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Review

Configurations and Control Strategies of Hybrid Powertrain Systems

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Abstract: The configuration and control strategy of hybrid powertrain systems are significant for the development of hybrid electric vehicles (HEV) because they significantly affect their comprehensive performance. In this paper, the types, features, and applications of the mainstream hybrid powertrain configurations on the market in recent years are summarized and the effects of different configurations on the comprehensive performance of HEVs are compared. Moreover, the technical routes for each hybrid configuration are highlighted, as configuration optimization methods have become a technical difficulty. In addition, the technological advances in the steady-state energy management strategy and dynamic coordinated control strategy for hybrid powertrain systems are studied. The optimization of the steady-state energy management strategy mainly involves assigning the working point and working range of each power source reasonably. However, with the increase in the complexity of optimization algorithms, real-time control of HEVs still needs to be improved. The optimization of the dynamic coordinated control strategy mainly focuses on the stability and smoothness of the dynamic process involving switching and shifting the working mode. The optimization of the dynamic control process for the system remains to be further improved. It is pointed out that the configurations and strategies should be optimized jointly to obtain a comprehensive improvement in the system performance. This paper provides an informative basis and technical support for the design and optimization of a hybrid powertrain system.

Keywords: HEV; hybrid powertrain system; configuration comparison and optimization; energy management strategy; dynamic coordinated control strategy

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1. Introduction

Global energy demand is growing rapidly and the contradiction between limited energy and the large energy consumption of traditional fuel vehicles has become increasingly acute. Efficient, energy-saving, and environmentally friendly new energy vehicles have attracted wide interest [1,2]. In recent years, hybrid electric vehicles have developed rapidly and their market share has gradually increased. HEVs have the advantages of both traditional fuel vehicles and electric vehicles and are considered a necessary transition vehicle from fuel vehicles to pure electric vehicles [3,4].

Hybrid powertrain systems are significant for the development of HEVs. The powertrain configuration and control strategy of hybrid powertrain systems determine the acceleration and fuel economy of HEVs in a coupled manner [5]. The powertrain configuration (including matching parameters) determines the method of power transmission, working mode, and energy conversion mode of the system [6,7]. The control strategy is based on the configuration, so the energy management strategy affects the actual fuel economy and emissions of vehicles and the dynamic coordinated control strategy affects the response speed and control robustness of vehicles [8]. Therefore, the optimization of hybrid powertrain configurations is the most direct way to improve the inherent performance, and the optimization of the control strategy is an effective way to achieve theoretically optimal performance for vehicles [9].

This paper reviews powertrain configurations and control strategies for HEV hybrid powertrain systems from recent years. In Section 2, the configuration schemes for the main hybrid powertrain systems in the market are introduced. In Section 3, based on a comparison of existing configuration schemes, optimization methods for powertrain configurations are discussed. In Section 4, various steady-state energy management strategies for hybrid systems are compared and the future development trend for energy management strategies is discussed. In Section 5, the main achievements regarding dynamic coordinated control strategies for hybrid systems are introduced and a future direction is proposed.

2. Hybrid Powertrain Configuration

According to system layouts and transmission modes, hybrid powertrain configuration schemes can be classified into series hybrid, parallel hybrid, and combined hybrid configurations.

2.1. Series Hybrid and Parallel Hybrid Powertrain Configurations

The series hybrid powertrain configuration is mostly used in extended-range HEVs. In this configuration, a motor drives the vehicle and an engine is connected as the auxiliary power source to the vehicle without mechanical connection components. The system raises the requirements for the drive motor and power battery, and the mechanical energy generated by the engine is converted into electrical energy by a generator to drive the motor.

The parallel hybrid powertrain configuration can be driven by an engine and/or a drive motor, depending on the working conditions. Generally, a motor is used to assist in adjusting the output power of the engine according to the power requirements of the vehicle. This configuration inherits the most advantages from the structure of traditional fuel vehicles and is equipped with traditional six- to nine-speed transmission.

Table 1 provides the features, working modes, and power transmission paths of the series hybrid powertrain configuration and the parallel hybrid powertrain configuration.

In the parallel hybrid powertrain configuration, P0–P4 sub-type parallel configuration schemes can be derived according to the different arrangement positions of the driving motors (Table 2).

2.2. Combined Hybrid Powertrain Configuration

Combined hybrid powertrain configurations have the advantages of both series and parallel hybrid configurations and can be adapted to a variety of working conditions, thus improving the performance of systems. The mainstream HEVs on the market generally adopt combined hybrid powertrain configurations. Combined hybrid powertrain configurations include the dual-motor series-parallel hybrid powertrain configuration and the power-split hybrid powertrain configuration based on the planetary gear mechanism. The series-parallel hybrid powertrain configuration avoids the gearbox and uses dual motors. The single-mode power-split hybrid powertrain configuration involves two sub-type power-split schemes (input-split scheme and output-split scheme) in accordance with the different connection methods used between the engine, generator, motor, and power-split device. In the input-split configuration, the engine and generator are connected to the two different central shafts of the planetary gear set correspondingly, and the motor is connected to the output central shaft. In the output-split configuration, both the engine and generator are rigidly connected to the input central shaft of the planetary gear set, and the motor is connected to another central shaft of the planetary gear set. The last central shaft acts as the output shaft (Table 3). The multi-mode (two-mode and multi-mode) power-split hybrid powertrain configuration is a combination of more than two power-split schemes [13,14] that can realize complex power-split methods (Table 3).

