Review on Energy Management Strategies of PHEV

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Abstract. The problems of air pollution and the shortage of energy sources are increasingly significant, and the traditional automobile industry plays a vital role in it. Consequently, Energy management strategy can adjust the energy allocation between the engine and the motor, achieving the purpose of improving fuel economy. Meanwhile, it can optimize the battery balance so that the comprehensive cost of the hybrid vehicle can be reduced, apart from the limited emissions and conserved energy. This paper first introduces the machinery configuration of the parallel hybrid electric vehicles, and then classifies their working patterns under different working conditions. After analysing the existing energy management strategies, we introduce and analyse the rule-based ones by two frequently used methods: logic threshold method and fuzzy logic control. Additionally, strategies based on optimization, including instantaneous and global optimization strategy, are also introduced and analysed, with each advantages, limitations and potential innovations. Finally, the contradiction between practicability and control effect is identified, which is one of the crucial problems to be resolved.

Keywords: hybird vehicles, energy management strategy, logic threshold, fussy logic control, instantaneous optimization, global optimization.

1. Introduction

Nowadays the problem of air condition and the energy crisis are increasingly significant. As vehicles are one of the main sources of resource consumption and exhaust emission, new energy vehicles with low emissions and low fuel consumption have now become the main direction of the development of automobile industry.

New energy vehicles mainly include pure electric vehicles, hybrid electric vehicles and fuel cell electric vehicles, where hybrid electric vehicles (HEV) with relatively mature conditions for industrialization are increasingly favored by public. HEVs are divided into Series hybrid electric vehicle (SHEV), Parallel hybrid electric vehicle (PHEV) and Split hybrid electric vehicle (PSHEV), according to their configurations. The energy of the SHEVs is converted several times, which means the mechanical efficiency is low. The PSHEVs are easy for controlling, but their configurations are too complex. While the PHEVs' engines can drive the wheels directly through the transmission mechanism, which is closer to the traditional automobile driving system, and their mechanical efficiency is similar to ordinary cars, hence they are widely used [1-2].

In the driving process, energy management strategies can control the distribution of the energy from different power sources through information feedbacks, ensuring the energy supply of the whole vehicle system [3]. For HEVs, energy management strategy directly affects their dynamic performance and economic performance [4].

This paper introduces four energy management strategies in two categories based on parallel HEVs. We first summary and classify the structure arrangement form and the working mode of PHEV under different working conditions. Then the strategies based on rules and ones based on optimization are introduced and analyzed, including Logical Threshold Energy Distribution Method, Fuzzy Logic Control Strategy, Global Organizational strategy and Instantaneous optimal strategy. Finally, conclusions are outlined and the future research is prospected combined with the progress of current research.

2. Parallel hybrid electric

2.1. System structure layout

The PHEV consists of an engine, a motor, a motor controller, a battery pack, a power synthesizer, and a mechanical transmission device. The output shaft of the engine and the motor is mechanically connected with the input end of the torque coupler respectively. The output power is transferred to the mechanical transmission device (transmission, main reducer, differential, etc.) through the output shaft of the power synthesizer to drive the vehicle.

Figure 1 is system of parallel hybrid electric vehicle. The biggest difference between parallel hybrid and series hybrid lies in the mechanical connection between the engine and the mechanical transmission device, which directly participates in the driving of the vehicle.

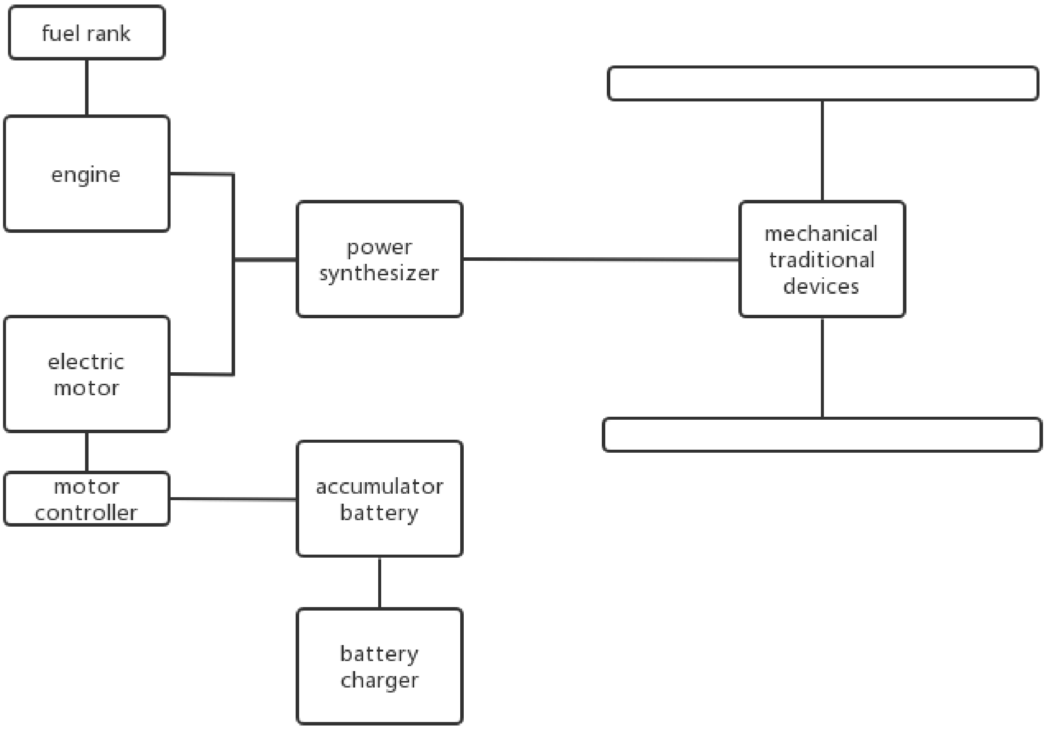

Figure 1. System of Parallel hybrid electric vehicle.

