NOVEL DESIGN OF ENERGY CONTROL STRATEGY FOR PARALLEL HYBRID ELECTRIC VEHICLE

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Abstract: A novel design method of control strategy for a parallel hybrid electric vehicle is proposed. The sequential quadratic programming (SQP) is first used to solve the optimal problem of maximizing system efficiency in terms of the global optimization. And then a fuzzy logic controller is developed to implement the optimal control strategy for a tradeoff between the engine and the battery in local. In addition, the performance of the fuzzy system is improved by optimizing the fuzzy rules based on the SQP results. Simulation results show that the proposed control strategy achieves better fuel economy under the duty cycle.

Key words: *fuzzy logic; power control; optimal control system*

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INTRODUCTION

Hybrid electric vehicle (HEV) can provide alternative solutions to cope with the worldwide energy crisis due to their fuel-effective and environment-friendly. A typical hybrid electric vehicle uses an engine as primary power source to provide the necessary energy, and the battery as auxiliary power source to supplement the transient and flexible power requirements of the vehicle. Furthermore, the battery can generate electricity using the excessive power from the engine as well as recover the kinetic energy in braking or coasting. These features make HEV more efficient than pure internal combustion engine or pure electric vehicle.

In the application of HEV, the parallel powertrain is the most versatile layout, because the engine-operating point and the battery-charging level can be randomly combined. This requires a novel energy control strategy (ECS) to efficiently distribute the power requirement between the available power sources. Most of the control strategies developed for parallel HEV can be roughly classified into three categories. One method is the rule-based system[1]. The power distribution depends on battery state of charge (SOC) by assigning different priority levels to the engine and the battery pack. The strategy only provides basic power distribution. The other method uses mathematical optimization algorithms[2-3]. The system efficiency or fuel consumption cost is formulated as the nonlinear optimization problems, and then the sequential quadratic programming (SQP) is used to solve them. From the global viewpoint, SQP is a good optimization method, but it is difficult to optimize the performance of the engine and battery simultaneously[4]. The SQP method is also infeasible to implement those strategies in real time because of its nature of the complex computation. However, the solutions of SQP provide some useful knowledge for designing an online energy control strategy. In contrast, the third method, the fuzzy logic system, is suitable for realizing an optimal tradeoff between the efficiencies of all components of HEV in terms of local optimization, but maximizing the system efficiency is not easy. One disad-

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vantage of fuzzy approach is that it is uneasy to design an excellent fuzzy rule system. So it is not guarantee that the developed fuzzy system will have sufficiently good performance.

Generally speaking, an ideal ECS should realize the goal of the maximizing system efficiency and optimizing the performance of all local components of HEV. If taking the advantages of the methods mentioned above, we can design an excellent ECS. In this paper, a novel design method is given for ECS. SQP is first used to solve the optimal control problem of maximizing system efficiency, which is a global optimization. And then a fuzzy logic controller is developed to implement the optimal control strategy in terms of further tradeoff between the engine and the battery in local. In addition, the fuzzy system performance is improved by optimizing the fuzzy rules based on the SQP results.

1 PARALLEL HYBRID VEHICLE SYSTEM

1.1 System configuration

The specific configuration of HEV used in the paper includes four major components: (1) a diesel engine; (2) two electric motors (A and B); (3) two battery packs; (4) a transmission. The performance requirements of the vehicle are shown in Table 1.

Table 1 Basic vehicle specification

Performance	Value/kW
Max. engine power	70.12
Max. battery power	87.65
Max. engine friction power	16.41

A schematic of the vehicle is shown in Fig. 1. The vehicle system is configured as a parallel hybrid with electric motor positioned after the transmission. The power of the vehicle is offered by both an internal combustion engine and an electric motor, with the engine providing the primary power. The operation of a vehicle can typically be divided into three basic phases: acceleration (peak power), constant speed (cruising) and deceleration (regeneration). In each mode, the engine and the battery operate with the appropriate behavior to meet the load power requirement and keep proper SOC in the battery. During full throttle acceleration, the load power can be much greater than that either engine or battery can produce alone. The battery also supplies power, thus boosting the motor output. During the cruising mode or a low power requirement, both the engine and the battery have a chance to provide power alone. Also, the engine can charge the battery when the battery pack is not full of energy. When the vehicle experiences a deceleration and braking, the engine is not at peak efficiency, and the engine is turned off or idles. The inertia of the wheels turns the motor, which acts as a generator. The recovered electricity is stored in the battery.

