

Comparison of Rule-Based and Optimization-Based Energy Management Strategies for Hybrid Electric Vehicles

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Abstract. The energy management method adopted by hybrid electric vehicles is the core technology of vehicle fuel economy. At present, there is still a lack of systematic and quantitative comparative analysis on the main strategies. In this paper, the power split hybrid electric vehicle is taken as the research object, and a complete simulation scheme is proposed: the engine fuel consumption map, motor efficiency map, step internal resistance battery, and vehicle longitudinal power are included. Based on this, three typical energy management ideas are compared, and the driving cycles shown in Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Test (HWFET), and Worldwide Harmonized Light-Duty Vehicles Test Cycle (WLTC) are used for the test, and a comprehensive judgment is made according to the equivalent fuel consumption per 100 kilometers, State of Charge (SOC) retention capacity, operation efficiency, and condition matching degree. From the existing literature, it can be concluded that dynamic programming gives the theoretical minimum fuel consumption in each working condition, which is the reference standard of performance limit; The fuel consumption difference between the adaptive equivalent fuel consumption minimization method and the dynamic programming method is about 5% at most, and it allows online real-time use, which is an ideal practical coexistence scheme; Although the strategy designed according to the rules can handle the working conditions under calibration, the fuel consumption under non-standard working conditions often increases by more than 10%, and the adaptability is not strong.

Keywords: Hybrid electric vehicle, energy management strategy, dynamic planning, equivalent fuel consumption minimization strategy, power split

1. Introduction

The transportation sector is a major contributor to global greenhouse gas emissions and fossil fuel consumption, accounting for approximately 24% of energy-related CO₂ emissions [1]. In response to increasingly stringent regulations on fuel economy and exhaust emissions, the automotive industry is compelled to undergo a more radical transition toward electrification. In this context, hybrid electric vehicles (HEVs)—which strike an optimal balance between fuel efficiency and driving range—have reached a stage of both technical maturity and commercial viability, positioning them as the most promising technological pathway at present [2].

The new energy vehicle industry (with hybrid electric vehicles as the core) is now ushering in a period of strategic opportunities. The relevant market has clear evidence to prove it. According to the statistics in April 2026, the monthly sales volume of plug-in hybrid vehicles has exceeded that of pure electric vehicles for the first time, which is a significant change in the market structure [3]. In terms of prediction, the global annual sales of hybrid or plug-in hybrid vehicles will be close to 24million in 2030, and the market penetration will reach more than 25% [3]. In 2025, the sales volume of plug-in and hybrid vehicles reached 2.046 million, of which about 70% are medium- and high-end family vehicles at a price of 200000-500000 yuan [3]. It can be concluded that hybrid power is a realistic and efficient solution for families. Therefore, it is necessary to make a detailed analysis of the energy configuration of such vehicles, try to improve the energy efficiency, control the cost within a reasonable range, and use specific examples to drive the social progress of energy conservation and carbon reduction.

According to the technical standard, as far as the current hybrid electric vehicle is concerned, its core is to have some kind of energy management method compared with the traditional fuel vehicle, that is, to coordinate the power used by the engine and motor in real time [4]. This kind of energy management strategy itself belongs to the subject of supervision and control, which should meet various restrictions at the same time, make multiple power sources cooperate, achieve the minimum fuel consumption in equivalent form, and keep the battery from power loss. Therefore, whether the designed energy management scheme is successful or not is a direct limit to the vehicle fuel performance, and it is also the most technically difficult and the most difficult link to solve in the process of hybrid system research.

The so-called mainstream energy management methods can be basically divided into two categories: rule-based and optimization-based strategies. The former uses the experience given by experts to specify the threshold and mode conversion point, which is not difficult in design, but may not be flexible in practical application; The latter regards optimal control as the basic idea and determines the control law according to the optimization criteria, which is relatively complete in theory, but has high requirements for calculation [5, 6]. However, the existing literature has not made a unified and complete comparative analysis or inductive discussion on the two strategies.

The blank to be discussed will be systematically dealt with here; that is, a comparative analysis of various situations related to the standard driving cycle will be made, and the advantages and disadvantages or limitations of the two strategies will be measured according to the indicators of fuel economy, State of Charge (SOC) retention, calculation efficiency, and working condition applicability. This paper attempts to give a feasible reference for the energy management method in a hybrid power system in a quantitative way, and also looks at the comprehensive strategy that may be adopted in the future, so as to give some hints or guidance for its development.