2.2. System Working Mode

(1) Starting/accelerating conditions

When the vehicle starts or when the throttle is fully open, the engine and the motor work at the same time and share the power required to drive the vehicle. For example, the engine and the motor bear 80% and 20% of the total power respectively. Figure 2 is the energy transmission route of staring conditions.

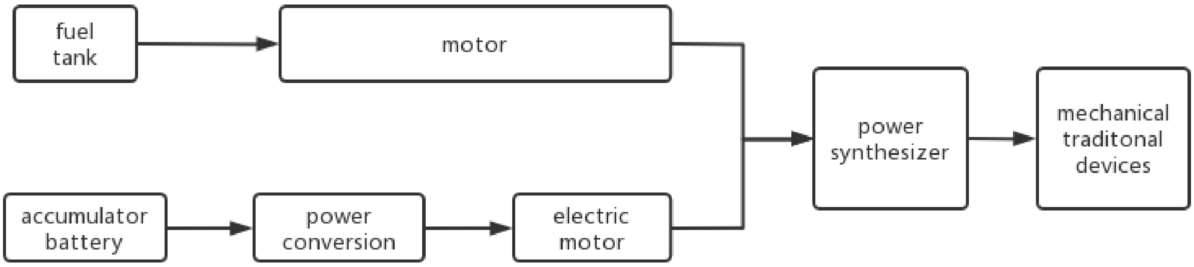

Figure 2. Energy transmission route of Staring conditions.

(2) Normal driving

When the vehicle is working normally, only the engine works to provide the power needed by the vehicle while the motor is turned off.

(3) Deceleration/braking conditions

When the vehicle decelerates or brakes, the motor works in engine mode for regenerative braking and charges the battery through the power converter.

(4) Charging the battery while driving

When the vehicle is loaded lightly, the output power of the engine drives the vehicle to run, while the excess power of the engine output drives the electric motor that works in the power generation state to charge the battery.

3. Rule-based energy management strategy

Rule-based energy distribution method is the most widely used control method at present. Due to its stable control and easy implementation, it is widely used in HEVs.

Rule-based energy distribution method can be divided into two forms. One is rule-based energy allocation method. The other is the energy distribution method based on fuzzy rules.

3.1. Logical threshold energy distribution method

This section establishes a rule-based logical threshold energy distribution method, which is highly stable and practical and widely used in HEVs [4]. Tong Yi et al. studied the rule-based energy management strategy of PHEVs [5]. Cui Shuhua et al. studied rule-based energy management strategies by taking driver demand torque [6], power battery SOC, accelerator pedal opening and speed as logical threshold parameters. Liu Hui et al. studied the dynamic adjustment method of logic threshold parameters [7].

The logical threshold energy allocation method is one of the most commonly used energy allocation methods and is simple to operate. It is mainly divided into three categories, namely optimal working point control, minimum fuel consumption curve control and optimal working interval control [8].

(1) Optimal working point control

The engine speed and torque are limited to the lowest fuel consumption and highest efficiency points of the engine as shown in Figure 3. The torque and speed are constant values and cannot be adjusted. The optimal working point control strategy takes battery SOC as a single parameter control, and its control logic is that when SOC is less than the minimum value of SOC, the engine starts to charge the battery, and the engine runs at constant speed and torque until the battery SOC reaches a reasonable state.

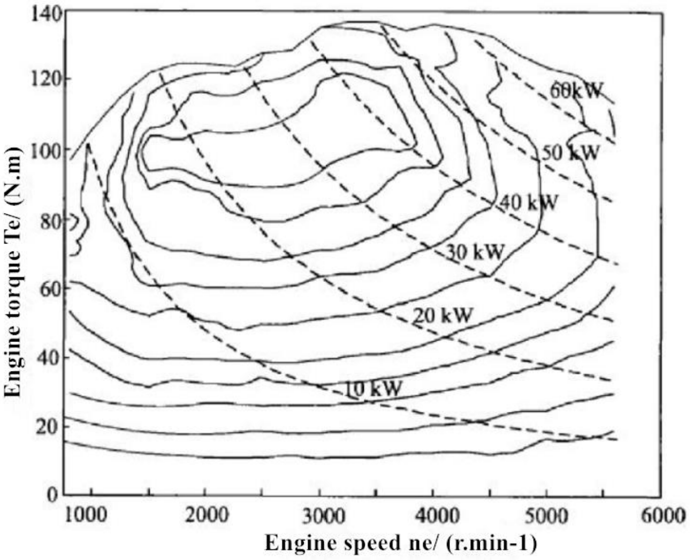

Figure 3. The universal characteristic curve of the engine [7].

(2) Curve control of minimum fuel consumption rate

Each speed engine characteristic performance curve corresponds to a fuel with the lowest fuel consumption, torque will fuel consumption with the lowest torque point connection into a minimum fuel consumption rate curve, when demand is lower than the engine torque output torque surplus torque, by adjusting the engine speed and torque make the engine work in the whole speed range on the lowest fuel consumption rate curve.