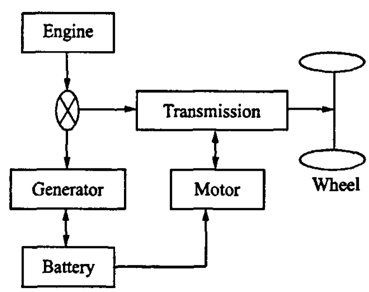

Fig. 1 Parallel HEV schematic

1.2 Energy control system model

The energy split strategy is implemented by a power controller. The controller analysis and the design here are based on the simulation model in the Matlab/Simulink environment. The model includes the possibility to implement different power split strategies and to evaluate the effect on parameters, such as fuel consumption, vehicle spe-ed, and battery state of charge, etc.. The interface of ECS is shown in Fig. 2.

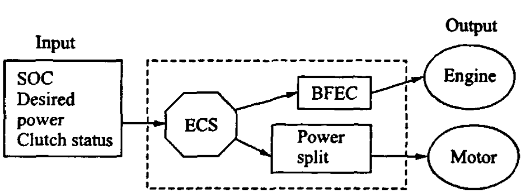

Fig. 2 Interface of ECS

In this module, the input variables are as follows: the battery SOC, the desired vehicle power demanded by the driver, the engine on/off, the clutch status, and the friction power. The output variables are the desired engine power and the desired battery power.

2 BASIC CONTROL STRATEGY

While HEV is operated, the energy control strategy should determine how much energy is needed to drive the vehicle based on the driver inputs, and how much is needed to charge the battery. Then it should split the power flow between engine and battery. If the power is split in an optimal manner, the power generation and the conversion of the individual components also have to be optimized[5-7].

2.1 Best fuel economy curve

Each engine has its own best fuel economy curve (BFEC)[8]. The curve shows the power-speed relationship of the engine. So the goal of the engine control strategy is to keep the operating points of an engine on BFEC such that the vehicle would minimize the engine fuel consumption and emissions. To realize this goal, in our ECS module, the desired engine speed and torque are derived from the desired engine power and the BFEC curve. The curve is obtained from the industrial partner of the author.

2.2 Maintaining SOC of battery

Three main aspects should be considered in the battery control strategy. Firstly, it is to maintain the battery SOC within 50%—70% for the minimum power losses in both charge and discharge. Then, the battery energy should be balanced in the entire duty cycle. Finally, for considering the battery life, the depth and the frequency of charges and discharges should be avoid. The battery pack system operating zone is shown in Fig. 3.

2.3 Rule-based energy control strategy

The specific fuel consumption of an engine is typically best at middle power levels and worst at

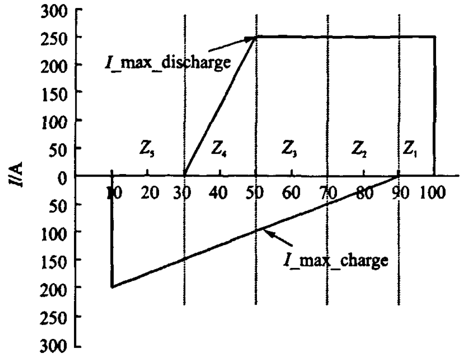

Fig. 3 Battery pack system operating zone

the low and high power extremes[10]. And the battery should avoid a deep charge and discharge in order to improve battery life. In rule-based ECS, the operation of the engine mode is actually dependent on the battery SOC, as shown in Table 2. For example, when the battery SOC is lower, the strategy will assign the engine to provide the desired power. Similarly, when the battery SOC is higher, then the strategy will let the battery supply all the power required by the vehicle, while the engine remains at a standstill or at idle.

Table 2 Basic power distribution rules

Zone	Priority	Charging	Discharging
Z_1	Battery	No(*)	Yes
Z_2	Battery	Yes	Yes
Z_3	Engine	Yes	Yes
Z_4	Engine	Yes	Yes
Z_5	Engine	Yes(**)	No

Note: * Use engine-braking & mechanical-braking only;
** Charging battery has the highest priority.

3 DESIGN OF FUZZY LOGIC CONTROLLER

3.1 Global optimization by SQP

In this section, a math-model optimal control strategy is developed in order to optimize the total system efficiency while satisfying the vehicle performance requirements. For convenience, the battery energy is usually converted into an equivalent amount of fuel consumption. In general, batteries can be modeled according to their electrochemical characteristics and empirical data. The battery resistance can be approximated by a function of the battery SOC and the battery current. Thereafter, the total system efficiency of the HEV system can be defined as

$$\eta_{\text{total}} = \left[\frac{\tau_{\text{req}}\omega_\gamma}{\tau_e\omega_e} - \frac{(U_o - \sqrt{U_o^2 - 4P_{\text{bat}}R_{\text{bat}}})U_o}{2R_{\text{bat}}\tau_e\omega_e}\right]\eta_e \tag{1}$$

where τ_{req} is the torque desired by driver on the gear, ω_γ the ring gear speed, U_o the open circuit voltage, P_{bat} the battery power, R_{bat} the battery resistance, η_e the engine efficiency, τ_e the engine torque, and ω_e the engine speed.

