

Article

Torque Coordination Control of Hybrid Electric Vehicles Based on Hybrid Dynamical System Theory

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Abstract: In order to reduce the vibration caused by mode switching of hybrid electric vehicles (HEVs) and achieve smooth mode switching, the hybrid input and output automation (HIOA) model of power control system of a parallel HEV is established based on the theory of hybrid dynamical system (HDS). Taking the switching from electric drive mode to hybrid drive mode for example, the torque coordination control is considered, and the performance is compared with the method without the torque coordination by using a rule-based control strategy. The simulation results in AVL Cruise show that, on the premise of ensuring the fuel economy and the emission, the mode switching process becomes smoother with smaller torque fluctuation and better driving comfort by considering the torque coordination.

Keywords: hybrid electric vehicle; hybrid dynamical system; mode switching; torque coordination control

1. Introduction

Hybrid electric vehicles (HEVs) combine the advantages of both traditional fuel vehicles and battery electric vehicles (BEVs), which include two or more energy sources and can work in coordination [1–3]. Under the current technical level and application conditions, HEVs are undoubtedly the most industrialized and market-oriented vehicle in the electric vehicle (EV) category, as a transitional product from traditional fuel vehicles to BEVs. The power system of HEVs consists of components such as the engine, electric motor, power battery and transmission. By controlling the combination of the clutch and the state of the transmission, the vehicle can be operated in different working modes, such as electric drive mode, hybrid drive mode, engine drive mode, and regenerative braking mode, etc.

Due to the complex structure of HEVs, the optimal energy distribution and control between the two or more energy sources are extremely challenging [1–3]. How to design an efficient energy management strategy (EMS) is one of the research hotspots in the field of vehicle control for HEVs. At present, research scholars have different concerns about EMSs of HEVs, including the optimal control of vehicle comprehensive cost [4], the effects of road information on energy consumption [5], the minimum fuel consumption [6], the regenerative braking energy recovery [7], and drivability and comfort [8,9], and so on. In order to fully utilize the potential of energy saving and emission reduction of HEVs, it is necessary to properly control the switching between multiple modes in the energy source distribution process to optimize its performance of fuel economy, emission and drivability.

Hybrid dynamical systems (HDSs) consist of discrete event dynamical subsystems (DEDSs) and continuous variable dynamical subsystems (CVDSs), and the interaction between them. For the control system of electric vehicles, the dynamical characteristics of HEVs in each specific operating mode can

be described by a CVDS, and the switching between different working modes can be seen as caused by a DEDS, and its multi-energy source control is a typical control issue of HDSs. Aiming at the hybrid dynamical characteristics of multi-energy source control, many scholars have studied the EMS of HEVs based on the HDS theory. It should be pointed out that the switching dynamic systems is also one of the representative HDSs, which is composed of several continuous time subsystems, discrete time subsystems, and the switching signal among them.

Yin A. et al. used the HDS theory to describe the hybrid power system of a hybrid electric bus, and designed a rule-based multi-energy control strategy, and verified the feasibility and effectiveness of the strategy [10]. Zhu Y. et al. proposed a four-step design method for the dynamical system of HEVs with planetary gears. The HDS theory was used to describe the hybrid system of the vehicle, and then the optimal power distribution and switching rules of optimal working mode were obtained to establish a real-time EMS [11]. Li W. et al. described the hybrid system of HEVs with hybrid input and output automaton (HIOA) model, and obtained the optimal switching sequence of multi-energy source power optimal allocation and working mode to realize the performance optimization of the vehicle [12]. Koprubasi K. et al. studied a hybrid control method based on HDSs, and divided the operating state space of HEVs, and designed controllers for each subspace to achieve smooth switching between different drive modes [13,14]. Banvait H. et al. described the dynamical system of the plug-in HEV by the HDS theory, and minimize energy consumption as a constrained optimization problem; finally, the dynamical planning algorithm was used to minimize energy consumption [15]. Song S. et al. intuitively described the regenerative braking system based on the HDS theory, and proposed a regenerative braking control strategy for coordinated control of the regenerative braking force of motor and the hydraulic braking force of front and rear wheels, and improved the recovery rate of vehicle braking energy [16].

The above research has achieved good results in achieving multi-energy source control, but the effects of the torque coordination process on the mode switching process are not or rarely considered during mode switching among different drive modes. However, if the mode switching process is not well controlled, the vibration of the drive train will occur, which will inevitably have a seriously negative effect on the driving performance such as the vehicle's power, driving and comfort. In addition, this is more likely to determine the willingness of consumers to purchase than fuel economy. Although the vibration caused by the mode switching can actually be attenuated by mechanical vibration, it will still affect the comprehensive performance of the vehicle: vibration and noise will cause the NVH performance of the vehicle to become worse. Therefore, if the vibration caused by the mode switching can be eliminated at the source by a targeted control method, the overall benefit will be better. Therefore, the significance of dynamical performance optimization has become increasingly prominent during the switching mode of HEVs, and it has quickly attracted the attention of various research and design institutions.