The curve control method of the lowest fuel consumption rate can always keep the engine in the environment with the best fuel efficiency, but it has great influence on the efficiency and life of the battery and poor stability in complex driving conditions [9].

(3) Optimal working interval control

The optimal working interval control strategy not only requires the engine to work in the optimal range, but also considers the optimal range of the power battery. On the premise of meeting the vehicle's required torque, the engine is specified in a high efficiency region, and the battery is also specified in a high efficiency region according to the SOC value. Division diagram of optimal engine working interval is shown in Figure 4. Optimal working interval control can effectively improve the fuel economy of vehicles and battery efficiency and life, and is suitable for complex driving conditions.

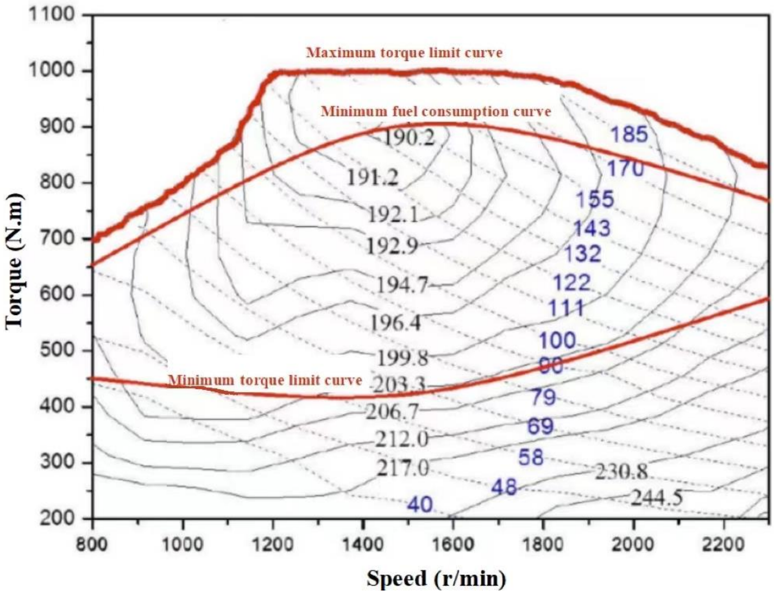

Figure 4. Division diagram of optimal engine working interval.

3.1.1. Establishment of rule-based logical threshold energy distribution method.

Energy distribution method based on the rules of logic threshold method to select the optimum working range control. The goal is to achieve optimal fuel economy and battery balance.It makes logical rules through static and dynamic thresholds. It has the speed as input, traffic demand torque and the battery SOC values as control variable. The engine and motor torque are output through the energy distribution method to achieve the driving force distribution of the vehicle [10]. Logical threshold an energy management policy first needs to determine logical threshold parameters. Threshold parameter selection: parameters of engine and battery in high efficiency zone are obtained through experience and experimental data. Threshold parameters are shown in Table 1.

Table 1. Threshold parameters

Static parameters	SOC_{min}	Minimum value of battery SOC high efficiency zone
	SOC_{max}	Maximum value of battery SOC high efficiency zone
Dynamic parameters	T_{e-max}	Maximum torque in high efficiency zone of engine
	T_{e-opt}	Maximum engine efficiency torque
	T_{e-min}	Minimum torque in high efficiency zone of engine

After the logical threshold parameters are set, control rules need to be established, and the following working mode switching control rules should be established based on the work requirements of PHEVs [10]:

Engine demand torque T_r, engine dynamic parameter torque $T_{e-max}, T_{e-opt}, T_{e-min}$. T_e is the engine output torque, T_m is the motor output torque.

(1) If $T_r < 0$, and $SOC < SOC_{max}$. Regenerative braking. $T_e = 0, T_m = -T_r$;
(2) If T_r <0, and $SOC \geq SOC_{max}$. Mechanical braking. $T_e = 0, T_m = 0$;
(3) If $T_r = 0$. In the parking state. $T_e = 0, T_m = 0$;
(4) If $T_r > T_{e-max}$. parallel drive, $T_e = T_{e-max}, T_m = T_r - T_e$;
(5) If $T_r > T_{e-opt}$, and $SOC > SOC_{min}$. Parallel drive, $T_e = T_{e-opt}, T_m = T_r - T_e$;
(6) If $T_r > T_{e-opt}$, and $SOC \leq SOC_{min}$. For driving charging, $T_e = T_{e-max}, T_m = T_{e-max} - T_r$;
(7) If $T_r > T_{e-min}$, and$SOC \leq SOC_{min}$. For driving charging, $T_e = T_{e-opt}, T_m = T_{e-opt} - T_r$;
(8) If $T_r > T_{e-min}$, and $SOC > SOC_{min}$. Pure electric drive, $T_e = 0, T_m = T_r$.

3.1.2. Analysis of rule-based logic threshold method

Jin Chuanqi used Matlab/Simulink software to establish vehicle and main component models, and he selected and designed rule-based logical threshold energy management strategy to realize switching control of engine and motor working modes [11]. His simulation results show that the logic threshold energy management strategy designed by him can effectively improve the fuel economy of hybrid vehicles by 24.2%. It can reduce fuel consumption and exhaust emissions while ensuring the working performance of vehicles.