In actual implementation of power distribution, the continuous control variables of the HEV transaxle are $v_c=\{\tau_e, \tau_g, \tau_m\}$, where τ_g and τ_m are the generator torque and the motor torque, respectively. However, from a mathematical point of view, this paper introduces a new control variable $v_c' = \{\gamma, P_{bat}\}$ so that the physical concept closely resembles conventional vehicles, where γ is the reduction ratio of the engine speed to the ring gear speed. Thus, the optimization problem can be cast as

$$\max_{\gamma, P_{\text{bat}}} = \eta_{\text{total}}(\gamma, P_{\text{bat}}) \tag{2}$$
$$\text{s.t.} \quad \phi, \text{Inv}$$

The optimization problem aims to find a set of optimal parameters (γ, P_{bat}). Basically, these two parameters are obtained by maximizing the objective function in Eq. (2), subject to equality or inequality constraints and/or parameter boundaries using an appropriate optimization algorithm. SQP is a good candidate for solving this optimization problem because of its robustness and iterative efficiency[7].

This paper gives the optimization results of the battery power (P_{bat}) in terms of a vehicle speed. In Fig. 4, '*' denotes that the optimal battery power is negative (charging); 'o' denotes that the optimal battery power is neutral (neither charging nor discharging); '+' denotes that the optimal battery power is positive (discharging). Fig. 4 is divided into three areas by two lines. It can be observed that the inclination of the battery power is different in the three areas.

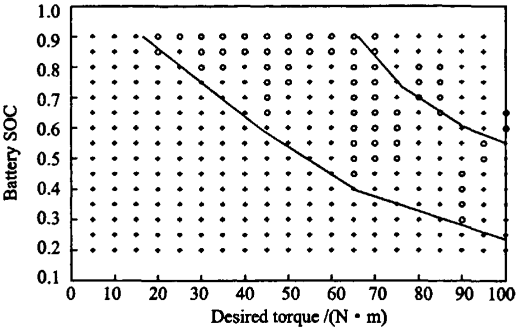

Fig. 4 Power distribution results

3.2 Local optimization by fuzzy system

In the paper, the fuzzy logic controller scheme consists of two inputs (the battery SOC and the desired vehicle power P_d) and one output (the desired battery power P_b). The engine power P_e can be obtained by subtracting the battery power from the desired vehicle power. The performance of the fuzzy controller actually mainly depends on its control parameters: membership functions and rule bases.

The universal of discourse of the input variable is derived through system constraints. SOC: [10, 100], P_d: [−320, 320], and P_b: [−120, 120]. The input SOC consists of five membership functions in universal of discourse that is named as Z_1, Z_2, Z_3, Z_4, and Z_5, respectively. In order to obtain a smoother control, seven membership functions are provided for P_d and P_b, respectively. Those are negative high (−H), negative medium (−M), negative low (−L), zero (OK), low (L), medium (M), and high (H).

When $P_d>0$, it means that the vehicle is operating at the load level, and the engine and the battery need to propel the load power. When $P_d<0$, the vehicle is experiencing a deceleration or stop, and the engine turns off and the battery is in the regenerating mode. Fuzzy set "high" (H) means that the vehicle desires more power. Fuzzy set "Low" represents that where either engine or battery can provide the power alone, and the engine provides the power as well as the charging battery. Similarly, $P_b>0$ represents discharging of the battery and $P_b<0$ represents charging. Fuzzy set "negative high" means that the battery may regenerate braking.

The tuning of the membership functions are mainly made through a manual trial and error process by simulations. It is frequently by modifying the shape and the domain of membership functions as well as how much they are allowed to overlap with each other. The original SOC is modified with five triangular membership functions into one with triangular and other trapezoidal shapes to represent the nature of the real world. The triangular is used for real "fuzzy" values, the trapezoidal shape for "crisp" values. For example, when SOC>90%, it is 100% available to provide power and 0% available for charging. Therefore, " crisp" membership functions are used to describe these intervals. On the other hand, if SOC is at Z_3, it is uncertain for the battery pack to be either discharging or charging. Therefore, the triangular membership functions are used to describe this "fuzzy" state. We also adjust domain-corresponding member functions. The final membership functions for SOC, P_d and P_b are shown in Fig. 5.