Table 1. Series hybrid and parallel hybrid powertrain configurations [6,10].

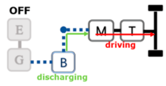
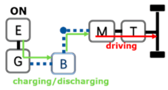
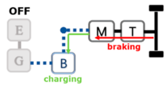
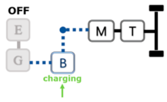
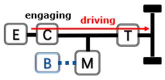
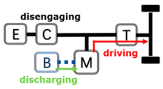
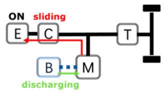
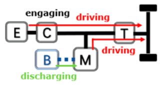
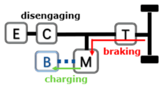
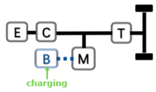
Types	Features	Modes	Power Paths	Applications	Evaluation
Series hybrid	Driving force provided only by motor	Electric drive		City buses Nissan e-POWER Li ONE	Disadvantages High requirements for motor power Heavy weight Large size High cost Low efficiency of energy conversion Advantages Simple configuration Easy to control Runs in optimal working area of engine
		Working of engine and motor			
		Energy recovery			
		Battery charging when parking (PHEV)			
Parallel hybrid	Driving force provided by cooperation between motor and engine (Taking the P2 configuration as an example)	Driving with engine		Most HEVs of Korean Hyundai or European Volkswagen, Mercedes-Benz, BMW	Disadvantages High requirements for battery charging capacity Complex transmission structure Advantages Power coupling of motor and engine Low cost Good acceleration performance
		Driving with motor			
		Engine on/off			
		Working of engine and motor			
		Energy recovery			
		Battery charging when parking (PHEV)			
Legends		E Engine G Generator	C Clutch Mechanical connection	M Motor	T Transmission Electric connection	B Battery

Table 2. Features and applications of parallel P0–P4 configurations [11,12].

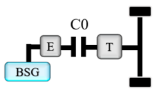
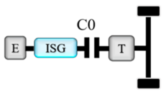
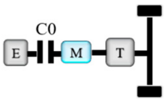
Types		Features	Applications	Evaluation
Configuration	Motor Position			
P0	 Input end of engine	Application of belt-driven starter/generator (BSG) system	Applied in micro- and mild hybrid systems Audi SQ7 TDI	Low efficiency Fewer achievable working modes No electric drive mode
P1	 Output end of engine	No flywheel after engine Application of integrated starter generator (ISG) fixed on the engine	Applied in mild and medium hybrid systems Benz S400	Fewer achievable working modes No electric drive mode
P2	 Input shaft of the transmission or integrated in the transmission	Independence of engine from the transmission system Combination with P0 to P0P2 series-parallel hybrids	Applied in full and plug-in hybrid systems Currently the most used configuration Audi A3e-tron	Electric drive mode Low cost Small size

Table 2. *Cont.*

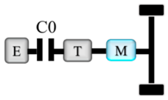
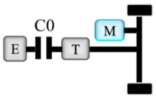
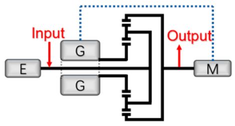
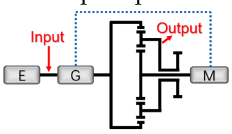
Types		Features	Applications	Evaluation
Configuration	**Motor Position**			
P3	 Output shaft of the transmission	Combination with P0 to P0P3 series-parallel hybrids	Applied in full and plug-in hybrid systems More commonly applied in rear-wheel drive BYD-Qin	High efficiency of electric drive
P4	 Driving half-shaft	Combination with other configurations, generally not used alone	Applied in plug-in hybrid systems More commonly applied in rear-wheel drive or four-wheel drive BMW i8	High cost
Legends	E Engine	T Transmission	Clutch	M Motor

Table 3. Characteristics and applications of combined hybrid configurations [15–18].

Types	**Features**	**Applications**
Series-parallel hybrid	Dual motors Both series and parallel configurations	Applied in Honda i-MMD hybrid system Honda Accord
Single-mode power-split hybrid  Input-split  Output-split	Dual motors Equipped with single or double planetary gear transmission mechanism	Applied in Toyota THS Four generations of evolution Single planetary gear (Corolla) to single Ravigneaux planetary gear (Lexus L600h)
Multi-mode power-split hybrid	Dual motors Increased numbers of clutches and brakes Equipped with double or triple planetary gear transmission mechanism	Applied in GM AHS Double (Lacrosse 30H) or triple (Cadillac CT6) planetary gear More achievable working modes
Legends	E Engine	G Generator M Motor

2.3. Summary of Combined Hybrid Powertrain Configurations

The driving modes, configuration characteristics, and representative models of series, parallel, and combined hybrid powertrain configurations on the market were compared and analyzed. The mainstream hybrid technological routes in Japan, the United States, Korea, and Europe have their own characteristics due to national conditions, including policies, technologies, and markets. The parallel PX hybrid powertrain configuration used in Korea and Europe retains the most features from traditional fuel vehicles. Toyota first proposed a power-split hybrid powertrain configuration, and then Honda also proposed a series-parallel i-MMD hybrid powertrain configuration. The technological routes of many auto companies were developed on the basis of the two configuration technologies. Hybrid powertrain configurations have various schemes and technological routes and are generally optimized based on accumulated technologies, policies, the market environment, and design requirements.