The threshold value is a fixed value set in advance based on engineering experience, so the energy saving effect is limited. The motor provides the remaining power with the highest engine operating efficiency as the core, but ignores the motor energy conversion efficiency and mechanical efficiency, so the optimal fuel economy of vehicles cannot be guaranteed [8].

3.2. Fuzzy Logic Control Strategy

3.2.1. Current research and introduction of fuzzy logic control strategy

Nicolas wrote a paper that named “Optimized fuzzy logic control strategy of hybrid vehicles using ADVISOR” [12]. In view of the driving torque desired and the state of charge,it aims at selecting the optimum power split between the dual sources, which is one of the key points for PHV. Yun zhang et al [13]. Had wrote Study of the PHEVs Drive Train Fuzzy Logic Control Strategy in 2013. In this paper, the drive train fuzzy controller structure and the fuzzy logic control strategies of PHV is presented. Simulation results illustrate the potential of the proposed controller and control strategy on the purpose of fuel economy and in keeping the deviations of SOC at a low level. In 2019 Wei Li et al. had researched implementation of a fuzzy logic control strategy on a harvester’s controller based on MATLAB environment [14].

In real life, some experienced operators can through observation, reasoning and judgment, with artificial control of the method control those complex objects better [15]. Fuzzy control system is to sum up people's practical operation experience into language control rules. The fuzzy control system is different from the copper closed control system. The fuzzy controller is used to replace the analog controller in the fuzzy control system. Figure 5 is fuzzy logic control flow chart.

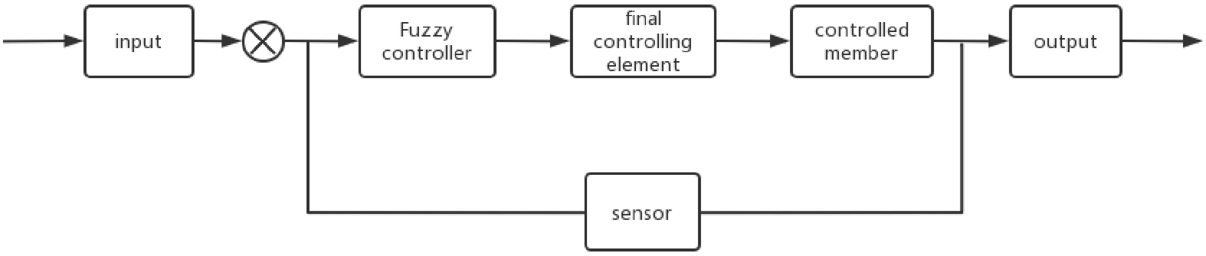

Figure 5. Fuzzy logic control flow chart

The comprehensive design of the traditional automatic control controller is based on the accurate mathematical model of the controlled object (i.e., transfer function model or state space model). However, in practice, there are many factors affecting the system, such as oil-gas mixing process, in-cylinder combustion process, etc., so it is quite difficult to find an accurate mathematical model. in this case, the birth of fuzzy control is of great significance. Because fuzzy control does not need to establish mathematical model and do not need to know the exact mathematical model of the process in advance, it makes the control mechanism and strategy easy to accept and understand, simple to design, and easy to apply.

Fuzzy control is the basic principle of the input to calculate precisely controlled variable fuzzy processing, again by the fuzzy control rules and conform to the actual conditions of reasoning, the amount of operation in a fuzzy controller, get blurred as a result, more motivation will result in a certain range, and then converting fuzzy quantity accurate quantity, In order to carry out specific operation control of each actuator [3]. Figure 6 is a fuzzy process diagram.

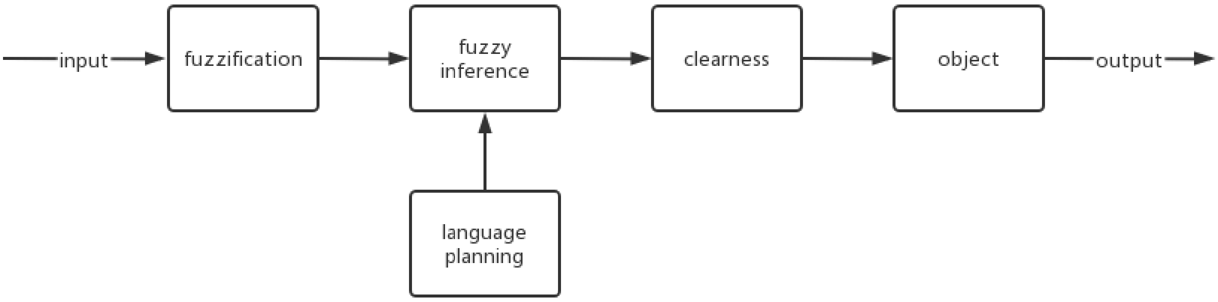

Figure 6. Fuzzy process diagram

3.2.2. The establishment of fuzzy logic control method

Referring to the fuzzy controller in some other literature, the PHEV fuzzy controller model in this paper is established [16-18]. In order to optimize the engine working interval, the difference between the required torque of the vehicle and the designed optimized torque ΔT is taken as an input variable of the simulation controller, and the SOC of the vehicle battery is taken as another input variable. Here, the engine speed is simply expressed as EnSpeed. The output variable of the fuzzy controller is the parameter U, and the calculated torque of the engine can be obtained by the product of the parameter U and the engine’s optimized torque. Then the output torque of the engine can be obtained, as shown in the structure diagram of the output torque obtained by the fuzzy controller of the drive mode.