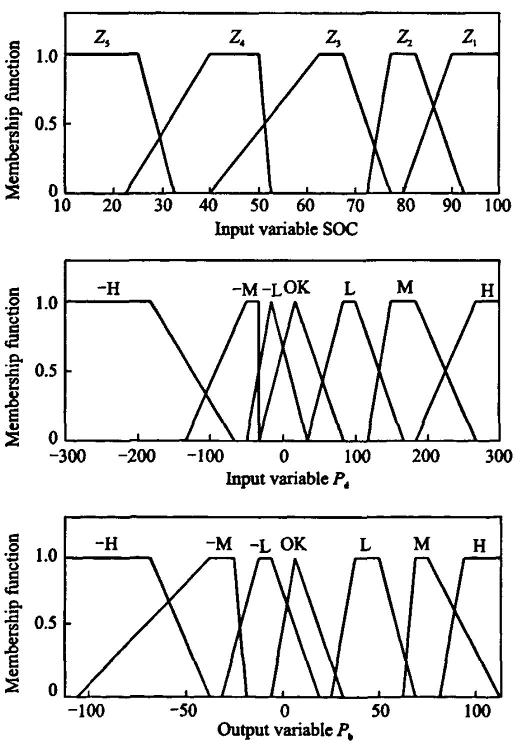

Fig. 5 Membership functions for SOC, P_d and P_b

3.3 Improving fuzzy rules by SQP

Prior design of fuzzy rule bases is drawn from expert knowledge and data, which is not guarantee an optimal rule bases. In this section, the rule bases of fuzzy system are constructed based on the SQP results, as shown in Fig. 4. These rules are applied to where the input SOC has five linguistic states, (Z_1, Z_2, Z_3, Z_4, and Z_5), and P_d has seven linguistic states, (−H, −M, −L, OK, L, M, and H), and the total number of possible no conflicting fuzzy inference rules is $5 \times 7 = 35$. Several threshold lines are drawn to divide the plot into 35 regions. Each region represents the desired battery power P_b under its specific condition. P_b is determined by three factors when we make the policy of the rule. The first factor is the SQP solutions, that is global optimal with denoting charge, discharge, or zero in the three areas. Based on the considering of SQP solutions, the rule for a region is determined by the state of SOC and P_d. That is further to compromise the two energy sources.

The inference rules in Fig. 6 have the canonical form:

If SOC is Z_1 and P_d is −H, then P_b is OK.

If SOC is Z_2 and P_d is M, then P_b is H.

		−H	−M	−L	OK	L	M	H
SOC	Z_1	OK	OK	OK	M	H	H	H
	Z_2	−L	−L	OK	L	M	H	H
	Z_3	−M	−L	−L	OK	L	L	H
	Z_4	−H	−H	−M	−L	OK	OK	M
	Z_5	−H	−H	−H	−M	−L	−L	OK

Fig. 6 Fuzzy rules

The proposed fuzzy controller is implemented by using the Matlab/Fuzzy Logic Toolbox. Once the initial statements of the rules and the membership function are completed, all rules in the rule base are fired in parallel. The Mamdani Type is selected for the fuzzificaiton. For the realization of the logical AND which is implicitly assumed for all rules in the rule bases, the minimum-operator is used. For defuzzification, the centroid method is used to determine the output.

4 SIMULATIONS

Three control strategies, i. e., the rule-based, the optimal and the fuzzy ECS are compared with each other under the arterial duty cycle. In Fig. 7, three curves show different SOC levels for the three strategies. The fuzzy ECS best keeps the SOC level, the optimal ECS tightly follows it, and the rule-based ECS is the last choice for a control strategy.

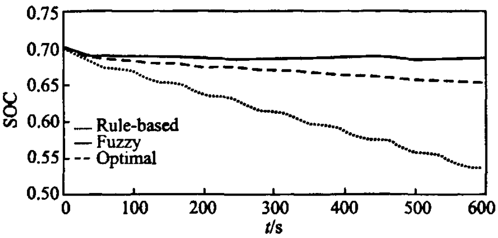

Fig. 7 SOC in arterial duty cycle for three strategies

Next, the power distribution among them is compared. In general, the power split is related to the duty cycle. In the acceleration mode, when a high peak of power is required, the engine and the battery will have to provide power together. Consequently, in the deceleration mode, it is always convenient for the engine to be turned off or idling. At this point the battery functions in the regeneration mode. In the above two cases, the three strategies are congruent. However, during the cruise phase, relatively low power is required from the drivetrain. There are several different power-split modes: (1) the battery provides the power alone; (2) the engine provides the power alone; (3) the engine delivers power both for powering the vehicle and for the battery recharge. Therefore, this is the most critical phase because the selected mode and the used degree will provide more mechanisms. From this point it can be known that whether a strategy is excellent or rudimentary.