3. Comparison of and Optimization Methods for Hybrid Powertrain Configurations

3.1. Comparison of Hybrid Powertrain Configurations

The various hybrid powertrain configuration schemes for HEVs are different in terms of their fuel economy, acceleration performance, configuration complexity, and manufacturing cost. The advantages and disadvantages of various powertrain configurations were analyzed and compared in order to determine the optimal configuration scheme.

HEV configuration schemes and control strategies jointly affect key indicators of vehicles, such as their emissions, power, and economy. Therefore, in the comparison of the different configuration schemes, the influence of the control strategy on the working performance was generally excluded in order to determine the influence of the configuration schemes and realize the decoupling of strongly coupled nonlinear systems. The optimal performance of a hybrid system under various control strategies can be obtained through the comprehensive evaluation of fuel consumption, electric energy consumption, acceleration performance, and other parameters [12,14,19,20].

3.1.1. Comparison of Parallel P2 and Power-Split Hybrid Powertrain Configurations

The parallel P2 and power-split hybrid powertrain configurations employ similar working modes for the hybrid powertrain system. However, in these different modes, the power transmission paths are different due to the different configurations, thus resulting in differences in performance. As shown in Tables 2 and 3, the parallel PX configuration is the mainstream configuration for European and Korean HEVs, whereas single-mode and multi-mode power-split configurations are the mainstream configurations for Japanese Toyota and American GM HEVs. In recent years, previous studies have compared the performance indicators of parallel P2, single-mode, and multi-mode power-split hybrid powertrain configurations [21–24].

An optimal selection method for the PHEV powertrain configuration has been developed to compare the performances of several configurations, such as series, parallel P2, output power-split, and multi-mode power-split hybrid powertrain configurations, and the test results showed that the parallel P2 configuration, multi-mode power-split configuration, and output power-split configuration showed the best acceleration performance, the best electrical efficiency, and the best fuel economy, respectively [21]. The efficiency and acceleration performance of the single-mode and dual-mode power-split configurations were compared using the optimal operation points and the dual-mode power-split configuration showed the better performance. A new power-split configuration containing two motors with the same small size has been proposed to improve the fuel economy [22]. To compare the power consumption and fuel economy of the 2010 Toyota Prius (power-split configuration) and the 2011 Hyundai Sonata (parallel P2 configuration) under different driving conditions, a hybrid configuration performance-testing tool based on a full-vehicle computer simulator was developed, and the parallel P2 configuration performed better than the power-split configuration in both tests [23]. The fuel consumption of a new single-motor velocity-coupling HEV system (an engine, a set of planetary gears, a motor, and two clutches) has been compared with those of parallel P1 and P2 configurations [24]. Compared with the P1 configuration, the P2 configuration reduced fuel consumption by 6.68% and the velocity-coupling HEV system reduced fuel consumption by 13.82% [24].

In the power-split hybrid configuration, a continuously variable speed function is used. However, the multi-mode power split configuration, composed of dual motors, four clutches, and more than two sets of planetary gear mechanisms, has led to structural complexity and increased the difficulty of integration and control. In contrast, the single-mode power split configuration, using dual motors or a single motor with fewer planetary gear sets, has fewer components and a low cost, and it can achieve better comprehensive performance with a specific control strategy. The P2 hybrid configuration, equipped with the traditional six- to nine-speed transmission, has better acceleration performance and the lowest cost for reconstruction from traditional fuel vehicles, but this configuration has less improvement space correspondingly. In addition, due to the complex coupling effect between transmission, motor, and engine, the control process for switching the working mode is complicated and the dynamic control of the shifting process and the engine on/off system is complex, so it is difficult to realize smooth dynamic control.

3.1.2. Comparison of Series-Parallel and Power-Split Hybrid Powertrain Configurations

The series-parallel hybrid powertrain configuration, as a combination of series and parallel configurations, is also a research hotspot. Representative companies for the series-parallel hybrid powertrain configuration include Honda and BYD. In the series-parallel configuration, the complex planetary gear mechanism is not used for power splitting. Instead, the opening–closing control of the motor functions in cooperation with the engaging–disengaging control of the clutch so as to realize power transmission in the series-parallel configuration. Comparison of the performance of series-parallel and power-split hybrid powertrain configurations is a research hotspot [15,25,26].

Four configurations of hybrid powertrain systems have been compared, including the Toyota THS, the Opel Ampera architecture (power-split configuration with three clutches), the series-parallel electrical variable transmission (EVT) configuration, and the EVT configuration with two clutches. Among the four configurations, the Opel Ampera architecture had the best fuel economy, whereas the series-parallel EVT configuration had the best compactness [26]. The simple series-parallel EVT configuration had a lower fuel economy than the power-split configuration, but its structure was more compact, thus facilitating the design of the system parameters and space layout. In order to improve the fuel economy of the series-parallel configuration, a hybrid powertrain configuration equipped with a two-speed EVT gearbox based on the early EVT has been proposed [15]. Compared with the hybrid configuration equipped with single-speed EVT and the THS configuration, the series-parallel hybrid configuration equipped with two-speed EVT showed better fuel economy [15].