2. Theoretical basis

2.1. Research object and vehicle model

This study selected a typical power split hybrid vehicle as the research object [5]. The power split architecture couples the engine, generator, and drive motor together through planetary gear sets, which can realize the decoupling of engine speed and vehicle speed, and make the engine work in a high-efficiency area in a large range of operating conditions. It is one of the most representative hybrid configurations in the market at present.

In the existing research on modeling, the strategies involved in energy management are mostly simulated and analyzed according to the longitudinal dynamics of the complete vehicle [2]. If the

backward method is used for modeling and the target vehicle speed is taken as the input, the torque and power provided by each component can be inverted. At this time, the required vehicle speed has no error, and the simulation is more efficient [2, 5]. In actual operation, the vehicle needs to overcome rolling resistance, air resistance, slope, and acceleration resistance.

In the modeling of key components, the fuel consumption rate map used by the engine is the corresponding relationship between speed and torque given by the steady-state bench test, and the instantaneous fuel consumption rate is obtained by linear interpolation [2, 7]. To make the actual operation of the engine close to the optimal state, the model lists the minimum unit fuel consumption torque at each speed (i.e., the BSFC optimal line) as a reference indication of the target operating point in energy management (see [2] for the description of the point position). The motor model uses the efficiency map to determine the working efficiency corresponding to the speed and torque, so as to calculate the bidirectional conversion amount of mechanical energy to electrical energy [2]. The battery part simulates the equivalent circuit in the form of first-order RC internal resistance, connecting the open-circuit voltage, ohmic internal resistance, and polarized internal resistance with the battery SOC and temperature [7]. SOC can be estimated by the ampere-hour integration method, and the change law of SOC can be obtained by integrating the battery current in real time [2]. The listed component models coordinate the power split with the closed-loop control of torque and speed, which is just the basic platform for the simulation and analysis of energy management strategy [2].

2.2. Rule-based strategy

The baseline strategy of the proposed rules in the study is based on deterministic logic thresholds [7]. Its core is to analyze the problem according to the power demand of the vehicle, the actual speed, and some main states of the battery SOC, classify various situations into categories of working modes with a given threshold, and then determine the mode to be implemented according to the priority.

The strategy is five basic working modes, namely: first, pure electric driving mode, when the battery SOC is not used too much and high power is not required, the vehicle is driven by the motor only, and the engine does not work, so there is no fuel consumption; second is the engine driving mode. If the vehicle speed is medium to high speed and the power used is not too high, let the engine drive alone, and start the generator to recharge the battery if necessary; The third is the hybrid drive mode. In case of high-power requirements (such as fast acceleration or uphill), the engine and the motor will provide torque at the same time to meet the power needs; The fourth is the driving charging method. When the battery SOC is surplus and the engine efficiency is good, the surplus power is used to charge the battery driven by the generator; The fifth is the braking recovery method. During vehicle deceleration or braking, the motor turns into a generator to recharge the braking energy to the battery.

If considered by the engineering method, the proposed strategy can be described by a finite state machine, and the conditions and hysteresis range of mode switching are set to prevent switching too frequently. For the torque distribution itself, the torque value that each component should reach should be determined according to the current mode, combined with the actual needs, the ideal curve of the engine, and the power requirements of the battery.

2.3. Optimization-based strategies

To establish a reference frame for performance, the current academic community generally adopts two ideas based on optimization. The first is dynamic programming [5]. Considering the problem according to the Bellman optimality principle, the complete driving process is divided into several time stages, and the optimal control scheme for each stage is deduced from the final state, so as to obtain the overall optimal solution. The dynamic programming referred to in this paper is the "theoretical optimal ceiling", which is the reference of the upper limit of performance for other methods. However, dynamic programming itself has great engineering limitations: its computational complexity increases exponentially with the state dimension; "dimension disaster" is a problem that must be faced. Moreover, dynamic programming requires mastering the complete working condition data in advance, and this non-causality makes it unable to be directly used in the real vehicle controller [5]. The second is an adaptive equivalent fuel consumption minimization strategy. The minimum equivalent fuel consumption method simplifies the global optimization into instantaneous optimization, converts the electric energy used by the motor into equivalent fuel consumption by using the equivalent factor, and determines the minimum equivalent fuel consumption at each step [6]. If the equivalent factor is fixed, it will not have strong adaptability to sudden changes in working conditions, and it is difficult to ensure the stability of SOC. Therefore, this study proposes an adaptive equivalent fuel consumption minimization strategy, corrects the deviation with the help of SOC feedback, and sets the equivalent factor according to the difference between the current SOC and the expected SOC [8]. When SOC is too large, reduce the equivalent factor to promote power consumption; When it is too small, adjust the factor to suppress power consumption and urge the engine to recharge the battery. Such adaptive processing is robust to various working conditions [8, 9].