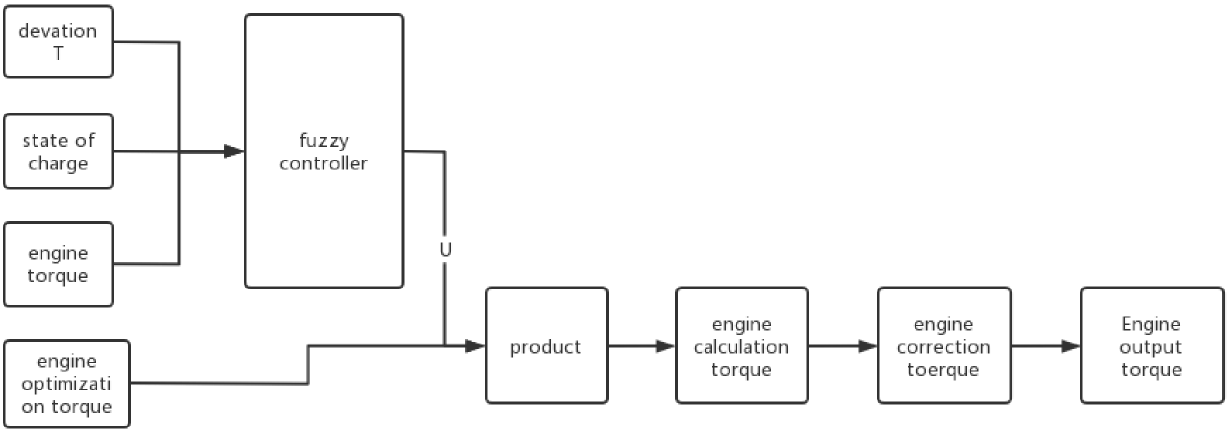

Figure 7. The Fuzzy Controller model [19].

According to the flow of fuzzy control, the input of fuzzy controller can only be used to control the output through fuzzification, and the function of fuzzification interface is to convert the real quantitative input into a fuzzy quantity. For a fuzzy input, its fuzzification can be divided into:

e={NB, NS, Z0, PS, PB}

e={NB, NM, NS, Z0, PS, PM, PB}

After the motor torque is calculated by fuzzy controller, the engine torque is further corrected by considering the maximum output torque and battery SOC value. The main idea of the modified control is as follows: if the battery SOC is within the set range, when the product of the output variable U of the fuzzy controller and the optimized torque of the engine is smaller than the set threshold value of the minimum working torque of the engine, or the speed is lower than the set value, the engine will be shut down and the motor will provide the required torque. When battery SOC is within the set range, if the product of fuzzy controller output variable U and engine optimized torque is greater than the maximum torque that the engine can provide, the motor and engine torque are allocated as follows considering engine characteristics [20]:

$$\begin{cases} T_m = T_{req} - T_e \\ T_m = T_{emax} \end{cases}$$

If the calculated engine torque obtained by product of the parameter U obtained by the fuzzy controller and the engine optimized torque is greater than the set minimum working torque threshold value, then the calculated engine torque is equal to the engine’s output torque. The torque value of the motor can be further calculate- d according to the demand torque. At this point, in the process of allocating the torque of the engine and the motor, there will be the following relationship:

$$T_m = T_{req} - T_e$$

This is the running process of fuzzy management strategy in energy management strategy in PHEV.

3.2.3. Strategy analysis

Compared with other optimization schemes, the fuzzy logic control strategy is simple in the calculation, easy to carry out, and has good stability and universality, but at the same time, the design of fuzzy control is not systematic, which is difficult to control the complex system. At present, it is difficult to establish a set of systematic fuzzy control theories to solve a series of problems such as fuzzy control mechanism, stability analysis, and systematic design method [16]. How to obtain fuzzy rules and membership functions is still carried out completely by experience, such a way is difficult to cover all the situations in display operation, simple information fuzzy processing will also lead to the system’s control precision and the dynamic quality deteriorates.

4. Optimization-based energy management strategies

These strategies are control methods that minimize the defined cost function under certain constraints by mathematical analysis. Generally, fuel economy, emission, power battery quantity and drivability of HEVs are taken as cost functions of the system, and its performance can be optimized by appropriate algorithms, which can better solve the problems existing in rule-based energy management strategies [21]. At present, they can be divided into global optimal and instantaneous optimal strategies according to the different optimization degree and stage.

4.1. Global Optimal Strategy

4.1.1. Introduction

To obtain the optimal strategy of a vehicle, a control strategy based on global optimization was proposed, where the optimization was continuously conducted from the start of the vehicle to the stop. This method usually takes vehicle fuel consumption, exhaust emissions and battery power as target state variables, and obtains the optimal energy distribution strategy of the vehicle according to specific cycle conditions by combining some optimization methods and theories [18]. There are various of algorithms based on global optimization, such as Genetic Algorithm (GA), Pontra Minimum Principle (PMP), Dynamic Programming Algorithm (DP). Among them, DP is the most representative, and the research on global optimization strategy based on it is the most developed as well. Hence, we focus on this strategy in this section.