Compared with the power-split configuration, the series-parallel configuration has a much simpler structure, fewer gears and clutches, simpler control and integration, and lower cost. Although the fuel economy of the early series-parallel configuration is not as good as that of the power-split configuration, it can be improved by setting two to three speeds. In the future, more studies on the series-parallel hybrid powertrain configuration could focus on the technologies for the components of each subsystem, such as the boosting technology and thermal efficiency of engines or the high-voltage solutions and cooling method for motors.

3.1.3. Technological Routes of Hybrid Powertrain Configurations among Chinese Auto Manufacturers

In recent years, the proportion of HEVs in the Chinese auto market has significantly increased. Major domestic auto manufacturers have improved the economy and acceleration performance of HEVs, leading to a trend of rapid development in multiple configuration schemes.

A novel configuration based on traditional EVT achieved a more compact structure and better fuel economy by improving the design, increasing the speeds of the hybrid transmission, and developing the dedicated hybrid transmission (DHT) [27,28]. The auto manufacturers of Great Wall and Trumpchi adopted two-speed DHT and the auto manufacturers of Geely and Chery adopted three-speed DHT. The efficient working range of an engine can be extended to a wider range of working conditions through multi-speed transmission, so that the matching efficiency of the engine and motor is enhanced and the fuel economy and acceleration performance of the EVT can be improved. Therefore, the requirements for the working characteristics of the engine and motor can be reduced. For example, the Geely Raytheon DHT Pro with three-speed transmission was realized with dual motors and two sets of planetary gears. Although the Geely Raytheon DHT Pro also uses planetary gears for power transmission, it differs from the power-split configuration in the power-matching method and the fixed-axis Honda i-MMD configuration. Compared with the complex single-mode and multi-mode power-split configurations, Geely shows advantages in its configuration complexity and fuel economy, and its comprehensive performance is better than that of the Honda i-MMD system.

The various HEVs developed by BYD have gained a high market share in China. Similarly to the technological route used by Honda i-MMD, they are mainly driven by a motor with the aid of an engine. In 2021, the fourth generation of the dual-motor series-parallel DM-i super hybrid powertrain system was launched and applied in the BYD Song model. The configuration of the BYD DM-i is different from Geely's hybrid powertrain configuration. BYD only use a one-speed deceleration mechanism, which is characterized by low cost and fewer integration difficulties. However, in order to achieve electric driving with a wider range of operating conditions, BYD has gradually increased the motor power and battery capacity from the first-generation DM hybrid powertrain system to the fourth-generation DM-i hybrid powertrain system. The 1.5 L high-efficiency hybrid special engine was developed by BYD and achieved thermal efficiency of 43.04%, thus making the engine an efficient and energy-saving power component. Compared with the Honda i-MMD, the BYD DM-i employing a hybrid powertrain system with a simple configuration optimized each subsystem component with the most direct methods and improved the comprehensive performance.

3.2. Optimization Methods for Hybrid Powertrain Configurations

An innovative hybrid powertrain configuration can increase product competitiveness. In the development of a new hybrid system powertrain configuration, after excluding the various existing hybrid powertrain configuration schemes on the market, designers still face a large number of scheme options. The combinations of various power components, transmission components, clutches, brakes, and other components in the hybrid powertrain system may generate a large number of options. Therefore, the optimization method for hybrid powertrain configurations has been extensively explored in order to identify feasible configuration schemes and determine the optimal scheme according to performance requirements and market demands.

At present, a unified optimization method for hybrid powertrain configurations has not yet been formed. The graph theory method for dynamics modeling of the planetary gear system has been gradually applied for the entire power split hybrid power transmission system over recent years [29], and the exhaustion method and the hierarchical topological graph method [30] have been applied to optimize the configuration scheme. For example, a design method for a power split configuration has been proposed to analyze three hybrid systems developed by Toyota THS, GM AHS, and Timken that have the similar characteristics of seven members, ten joints, and four separated links, and then all the possible generalized kinematic chains and input and output positions under the constraints of the design conditions were determined [31]. The exhaustive search method has been used to generate a series of new possible configurations [31].

The graph theory method generates numerous configurations through the topological connections of the structural components, but the optimization algorithm for the configurations is based on the number domain. Searching and optimization for the hybrid powertrain configuration with the numerical optimization algorithm involved the transformation from the topological domain to the number domain. Then, the numerical optimization results could be transformed into the topological expression, in which a matrix was generally used to express the numerical information contained in the topological graph [32–36]. For example, the kinematic matrix was extracted to realize the transformation from a topological domain problem to a number domain problem in the bond graph models of single-mode and dual-mode power-split systems [33]. A hierarchical topological graph model and an adjacency matrix were constructed, and then new configurations were obtained with the optimal performance analysis algorithm [34–36].

3.3. Summary of Configuration Optimization Methods

The performances of the parallel P2 configuration, series-parallel configuration, and power-split configuration were compared and the technical routes used for hybrid powertrain systems in China were introduced. Optimization methods for hybrid powertrain configurations based on the graph theory and exhaustive search methods were discussed.

Single-mode and multi-mode power-split hybrid power systems have low fuel consumption and high driving efficiency, but their structures are complex, so integration of components and simplification of control strategies are significant in the design. The parallel P2 configuration shows poor fuel economy and adopts traditional six- to nine-speed transmission with a complex structure, thus leading to great difficulties in integration and control. The series-parallel configuration has good development prospects and multi-speed transmission has become an inevitable aspect of improving the fuel economy in the development of EVT. Two-speed or three-speed transmissions have the most potential. In addition, for the series-parallel configuration with a simpler structure and fewer components, the overall performance of the hybrid powertrain system can be enhanced by improving the performance of each component. Furthermore, the optimization method for hybrid powertrain configurations has become a difficult problem in recent years. The existing configuration optimization models and methods are suitable for specific configurations and design constraints and have poor universality, so it is difficult to realize high efficiency and accuracy in the solution algorithm. Configuration optimization algorithms are significant in the development of efficient and economical configurations.