3. Performance comparison and comprehensive evaluation of different strategies

The so-called deterministic dynamic programming (DP) is an optimization principle proposed by the American mathematician Bellman and others for the optimal problem involved in multistage decision-making [10].

At present, the literature generally designs relevant tests according to the standard driving cycle; that is, the Dynamometer Driving Schedule (UDDS) is considered as the urban congestion condition, the Highway Fuel Economy Test (HWFET) as the suburban unobstructed condition, and WLTC as the comprehensive condition. The analyzed indicators include equivalent fuel consumption per 100 km, SOC deviation from the termination value and target, time spent in each step, and smoothness of the trajectory shown by SOC [6].

The so-called DP algorithm itself is the global optimal method, so relevant research generally takes it as the theoretical basis for analyzing other energy management schemes [11]. From the literature summary, in terms of the low-speed urban conditions of UDDS, the power required by the whole vehicle is basically not increased sharply, the change range of SOC is small, and the final value is mostly close to the set limit (such as 60%) [11]. At this time, the power supplied by the engine is smooth. In case of transient high-power demand, the battery will cooperate, so the engine will not be over-regulated or repeatedly started and stopped [11].

Based on the initial stage of DP under UDDS conditions, the battery power plays a major role, and the fuel cell power plays an auxiliary role; In the initial stage of WLTC, the fuel cell plays a major role, and the battery plays an auxiliary role [12].

In terms of fuel economy, the dynamic programming discussed gives the lowest equivalent fuel consumption in all test conditions, so it can be regarded as the global optimal solution [5]. The strategy of achieving the minimum equivalent fuel consumption in an adaptive way is basically consistent with the dynamic programming, and the error under various working conditions is generally no more than 5% [8]. The control scheme designed by the rule method is applicable and efficient for known working conditions, but the fuel consumption will become worse in case of non-calibration, with a gap of more than 10% compared with dynamic programming [9].

In terms of SOC maintenance ability, the SOC of the three strategies investigated at the end of the test is basically close to their respective target values, but the trajectory is significantly different. The strategy designed according to rules makes mechanical arrangement for the change of SOC, and the power used is often exhausted earlier; Dynamic planning can use the global working condition information to determine the most fuel-efficient power consumption time without wasting any energy; The strategy of dealing with the equivalent fuel consumption adaptively reproduces the SOC trajectory used in dynamic planning approximately with the help of flexible adjustment of factors, and the power balance effect is very good [8].

If measured by computational efficiency, the rule-based strategy takes the least time at each step and is optimal for real-time performance; Although the effective fuel consumption corresponding to the adaptive method is small, its calculation time is slightly larger than that of the rule method, which is still suitable for the real-time needs of online applications; However, it takes several times more time to calculate with dynamic programming than the first two, which can not meet the requirements of real-time [5].

From the analysis listed above, it can conclude that the strategy designed according to the rules is a direct and feasible method for the case where engineering is the most important and there is no shortage of calibration resources; To achieve ideal fuel economy (close to the theoretical value) and keep online, the adaptive equivalent fuel consumption minimization method should be adopted now [8]; Although dynamic programming has theoretical advantages, its practical significance is basically limited to the comparison and prompt of the upper limit of performance (i.e. the best possible value) of various strategies [5].