DP method adopts the Bellman Principle, which states that any sub-sequence of the optimal decision sequence is also the optimal decision sequence corresponding to the corresponding initial state [22]. In short, a sub-strategy of an optimal strategy must also be optimal for its initial and final states. Figure 8 illustrates four steps throughout the DP:

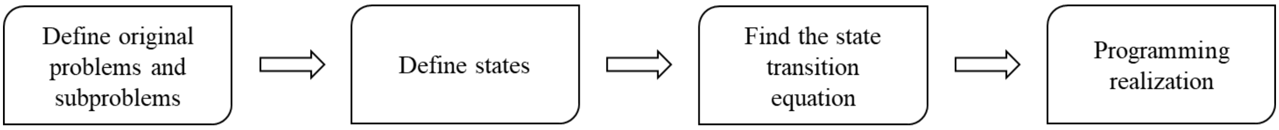

Figure 8. Illustrates four steps throughout the DP

The main idea of this method is to transform the original problem into a series of interrelated sub-problems. After solving the optimal solution of the sub-problems, the optimal solution of the whole original problem is then recursively deduced. In industrial applications, dynamic programming is very important, which is widely used in computer network, electronic communication, vehicle design and management fields.

4.1.2. Modeling and Solving

The energy management strategy for hybrid vehicles is a multi-stage decision process, for instance, to design a global optimization strategy based on DP which can achieve the minimum fuel consumption under a certain path, assuming that in certain conditions, it can be divided into multiple single-phase optimization subproblems, and then the optimum solution of the subproblem is used to calculate the global optimal solution [3]. The solution process can be summarized in Figure 9:

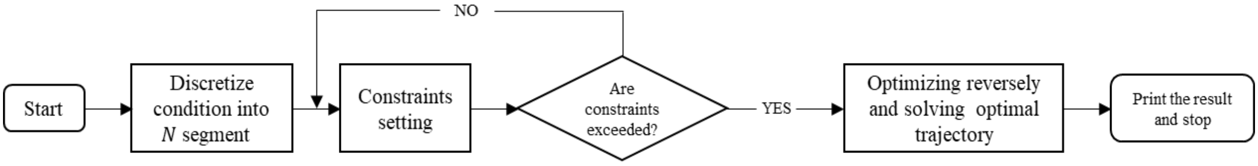

Figure 9. Energy management strategy solution procedures

For this problem, we can establish a DP model:

Determine the original problem be how to allocate energy from the power source to minimize fuel consumption at a given mileage. Then, the state variable and the duration of the cycle condition were separated into N segments, to facilitatse the subsequent calculation of the transfer cost at each stage. In the process of defining states, state variables and decision variables are involved, hence these two quantities need to be determined first.

(1) Determination of state variables and decision variables

For PHEV, the all-time energy state of vehicle battery can be reflected by its state of capacity (SOC), and the real-time vehicle condition can be represented by the required torque $\mathrm{T}_{\mathrm{req}}$, while the energy distribution of power source can be transformed into the torque distribution of engine and motor. As a result, we select SOC and $\mathrm{T}_{\mathrm{req}}$ as system variables, and engine torque T_{m} and motor torque T_{e} as system decision variavles.

(2) Constraints setting

With the variation of speed, the working interval of power battery, engine and motor will also change accordingly. To shorten the time for optimization, reduce the amount of calculation and have a safe and smooth driving experience, the motor and power battery need to satisfy the following constraints [3]:

$$SOC_{min} \le SOC(k) \le SOC_{\max} \tag{1}$$

$$\begin{cases} w_{e\_min} \le w_e(k) \le w_{e\_max} \\ T_{e\_min}\big(w_e(k)\big) \le T_e(k) \le T_{e\_max}(w_e(k)) \end{cases} \tag{2}$$

$$\begin{cases} w_{m\_min} \le w_m(k) \le w_{m\_max} \\ T_{m\_min}\big(w_m(k)\big) \le T_m(k) \le T_{m\_max}(w_m(k)) \end{cases} \tag{3}$$

Where w_{e_min} and w_{e_max} are the maximum motor speed, w_{m_min} and w_{m_max} the maximum motor torque, which can be obtained from experimentally obtained motor and engine characteristic curves. $SOC_{\max}$ and SOC_{min} are the upper and lower limits for battery SOC to avoid overcharge or over-discharge.

(3) Determination of state transition equation and objective function

The global problem treated by discretization can be regarded as a nonlinear discrete system, and its state transition equation can be set as:

$$\begin{gathered} s(k+1) = f[s(k), u(k), k] \\ s(0) = s_0 \end{gathered} \tag{4}$$

Where, the state variables are represented by s, decision variables by , and f is the state transfer function, and,

$$s(k) \in S(k) \subset R^n, u(k) \in U(s(k), k) \subset R^m$$

The specific content of the state transition function should be determined by the specific vehicle model, which is omitted here as the vehicle model is not modeled in this paper.

To make the goal optimal, the optimal array of decision variables $\mathrm{U}(\mathrm{u}_1, \mathrm{u}_2, \cdots, \mathrm{u}_{\mathrm{N}-1})$ should be solved when the state variable $\mathrm{s(k)}$ and decision variable $\mathrm{u(k)}$ will satisfy:

$$u_{optimal}(k) = u_k(s(k)) \tag{5}$$

Therefore, $\widehat{\mathrm{U}}(\mathrm{u}_{\mathrm{r}}, \mathrm{u}_{\mathrm{r}+1}, \cdots, \mathrm{u}_{\mathrm{N}-1})$ and $0 < \mathrm{r} < \mathrm{N} - 1$ can be assumed as the bearing capacity of the original problem. The objective function of each subproblem can be obtained as follows:

$$\hat{J} = \min_{u(k)\in\hat{U}} [J_{k+1}\big(s(k+1), u(k+1)\big) + L_k\big(s(k), u(k)\big)] \tag{6}$$

Where J is the objective function and L is the function of cost.