4. Steady-State Energy Management Strategy for Hybrid Powertrain Systems

The optimization of the steady-state energy management strategy is important to improve the performance of hybrid powertrain systems. HEVs have several power sources, so it is important to match the working point and working range of each power source reasonably. The optimization methods for the steady-state energy management strategy are relatively mature. The current control strategies for hybrid systems are classified as the rule-based energy management strategy, optimization-based energy management strategy, and prediction model-based energy management strategy [9,37].

4.1. Rule-Based Energy Management Strategies

Rule-based energy management strategies are simple and they were widely adopted in the HEVs developed early on [38,39]. They are generally classified into two categories: deterministic rule-based energy management strategies and fuzzy rule-based energy management strategies.

In a deterministic rule-based energy management strategy, a deterministic SOC threshold is generally set based on engineering experience. In accordance with the charge and discharge methods of the batteries, the working states of an HEV can be classified into a charge-depleting (CD) mode and a charger-sustaining (CS) mode, and the corresponding control strategies are set for the CD or CS modes. Two control methods for the CD state have been proposed according to whether the engine enters the CD state to provide the driving force: the maximum depletion mode and the blended mode. Two control strategies for the CS state have been proposed according to the functional envelopes of the engine: the load-following strategy and the engine-optimal strategy [40]. The earlier deterministic rule-based control strategies applied in different configurations of HEVs were also different. The thermostat- and power-following strategy based on engine optimization [41] is a mature deterministic rule-based energy management strategy applied in series hybrid electric buses. The working range of the engine is optimized so as to avoid frequent changes in the rotational speed and realize better fuel economy. The motor-assisted control strategy [42] is a deterministic rule-based energy management strategy widely used in parallel hybrid electric vehicles. In the parallel configuration with the motor as the auxiliary power source, the working range of the engine is controlled within the optimal range and the torque is controlled according to the SOC value so as to ensure the power of the power battery [42].

Another rule-based control strategy is the fuzzy rule-based control strategy. Slightly different from the energy management strategy based on deterministic rules, fuzzy logic control has a high degree of freedom and nonlinearity and its control rules are formulated based on engineering experience. In recent years, the fuzzy rule-based control strategy has been extensively explored [38,43–45]. For example, a fuzzy control method based on the three variables of driver demand torque, vehicle speed, and battery SOC was established for a power-split vehicle and compared with the deterministic rule-based energy management strategy used in the Toyota Prius in order to verify the effectiveness and applicability of the fuzzy control strategy [43]. The fuzzy rule-based control strategy improved the fuel economy of the vehicle. In addition, the fuzzy rule-based control strategy had good robustness and was not sensitive to the changes influencing parameters, so some complex nonlinear systems with uncertainty could be analyzed. Compared to the deterministic rule-based control strategy, the fuzzy rule-based control strategy could improve the energy conversion efficiency [38,45].

As the most widely used control strategy, the rule-based energy management strategy can be easily applied in HEVs. The control strategy is simple and the comprehensive performance of vehicles, such as the fuel economy and emissions, can be greatly improved by reasonably setting and calibrating the parameters of the strategy. In contrast to the deterministic rule-based strategy, the fuzzy rule-based strategy is the mainstream strategy and can improve the energy conversion efficiency and robustness of control systems more significantly. However, the formulation of the operating points of the two rules is largely dependent on the individual experience of engineers, and it is impossible to achieve the optimal acquisition of system control parameters with the two rule-based strategies.

4.2. Optimization-Based Energy Management Strategy

The development of energy management strategies is essentially a mathematical optimization problem. The hybrid powertrain systems of HEVs are complex powertrain assemblies and involve multiple performance indicators, so optimizing one indicator may lead to a decline in other indicators [46]. Therefore, the optimization of the energy management strategy is often a multi-objective optimization problem that involves seeking a comprehensive balance among various performance indicators. It is necessary to reasonably determine the optimization objectives according to the characteristics of a product. In this way, coordination and cooperation between various components can be realized to improve the overall performance.

4.2.1. Energy Management Strategy Based on Global Optimization

The energy management strategy based on global optimization is a research hotspot. In this control strategy, with fuel economy and emissions as control objectives, the optimal control method for HEVs can be determined according to the determined driving cycle conditions with optimization algorithms: dynamic programming (DP), the convex optimization method, and Pontryagin's minimum principle (PMP). In the energy management strategy based on global optimization, the state variables and control variables of the system are selected and the optimization objectives are set in order to solve control variables with optimization algorithms. The global optimization algorithm can provide the optimal solution for the control process and plays an important role in the performance analysis and optimization of the hybrid powertrain system [46–50].