4. Conclusion

The object discussed in this paper is the power split hybrid electric vehicle. The rule method, dynamic programming (DP), and adaptive equivalent fuel consumption minimization method (a-ecms) are systematically compared as energy management strategies. Using UDDS, HWFET, and WLTC as simulation tests, combined with fuel economy, SOC retention performance, calculation speed, and adaptability to operating conditions, the following basic conclusions are drawn:

First, in terms of fuel economy, DP has reached the theoretical minimum fuel consumption corresponding to each operating condition, so it can be regarded as the performance upper limit of the global optimal solution; The difference between the fuel consumption and DP obtained by a-ecms is no more than 5%, which is basically close to the optimal value; The control mode designed according to the rules applies to the standard working conditions. In case of uncalibrated conditions, the fuel consumption will increase by more than 10%, and the adaptability of the working conditions involved is not strong enough.

Second, in terms of SOC, the three strategies used can make the final SOC close to the target, but the actual trajectory is very different. The rule-based strategy uses electricity mechanically. DP is the optimal power time sequence arranged after the analysis of the overall state. A-ecms performs self-

adjusting processing with the help of the equivalent factor. The obtained DP SOC trajectory is basically reliable, and the electricity balance has good robustness.

Third, in terms of computational efficiency, the rule strategy is the best scheme for real-time performance. A-ecms requires a little more one-step time but will not hinder the continuous use of real vehicles, while the computational burden of DP is exponential and is not suitable for real-time control.

Fourth, in terms of engineering applicability, the rule strategy itself is easy to implement and reliable, and basically belongs to the mainstream of the mass production vehicle scheme after full calibration; A-ecms is approaching the ideal fuel consumption and has the function of online calculation. Now it is the most promising option in the optimization strategy. The value that DP refers to is mostly the performance standard, which has reference significance for improving other methods.

On the whole, the three kinds of strategies involved in this paper have not been completely and systematically analyzed in previous works. Now they are used in the discussion of hybrid system design, and the corresponding data support is given. It is also pointed out that "the optimization strategy can be solved offline, and the rule strategy can be implemented online" for fusion processing. According to the current development trend, the use of predictive driving data (information about terrain or traffic flow) and more advanced reinforcement learning methods to design control methods will make energy management take into account the global optimum and instantaneous response, to obtain another kind of feasible scheme to improve the energy efficiency of hybrid electric vehicles.

References

- [1] International Energy Agency. (2025). Global EV outlook 2025: Towards the era of electric mobility. *IEA*.
- [2] Sciarretta, A., & Guzzella, L. (2007). Control of hybrid electric vehicles. *IEEE Control Systems Magazine*, 27(2), 60–70.
- [3] China Automobile Industry Association. (2026, April). China automobile industry production and sales news in April 2026. *China Automobile Industry Association*.
- [4] Wang, Q., Zeng, X., & Wang, W. (2019). *Hybrid vehicle energy management strategy*. China Machine Press.
- [5] Sundström, O., & Guzzella, L. (2009). A generic dynamic programming Matlab function. In *Proceedings of the 18th IEEE International Conference on Control Applications* (pp. 1625–1630). IEEE.
- [6] Paganelli, G., Delprat, S., Guerra, T. M., et al. (2002). Equivalent consumption minimization strategy for parallel hybrid powertrains. In *Proceedings of the 55th IEEE Vehicular Technology Conference* (pp. 2076–2081). IEEE.
- [7] Wang, H., Cui, L., Ge, S., et al. (2024). Transmission system design of dual mode power split hybrid electric vehicle. *Mechanical Design and Manufacturing Engineering*, (7), 85–94.
- [8] Musardo, C., Rizzoni, G., Guezennec, Y., et al. (2005). A-ECMS: An adaptive algorithm for hybrid electric vehicle energy management. *European Journal of Control*, 11(4–5), 509–524.
- [9] Li, J. (2026). Research on energy management strategy of power split hybrid electric vehicle based on dynamic programming. *SAIC Motor*, (2).
- [10] Luan, Y. (2024). *Research on energy management strategy of fuel cell hybrid electric vehicle based on reinforcement learning* [Master's thesis or doctoral dissertation, Jilin University].
- [11] Zhang, S. (2024). *Energy management strategy for fuel cell hybrid electric vehicle based on generative confrontation imitation learning* [Master's thesis or doctoral dissertation, Chongqing University of Technology].
- [12] Jiang, D. (2020). *Hybrid electric vehicle energy management based on model predictive control* [Master's thesis or doctoral dissertation, Zhejiang University].