(4) The solution of the reverse optimization process and energy distribution trajectory

In the optimization process, the calculation is started at the terminal side, and successively reversed back to the initial state, then the minimum objective function from the current state to the previous state is attained. The last stage can be expressed as follows:

$$J_N(s(N),N)=\min_{u(N)}[L(s(N),u(N))] \tag{7}$$

Proceeding to stage K:

$$J_k(s(k),k)=\min_{u(k)}[J_{k+1}\big(s(k+1),u(k+1)\big)+L_k\big(s(k),u(k)\big)] \tag{8}$$

Then recursively calculate forward successively from the termination state, obtain the cumulative minimum fuel value of each state to the termination state, until the initial state $\mathrm{k}=1$, plan the trajectory that minimizes fuel consumption of the whole driving cycle, and determine the corresponding coordinate value.

4.1.3. Analysis of the strategy

The verification of this strategy can be realized by MATLAB, where the simulation process selects the New European Standard Driving Cycle (NEDC) and divides the working Cycle into 1180 stages with an interval of 1 second. The SOC working interval is set to $[0.4, 0.8]$, and the expected values of the SOC are set to 0.7. According to the experimental results, the required torque of the engine and motor is satisfied, indicating that this strategy can well adjust the power output and make the actual driving condition of the vehicle conform to the target driving condition. According to the SOC change curve, it turns out that the SOC fluctuation range does not exceed the feasible region and remains between $[0.65,0.75]$, which is in the high efficiency range. Meanwhile, at the end of the experiment, its final value was 0.6918, which was very close to the initial value of 0.7. The fuel consumption is $0.6\mathrm{L}$ and $5.5\mathrm{L}/100\mathrm{km}$ in the NEDC cycle condition, indicating that these torque distribution data can be used as the optimal strategy in this condition.

However, the experimental data show that this strategy requires huge computation time and storage space. During the whole experiment, DP algorithm has been calculated for 14160,000 times (1180×40×300), and it needs to run for 20154 seconds on a computer with a main frequency of 3.2ghz and 8G memory, which would be difficult to realize real-time control. Although DP method has poor real-time performance, it is the theoretically optimal strategy. Its experimental results under certain cycle conditions can be used as a standard to evaluate the advantages and disadvantages of other energy management strategies. For example, Wang [7] designed a global optimized energy management strategy for evaluating other strategies based on an oil-electro-hydraulic parallel hybrid model, with energy consumption cost as the objective function, battery SOC, and accumulator SOC as state variables, cvt speed ratio and engine torque as decision variables.

4.2. Instantaneous Optimal Strategy

4.2.1. Introduction of instantaneous optimal strategy

Although the global optimal strategy can maximize the performance of the hybrid system to achieve the global optimization, to increase the fuel economy, the organizational calculation can be carried out only by obtaining the information of future driving conditions. At the same time, it can not avoid the disadvantages of large amount of calculation and long calculation time of the algorithm [23]. To realize the real-time state on-line control of HEV, the instantaneous optimal strategy was born. Compared with the global organizational strategy, the instantaneous one is to optimize the energy distribution of HEVs under instantaneous working conditions. The amount of calculation is relatively small and easy to be applied in real vehicles, the main starting point is to ensure the minimum energy consumption in the current time energy management process. The instantaneous optimal working point is obtained based on the optimal working curve of the engine (map of fuel consumption, power and efficiency). According to the current driving conditions, the target value of engine and motor torque is optimized in real time by using dynamic programming method with the goal of optimal fuel economy of HEV [24], each state variable of hybrid power is controlled for dynamic energy distribution, so that the engine and motor work at the instantaneous optimal state point. the instantaneous optimal energy management strategy is to optimize the energy flow of vehicle under instantaneous working conditions [4,23]. At present, the most widely studied optimization methods in the instantaneous optimal energy management strategy are equivalent consumption minimization strategy (ECMs) and model predictive control strategy (MPCs).

4.2.2. Establishment of the strategy

The principal idea of the instantaneous optimal energy management strategy based on ECMs is to equivalent the electric energy consumed by the motor to the engine fuel consumption and add it to the actual engine fuel consumption to obtain the equivalent fuel consumption. Under a certain instantaneous working condition, the power source energy distribution mode, the optimal distribution mode, is obtained with the purpose of minimizing the equivalent fuel consumption, so as to realize the instantaneous optimal control of the hybrid power system. The equivalent factor is introduced to establish the total fuel consumption cost function at each instant, the emission can also be optimized through the weighting factor at the same time to form a multi-objective function for optimization solution [4,23]. ECMs obtains the optimal power distribution between engine and motor by calculating the minimum equivalent fuel consumption at each time. The equivalence factor defines the relationship between power demand and secondary energy consumption conversion, and is the most important control variable. Although the equivalent factor can be calculated in the light of the average fuel consumption rate and battery power, this method does not consider the influence of road conditions, and its fuel saving efficiency is not ideal. If the equivalent factor is optimized by genetic algorithm, the fuel economy can be improved, but the optimization result is correct only under the known conditions used in the optimization, and for other road conditions,this equivalence factor does not guarantee optimal fuel economy [25]. It is also one of the main research directions to increase the performance of ECMs by adjusting the equivalent factor.