The DP algorithm has been used to realize the global optimal control strategy and undertake the fuel economy evaluation of different HEVs [46,47]. A convex optimization method has been used to optimize the energy management strategy for parallel HEVs and its calculation time was shorter than that of the DP algorithm [48]. PMP has also been used to optimize the energy management strategy for parallel HEVs and the performance indicators, including the output torque range of the engine, motor efficiency, and fuel economy, were greatly improved compared to the results obtained with the rule-based energy management strategy [49]. In applications of global optimization algorithms, several algorithms are combined together in order to improve the system performance. For example, a combined algorithm utilizing DP optimization and convex optimization has been proposed to evaluate the global optimal performance of the energy management strategy, and the evaluation results indicated that the proposed new optimization algorithm was better than the traditional DP algorithm [48]. An energy management strategy based on the combination of convex optimization and PMP has been developed and compared with the energy management strategy based on DP. Its analytical solution was close to that of DP algorithm, but its computation time was shorter than that of the DP algorithm. In general, the optimization method based on the DP algorithm is the most widely used optimization method for the energy management strategy. Compared with the DP algorithm, the optimization algorithm based on convex optimization and PMP has a shorter calculation time. Convex optimization does not introduce state variables or control variables [50] and can be combined with the DP algorithm. The PMP method is more easily implemented and more robust than the DP algorithm.

The energy management strategy based on global optimization plays an important role in the performance evaluation of hybrid power systems and can provide the basis for the comparison of hybrid powertrain configurations and the development of advanced algorithms [51]. However, it is based on certain driving cycles that are different from actual driving conditions. The optimization results obtained with this algorithm are rarely used in real-time vehicle control and the algorithm involves complex calculation and is not applicable in online real-time calculation. For the purpose of real-time control optimization, energy management strategies based on real-time optimization and predictive models have been extensively explored due to their application convenience.

4.2.2. Energy Management Strategy Based on Real-Time Optimization

The key to energy management strategies based on real-time optimization is the equivalent consumption minimization strategy (ECMS). At each instant, the fuel consumption and electric power consumption corresponding to the torque required by the driver (the combined torque output from the engine and the motor) are calculated. The calculated instantaneous engine fuel consumption and electric power consumption are expressed as the minimum value of the instantaneous equivalent fuel consumption. The combined output torque of the engine and motor corresponding to the minimum value is used as the working point of the powertrain system. The objective function of energy management strategies based on ECMS real-time optimization is the optimal value of each instant rather than the global optimum. The strategy is simple and its calculation speed can meet the requirements for working online.

The ECMS real-time optimization method is always combined with rules or other advanced optimization algorithms, such as the adaptive equivalent consumption minimization strategy (A-ECMS), to obtain a better control effect [52–54]. Some examples are provided below. A real-time optimal control method based on a standard convex quadratic programming (QP) problem and ECMS has been proposed to solve the nonlinear control problem in highly coupled hybrid powertrain systems and improved the calculation speed and efficiency of the controller [53]. A real-time control strategy based on the combination of the DP algorithm and ECMS has been proposed and the obtained simulation results for the real-time controller showed that the fuel consumption of the new energy management strategy was close to the optimal solution calculated with the DP algorithm [54].

However, the energy management strategy based on real-time optimization is affected by many uncertain factors in the real-time conversion process, which highlight several difficulties in the calculation of real-time optimization algorithms. The equivalent factor of the ECMS is considered to be one of the most challenging factors. In order to reduce the deviation between the battery SOC value and the equivalent fuel consumption in the conversion process, more multi-layer optimization methods have been applied [52,55]. For example, a two-level control strategy based on A-ECMS and adaptive dynamic programming (ADP) has been proposed for the instantaneous calculation of the equivalent factor in A-ECMS [52]. A double-layer multi-objective optimization method has been proposed to realize the minimum deviation and achieved lower energy consumption than the traditional ECMS control strategy [55].

4.3. Energy Management Strategy Based on Predictive Models

Energy management strategies based on predictive models, which are essentially methods of model predictive control (MPC), have also become a research hotspot in recent years. The predictive model of objective functions with different weights, such as emissions and fuel consumption, can be established with predicted key parameters, such as driving speed. Then, the predictive model is combined with rules or optimization algorithms to obtain the energy management strategy, which can improve the fuel economy and reduce emissions [56]. The battery SOC rules for the rule-based energy management strategy are formulated based on engineering experience, whereas the battery SOC for the energy management strategy based on real-time optimization is predetermined in the offline state. The predictive model can provide the dynamic reference value for the battery SOC online. Studies on energy management strategies based on predictive models mainly focus on predictive control of driving condition recognition and drivers' intention recognition.

The uncertainty of actual driving conditions increases the difficulty of developing energy management strategies. Due to the development of intelligent transportation networks, the recognition method for driving conditions has developed rapidly in recent years. Working conditions can be inferred from the driving conditions in the past period or directly obtained with the GPS and other means to adjust battery power and formulate energy management strategies, helping to adapt vehicles to driving conditions [57–59]. Some examples of control methods based on driving conditions are introduced below. The optimal solution for the energy management strategy under future driving conditions was calculated with the DP algorithm to update control rules and an optimized controller based on future operating conditions was then developed [57]. An adaptive control strategy combined with the adaptive neuro-fuzzy inference system (ANFIS) and ECMS was developed based on consideration of the conventional driving routes of urban buses to improve the fuel economy of buses [58]. A new real-time energy management control strategy combined with ANFIS and MPC was developed based on short-term future driving conditions to provide the reference value for the battery SOC in real time, and 93% to 97% of the data were consistent with the results obtained with the DP algorithm [59].

