rule-based EMS is mainly derived from engineering experience, and has been widely used because of its simplicity. However, this kind of method also has obvious limitations. Because the rule making depends on experience and static data, it is not flexible and cannot be applied to a variety of conditions, and cannot guarantee the global optimization. Therefore, global optimization based EMSs attract more and more attention in these years.

2.2. Global optimization based energy management strategy
EMS based on optimization algorithm generally abstracts the energy management problem of HEV as a nonlinear optimal control problem with constraints. It is common to incorporate fuel consumption, emission, battery life and other factors into the multi-objective optimization function. The optimal control solution of the objective function is obtained by using the optimal control theory and methods such as DP and PMP. These optimization methods can achieve global optimal solution, but the driving condition information is required to be known in advance, which greatly hinders its application.

In [9], DP is applied to the research of EMS of HEV to seek the global optimal solution under the condition of known working conditions, and the simulation experiments are carried out to calculate the optimal torque distribution. In [10], the optimal distribution rules are obtained by using the data of
historical condition. It used DP to solve the global optimal control strategy for historical condition offline and generated online rules based on offline optimization results.

In view of the disadvantage that DP needs to know the global working conditions in advance, F Qin et al. [11] modelled the uncertainty of total demand torque by Markov chain to realize speed prediction. In [12], a kind of PMP based EMS using online self-learning is designed, which can adapt to the situation of time-varying traffic information of commuter vehicles. Xian [13] improved the traditional PMP algorithm and proposed a new linear approximation algorithm of segmented distance, which not only reduced the fuel consumption, but also greatly reduced the calculation time of the traditional algorithm.

However, the actual driving conditions cannot be predicted actually in advance. Therefore the optimality of its application in real-world driving scenario cannot be guaranteed. Although it is difficult for this kind of EMS to realize real-time operation, it is still useful in theory because it can be used as the evaluation standard of other energy management methods.

2.3 Instantaneous optimization based energy management strategy
Instantaneous optimization based EMS has the advantages of lighter calculation, potential of online application and less dependence on the working condition information compared with the global optimization algorithm, but it also has the problem of being unable to guarantee the global optimal solution. At present, the research of instantaneous optimal energy strategy can be mainly divided into ECMS and fuzzy predictive control strategy.

ECMS is derived from PMP algorithm, which introduces equivalent factor to unify instantaneous fuel consumption and electric energy consumption into equivalent fuel consumption. It takes the sum of fuel consumption and equivalent fuel consumption as Hamilton function, and in the algorithm, it needs to select appropriate equivalent factor to match different working conditions. ECMS has the advantages of light calculation, and being easy to meet the requirements of online applications, so it is the research hotspot of real-time energy strategy. The dependence of ECMS algorithm on working conditions is reduced, but there is also a problem that the global optimization cannot be guaranteed. Larsson V et al. [14] studied the application of ECMS in two cases of known and unknown driving conditions, and carried out real vehicle verification, which showed that the energy saving potential can be improved under known driving conditions. In [15], it is assumed that HEV vehicles pass the same road several times before, and the information of feasible operation conditions in the global driving cycle is extracted. The space dependent transition probability matrix is established by using the history of vehicle speed and position. Then, the Markov chain method is used to estimate the driving conditions in the driving cycle, The torque distribution problem can be solved by ECMS. The optimization problem established in this way cannot guarantee the optimal performance in each driving scenario. Similarly, Li J et al. [16] proposed an on-line ECMS based EMS based on the fixed driving conditions for plug-in series hybrid electric bus to realize the power distribution between battery and engine. In [17], a new real-time EMS was proposed to minimize the weighted sum of gasoline power and battery output power. This method does not need to predict the driving conditions, and improves the fuel economy by calculating and reducing the equivalent fuel at each sampling time. By comparing the simulation results with the traditional rule-based EMS under different conditions, it is found that this new real-time energy management method has its advantages in fuel economy.