The instantaneous optimal energy management strategy of ECMs still needs to obtain the parameters under real-time working conditions, the calculation process and amount of calculation are still large by solving the optimal working point of engine and motor at the current time through function. Consequently, the control rules of instantaneous optimal energy management strategy can be extracted by offline simulation. Because the neural network can approach the complex nonlinear mapping with arbitrary accuracy, has the ability of learning and induction, and has good real-time performance, the control rules of instantaneous optimal energy management strategy are realized based on the neural network, in order to make the vehicle obtain the optimal fuel economy performance in practical application [26]. Therefore, an adaptive ECMs is proposed to meet the driving requirements under various complex working conditions by adaptively adjusting the equivalent factor [27]. The multi-condition fuzzy adaptive instantaneous optimization energy management strategy needs to calculate the effective range of the equivalent factor off-line, and design the fuzzy controller based on the effective interval of the equivalent factor. The effective range of the equivalent factor can be obtained by the change of engine fuel consumption alone. The off-line calculation of the effective range of the equivalent factor needs to be based on a variety of complex working conditions, and the total fuel consumption of the engine under the working conditions corresponding to each equivalent factor can be obtained by traversing all possible equivalent factors [27]. According to the scaling of the input, the fuzzy controller can effectively control the input within a certain range. The solution process can be summarized by Figure 10:

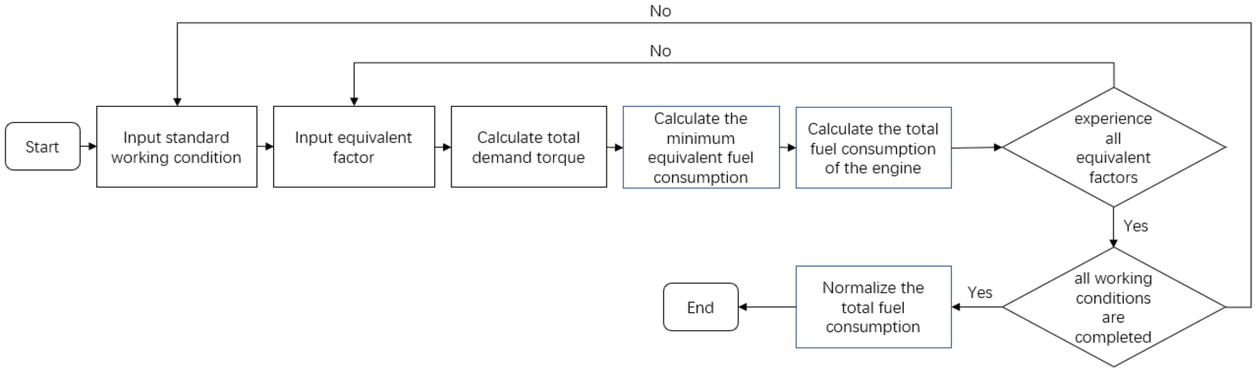

Figure 10. Instantaneous optimal energy management strategy solution procedures

In recent years, MPCs method has strong robustness, good prediction ability and strong real-time calculation ability. It is suitable for the control of nonlinear and imprecise dynamic systems. To a certain extent, it can also overcome the shortcomings of ECMs, such as no prediction ability and sensitivity to driving conditions [20]. The central idea is to transform the global optimization of fuel economy in the whole cycle into local optimization in the prediction interval by identifying the dynamic parameters of the hybrid system online. Through the rolling cycle optimization of the dynamic parameters, the working state of the vehicle in the next time interval is updated and predicted, so as to obtain the optimization results [4].

4.2.3. Analysis of the strategy

To sum up, the instantaneous optimal energy management strategy has achieved good control effect in HEVs. The amount of calculation is relatively small and it is easy to be used in the real vehicle. However, it still has shortcomings: 1. The working condition studied in the current research can not fully reflect the actual working condition. After optimization, it also needs the input of multiple parameters to achieve accurate control, and the instantaneous optimization can not ensure the global optimization; 2. The energy management strategy based on ECMs needs to determine the initial value of the equivalent factor, but the initial value of the equivalent factor is not exactly the same under different driving conditions, resulting in the cross of its robustness to adapt to different working conditions, so it is no longer possible to ensure the fuel economy and SOC maintenance of the vehicle under different driving conditions [27].

5. Conclusion

This paper mainly includes the classification of working modes of PHEV system and the introduction of four energy management strategies. These energy management strategies take energy conservation and emission reduction as the ultimate goal. On the premise of meeting the vehicle power, adjust and control the working state of the engine and motor to achieve the best implementation scheme.

Firstly, for parallel vehicles, there are many factors that lead to the fact that PHEV can not achieve real zero pollution. As people gradually improve their awareness of energy conservation and emission reduction and reduce environmental pollution, PHEV will maintain good development potential. It is believed that in the near future, the proportion of energy provided by internal combustion engine in parallel hybrid vehicles will be lower and lower, gradually approaching the ultimate goal of zero emission.

Energy management strategy is a research hotspot of PHEV. The energy management strategy realizes the reasonable distribution of the target value of engine and motor torque, and affects the economic performance and emission performance of PHEV. This paper summarizes and analyzes four energy management strategies and their research status. The rule based energy management strategy has a wide range of applications, but it is difficult to achieve the optimal performance of the whole vehicle; global organizational energy management strategy and instantaneous optimal energy management strategy has high requirements for computing performance, which limits its application range. There is a contradiction between the practicability of energy management strategy and control effect, which can be the direction of our future research on energy management.

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