In a traditional method, the recognition of drivers' intentions depends on the information from the accelerator pedal [60]. At present, the recognition of driving intention is mostly based on the speed and acceleration of vehicles. Intelligent recognition methods have been proposed based on machine learning and neural networks, with the neural network trained with sample data to accurately identify driving intention and solve the problems related to HEVs [61–63]. Several application examples of intelligent recognition methods are introduced below. An HEV control method has been proposed based on supervised machine learning combined with PMP that can formulate an optimal control strategy according to drivers' specific driving intentions [62]. The developed controller was retrained automatically and performed better in new driving cycles [62]. An online vehicle speed prediction method has been proposed based on speed limitations, road curvature, traffic and road signs, and other signals, and the predicted speed signals were used in the training for the solution with the Pegasus algorithm [63]. The testing results showed that the fuel economy and emissions performance of the control strategy based on this speed prediction method were better than those obtained with the SOC-feedback A-ECMS [63].

For the energy management strategy based on the predictive model, the accuracy of the nonlinear model can improve the performance of the system controller, but it often reduces the real-time control performance. Fast algorithms can be developed based on

MPC [64] to improve real-time control capabilities. An MPC bi-level methodology based on urban driving conditions was proposed and applied in a seven-speed parallel HEV that ultimately improved the energy efficiency and computational speed of the control system [65]. A predictive energy management controller was developed with a nonlinear model based on consideration of short-term load prediction and cycle detection, and it reduced fuel consumption without compromising power performance [66]. A nonlinear-control predictive model was developed based on the control-relevant parameter estimation method, and the simulation results of hardware-in-the-loop (HIL) simulation showed that the proposed new controller performed better than the MPC controller, reduced fuel consumption, and improved the operating speed and real-time operation capability significantly [67].

4.4. Summary of Energy Management Strategies

Various energy management strategies for HEVs have been explored in recent years. Energy management strategies are an effective means to improve the fuel economy and emissions performance of HEVs. Most of the current mainstream HEVs adopt rule-based energy management strategies, which are simple and easily implemented, but these strategies also rely too much on engineering experience. Due to the development of automobile intelligence and the transportation network, more optimization algorithms are being used to realize online control and intelligent control, thus raising the requirements for the computing capability of the control system. The performances of different strategies are summarized in Table 4. It is worth noting that various energy management strategies are not independent of each other. A new strategy is generally a supplementary and optimized version of traditional strategies obtained through the combination of multiple strategies and the introduction of a more easily applicable intelligence strategy.

Table 4. Summary of energy management strategies.

Strategy	Algorithm	Calculation Work	Real-Time Ability	Performance
Rule-based	Deterministic rules	●	●●●●●	●
	Fuzzy rules	●	●●●●●	●
Global optimization	DP	●●●●●	●	●●●●●
	Convex optimization	●●●	●●●	●●●●●
	PMP	●●●	●●●	●●●●●
Real-time optimization	ECMS	●●●	●●●●●	●●●
	A-ECMS	●●●	●●●●●	●●●●●
Predictive-based	MPC with rules/optimization methods	●●●	●●●	●●●●●

5. Dynamic Coordinated Control Strategies for Hybrid Powertrain Systems

The dynamic control process for HEVs mainly involves the shifting of transmission, the engine on/off process, switching working modes, etc. A good dynamic coordinated control strategy is one of the key technologies for improving the dynamic performance of HEVs. If the dynamic process is not controlled properly, it may cause power interruptions or torque ripples in the transmission system, insufficient power, and excessive impacts. At present, a complete and unified evaluation standard for the dynamic quality of HEVs has not yet been formed and evaluation is usually performed based on consideration of the response capability, robustness, and comfort performance of the dynamic process.

5.1. Torque Coordination Control Strategies for Mode Switching

In the steady-state energy management strategy, only the torque distribution among the power sources is considered, while the rotational inertia of each component and the response speed of the component to a control signal are not considered. During the process of mode switching, due to the different dynamic characteristics of the engine and motor, if each component is only controlled according to the target torque, the control result may involve a large deviation from the required torque. In order to ensure a smooth mode-switching process and rapid response, it is necessary to analyze the process of dynamic implementation of control signals and determine the influence of the torque switching and transmission process on the evaluation indicators before establishing the system torque coordination control strategy [68].

The energy management strategy involving torque coordination control performs better than the rule-based control strategy in the mode-switching process, and the dynamic coordinated control strategy improves the fuel economy and makes the dynamic process of mode switching smoother and the torque ripple slighter [69]. In addition, torque coordination control methods for different mode-switching processes have been studied. Two torque coordination methods have been proposed [70]. In the first method, the change rates for the pressing force of the clutch and the braking force of the engine are controlled for torque coordination. In the second method, torque coordination is realized by changing the target braking torque in real time and making the motor participate in active coordinated control [70]. Application examples of dynamic control strategies are provided below. An impact prediction model based on a dynamic model of the power-split HEV system has been proposed to realize a torque coordination control strategy that could be adapted to a complex driving cycle and improve the smooth dynamic process of the system [71]. A nonlinear model of the mode-switching process in a series-parallel HEV has been established based on consideration of the engagement and disengagement process for the clutch to predict and verify the instability boundary during the mode-switching process and guide the mode-switching process [72].