Model predictive control (MPC) algorithm is based on the current time measurement information to solve the finite time open-loop optimization problem online, and the first element of the control sequence was selected to act on the controlled object, which has the characteristics of online application. For example, Huang et al. [18] used MPC to predict the next state traffic information according to the historical traffic information. According to the predicted driving information, the real-time energy allocation is carried out, and the global optimization problem is transformed into a local optimization problem under one state. Guo et al. [19] combined Gaussian pseudo-spectral method with MPC. On the premise of ensuring the accuracy, the optimal control problem is transformed into a nonlinear programming problem with fewer discrete points.
Compared with the rule-based and global optimization EMS, the instantaneous optimization based EMS has a significant improvement in improving the fuel economy of HEVs. However, its performance still affected seriously by uncertain operation conditions.

With the in-depth study of intelligence, control theory and optimization methods, a large number of researchers combine neural network, machine learning, reinforcement learning and many other intelligent algorithms to achieve better torque distribution of power sources. Because this kind of method effectively integrates neural network, optimal control and reinforcement learning, it can solve the "Curse of dimensionality" problem of DP algorithm in HEV energy management optimization. Compared with the rule-based algorithm, it has better adaptability to a variety of driving conditions. Compared with the optimization based algorithm, it has better real-time performance. For example, in [20], the transfer probability matrix of power demand is obtained from some specific driving conditions according to Markov chain model. By using Q-learning, the mathematical model of EMS based on minimum cumulative revenue is established to obtain the optimal control strategy. In [21], the fast Q-learning algorithm is used to obtain the optimal EMS. Compared with the standard Q-learning algorithm, the fast Q-learning algorithm has faster convergence speed and can save 16% of the calculation time. In order to achieve better accuracy and real-time performance, as well as better convergence and stability, it is necessary to reasonably select the number of vehicle input parameters, reasonably design the instantaneous cost function and error function equation, and use the existing prior knowledge to guide the design of each module. Limited by the calculation performance of vehicle used chips, the real-time performance of this algorithm still needs to be improved.

3. Energy management strategy of HEV based on adaptive driving mode

Traffic information has a great impact on the energy consumption of HEVs. As a result, the EMS based on fixed road conditions cannot meet the real-time requirements of dynamic real-world driving. With the development of global positioning system (GPS), intelligent transportation system (ITS) and other technologies, the extraction and use of traffic information is gradually introduced into the energy management of HEVs. How to use these historical data or real-time data to predict the future traffic information and improve the prediction accuracy is also a big challenge.

The HEV energy management method considering real-time traffic information has made great progress in recent years. With the assistance of related communication and intelligence technologies, vehicle speed prediction model, driving mode prediction model and driver behavior prediction model have been proposed to further exploit the energy-saving potential of HEV under dynamic traffic environment. Based on the traffic information collected by ITS, adaptive equivalent consumption minimization strategy (AECMS) is proposed in [22], in which the equivalent factor of ECMS can be updated at any time. In [23], the energy management problem is considered as a two-layer control problem. The upper layer calculates the total energy consumption according to the real-time road information and vehicle dynamics, and the lower layer performs energy distribution and vehicle control according to the total energy consumption. In [24], the parameters of the control network are updated by using the experience data of the most recent driving cycle, and the online iterative updating of the control algorithm is realized. The fuel economy of the control network reaches nearly 90% of the DP.

4. Conclusion

HEV is a good solution to current traffic problems of large energy consumption and serious environmental pollution. However, current EMS cannot fully exploit HEV energy-saving potential. Researches of current EMS based on traffic information prediction focus on the energy allocation using current driving conditions or established reference conditions. Online updating mechanisms are rare to see. In the future, the research on the optimization control of EMS needs to consider a variety of road information comprehensively, and it is necessary to build a multi-dimensional traffic network information prediction model, and develop EMS which integrates dynamic changes of road network information. At the same time, parallel computational framework that can fast solve this kind of problem needs to be proposed to facilitate its real-time application.
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