Fig. 8 shows the battery power distributions for the three strategies, respectively. The segment between the two arrows (numbers 1 and 2) on each P_b curve represents the cruise phase. We can find that all of the three strategies use the engine to propel the vehicle. The difference is how much energy is charged to the battery while the engine is used. The rule-based strategy does not use the engine to charge the battery during cruising, thus the battery gained power wholly from the regeneration phase. The optimal strategy charges the battery, thus the battery has the more SOC; when braking occurs, the battery has little space for charging. This is the other extreme case. In contrast, the fuzzy strategy properly charges the battery, and the battery charge power at the cruise phase is 19. 39 kW, which means that it can capture more braking energy.

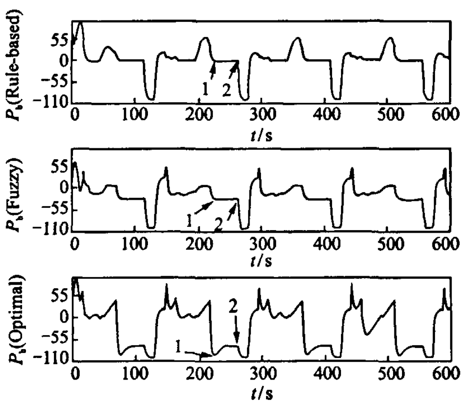

Fig. 8 Battery power distribution in arterial duty cycle

Fig. 9 gives the engine power distribution for the three strategies. The rule-based strategy has large charging and discharging power sequence, which results in the engine switching idle and load level frequently. In the optimal strategy, charging is greater. The result is high fuel-consumption and the engine works at full load. In contrast, the fuzzy strategy charges the battery properly at the cruise phase, which means that the engine operates at middle power levels and therefore it is not at the low or high power extremes. Thus, it operates at the optimal working point. Since charging is not too great, the battery has enough capacity to continue charging at the regeneration phase. The fuel consumption is lower than that in the optimal strategy and the best benefit for charging is divided into two different phases, i. e., cruise and regenerating mode. In addition, the charging current is smooth. Table 3 shows that fuzzy ECS has lower fuel consumption and keeps higher SOC than mathematical ECS. Therefore, compared with the rule-based and the optimal ECSs, the proposed fuzzy strategy is an excellent control strategy.

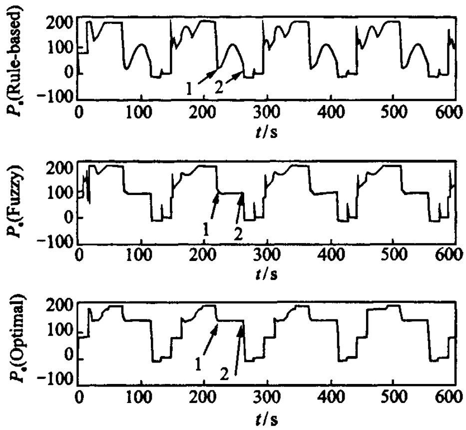

Fig. 9 Engine power distribution

Table 3 Arterial duty cycle simulation results

Condition	Math-optimal	Fuzzy	Difference/%
SOC	0.645 1	0.653 1	+0.8
Fuel consumption	0.907 8	0.845 8	−6.2

5 CONCLUSION

An optimal fuzzy energy control system is developed and integrated into the parallel HEV simulation model. Two computational tools are employed. The mathematical optimal algorithm is used to achieve a global optimization in term of maximizing the system efficiency of HEV. The fuzzy system is used to tradeoff the performance of two power sources based on the mathematical optimization results. The simulation results demonstrate the potential improvement by using the proposed method, over other strategies that optimize only the engine efficiency.

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并联式混合动力车能量控制策略设计

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摘要:提出了一种新颖的能量控制策略的设计方法用于并联式混合动力车。首先用SQP算法求解最大系统效率问题以实现全局优化;然后用模糊控制系统来协调发动机和电池的工作点实现局部优化。模糊系统的模糊规则建立则是汲取了SQP优化结果,从而保证全局与局部的统一。计算机仿真结果表明,运用该能量控制策略的混合动力车能达到较好的燃料经济性。

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