However, the model-based torque coordination control strategy depends on the accuracy of the system model. The transmission system is a complex nonlinear system, so it is difficult to establish an accurate model that takes into account the dynamic response characteristics of nonlinear components, such as clutches. Therefore, intelligent torque estimation models, such as the fitting method [73], fuzzy logic [74], and neural networks [75], have been used to formulate the control strategies for the mode-switching process. Several application examples of dynamic control strategies based on intelligent torque estimation models are listed below. A sliding mode control method has been proposed based on disturbance compensation and the control strategy of the mode-switching process was formulated [76]. A torque coordination control strategy was formulated based on a data-driven predictive control model [77]. The established predictive model only depended on the measured input–output data, and the simulation results showed that this strategy could reduce the impact and clutch friction loss in the mode-switching process significantly [77]. A BP-smith predictive controller based on a composite torque coordination control strategy has been proposed to solve the problem of torque fluctuation at the output end [78]. The composite torque coordination control strategy solved the problem that affected the implementation of the mode-switching process strategy in the non-ideal communication network state [78].

5.2. Other Dynamic Control Strategies

Engine on/off control is also a key dynamic control technology, especially for parallel configurations, in which a clutch is used to assist in starting the engine so as to improve fuel economy [79]. Engine on/off control strategies have been extensively explored [80–83]. In order to realize the fast start of engines under specified operating conditions, a dynamic coordinated control strategy for engine starting with a single-motor parallel P2 configuration was studied, and a combined start strategy was proposed [80,81]. When the SOC was lower than the limit value, a soft start strategy was adopted. When the motor torque was insufficient, a dynamic engine start strategy was adopted. The combined control strategy could improve the dynamic process of engine starting [80,81]. An engine start control strategy for HEVs with a belt-driven generator was studied and a model-based control method adopted to ensure the fast and smooth starting of the engine [82]. A coordinated clutch slip control method was developed for the disconnect clutch in the P2 configuration that reduced the driveline oscillation of the coordinated clutch and improved the comfort performance of the power transmission significantly [83].

As mentioned above, the parallel hybrid powertrain configuration is often equipped with traditional AT, AMT, and CVT transmissions [84]. The series-parallel hybrid powertrain configuration adopted by Geely and other manufacturers was also equipped with a multi-speed DHT. Therefore, dynamic control of the shifting process has also become one of the key technologies for the control strategy for hybrid powertrain systems [85,86], and several optimization algorithms, such as the genomic algorithm and particle swarm optimization [87,88], are used to optimize the dynamic process of shifting. A shift controller based on the triple-step nonlinear method has been developed for a hybrid powertrain system equipped with an AMT transmission and the engine compensated for the power loss during the shift process so as to ensure the stability and smoothness of the shift process [85]. The shifting control process in the 3DHT of a P1/P3 series-parallel configuration has been studied [86]. A finite-time linear quadratic regulator (LQR) was developed to achieve torque transmission smoothly, and a predictive sliding mode control (SMC) model was established to ensure the stable engagement of the clutch [86]. An optimal strategy for gear-shifting in HEVs was proposed with the dynamic particle swarm optimization algorithm and the results showed that the strategy reduced energy consumption significantly [88].

5.3. Summary of Dynamic Coordinated Control Strategies

In recent years, dynamic control strategies, such as torque coordination of mode switching and the engine on/off process, have developed rapidly and been successfully applied in various HEVs. However, in order to enhance the control quality of the dynamic process of hybrid powertrain systems, dynamic control strategies must be further improved. Compared with steady-state energy management strategies, dynamic control strategies have seldom been explored, and the related research results obtained were mainly reported in recent years. With regard to dynamic control strategies, more researchers have focused on the different structures and components of hybrid powertrain systems. Dynamic control strategies are formulated based on the dynamic characteristics of each structure or component and can improve the control quality of the dynamic process of the system and ensure the stability and smoothness of the driving process in vehicles. Based on the actual working conditions of vehicles, various control methods can be combined together to achieve strong adaptability and high robustness in the field of dynamic control systems.

6. Conclusions

This paper summarized the configurations and control strategies for hybrid powertrain systems, including the main types and characteristics, representative configuration schemes, and optimization methods for hybrid powertrain configurations, as well as the types and applications for steady-state energy management strategies and dynamic coordinated control strategies.

Through a comparative analysis of hybrid powertrain configurations, the technical characteristics of several mainstream configurations, such as parallel, series-parallel, single-mode, and multi-mode power-split configurations, were clarified. Future development directions for different configurations in HEVs were proposed.

At present, a universal configuration optimization method has not been established. Configuration optimization methods are based on graph theory, and solution algorithms based on the number domain have developed rapidly in recent years.

Among the control strategies for hybrid powertrain systems, steady-state energy management strategies are more mature than dynamic control strategies. Due to the improvements in the completeness and complexity of control strategies, the control effect can be significantly improved. Newly developed control algorithms show trends of higher complexity and better real-time performance and intelligence, but the higher complexity also increases the difficulty of engineering development. Therefore, it is necessary to produce reasonable configuration designs and optimizations according to actual demands so as to avoid excess performance.

In summary, in order to develop a hybrid powertrain system with excellent comprehensive performance, multiple design objectives, such as cost, fuel economy, acceleration, emissions, and control robustness, should be jointly considered. Through the optimization of the design of the hybrid configuration and improvements in static and dynamic control strategies, a high-performance system can be finally developed. This paper provides an informative basis and technical support for the design and optimization of hybrid powertrain systems.

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