The research ideas and arrangement of the rest of the paper are as follows. In Section 2, the HDS of HEVs is described based on the HDS theory. According to the characteristics of energy control system of HEVs, the relatively independent DEDSs and CVDSs are considered comprehensively, and the HIOA model is constructed. The interaction between DEDSs and CVDSs is studied, which provides a method and means for performance analysis of hybrid vehicles. In Section 3, the methods with and without the torque coordination process are adopted in the mode switching control, respectively. In Section 4, the simulation comparisons were made by using co-simulation of AVL Cruise and Matlab. The results show that the control considering the torque coordination has better suppression of the disturbance generated during the mode switching and improves the drivability of the vehicle, followed by the conclusion in Section 5.

2. Description of the HEV Power System

2.1. Hybrid Dynamical System Theory

The HDS had a strong engineering background when it was proposed, and is essentially a product of the penetration of digital control technologies such as modern computers into continuous manufacturing and continuous processing systems. At present, there are many models of HDS, such as the hybrid automata model, the hybrid Petri net model, etc. [17,18].

Hybrid automata is a formal model of a hybrid dynamical system. It has the intuitive and verifiable features of discrete and continuous hybrid characterization. In order to facilitate the design and synthesis of the controller, both the control object and the controller are regarded as a structure with input and output structure, that is, a hybrid automaton model with an input and output structure is called the hybrid input and output automaton (HIOA) model [18], and it is defined as follows:

$$H = (Q, X, U, Y, Init, f, Inv, E, R, \phi) \quad (1)$$

$$Q = \{q_1, q_2, \dots, q_m\} \quad (2)$$

$$X = R^n \quad (3)$$

$$U = U_D \cup U_C \quad (4)$$

$$Y = Y_D \cup Y_C \quad (5)$$

$$Init \subseteq Q \times X \quad (6)$$

$$f : Q \times X \times U \rightarrow R^n \quad (7)$$

$$Inv : Q \rightarrow \wp(X \times U) \quad (8)$$

$$E \subseteq Q \times Q \quad (9)$$

$$R : E \times X \times U \rightarrow \wp(X) \quad (10)$$

where Q is a set of finite discrete state variables, describing the discrete state of the system; X is a set of continuous state variables, describing the continuous state of the system; U is a set of input variables, which may be continuous or discrete, in which U_D represents discrete inputs, and U_C represents continuous input; Y is a set of output variable, which can be continuous or discrete, in which Y_D represents discrete output, and Y_C represents continuous output; $Init$ is a set of initial state; f is the differential or difference equation for state variables and input variable; Inv is discrete state $q \in Q$ specified the invariant set related to X and U ; E is the set of discrete events between discrete states of the system; R is the reset relationship of the independent variables $e \in E$, $x \in X$, and $u \in U$, which describes the continuous state of the instantaneous system after the discrete transition, and ϕ specifies an allowable input domain for each (q, x) .

Compared with the traditional automata model, the HIOA model overcomes the shortcomings of the complex and hard-to-describe relationship of the input and output variables, and is more suitable for the application of the control system.

2.2. Description of Hybrid Power System Based on HDS Theory

The powertrain of HEVs has different operation modes, which represent the different states of the vehicle. The driver's acceleration/deceleration and clutch engagement can be seen as a series of discrete events that enable the hybrid control system of HEVs to switch between different drive modes, such as from electric drive mode to hybrid drive mode, and in a particular mode, the hybrid control system can be viewed as a CVDS. Therefore, the entire dynamical control system of the HEV has both dynamical system features of discrete events and continuous variables, which can be considered as a

hybrid system. Therefore, this paper introduces a finite state HIOA model to establish a mathematical model of the power control system of HEVs [10–12]:

$$H_{hev} = (Q, X, U, Y, Init, f, Inv, E, R, \phi) \quad (11)$$

where H_{hev} is the power control system of HEVs.

When the mode of HEVs is switched from the electric drive mode to the hybrid drive mode, the transient response characteristics of the engine and the motor are different, and the torque transmitted by the clutch is discontinuous. Therefore, if the control method is not proper, the sudden change in the output torque of the power system will cause the vehicle to generate a large longitudinal jerk, which deteriorates the driving comfort of the vehicle. Therefore, controlling the seamless switching is critical to improving the driving performance of a HEV. This paper assumes that the vehicle operates in electric drive mode after starting, considering the switching process between electric drive mode, hybrid drive mode and engine drive mode, and mainly focuses on the torque coordination process during the switching from electric drive mode to the hybrid drive mode. According to the above description, the states of the power control system of the HEV are divided into five states: $q = \{q_1, q_2, q_3, q_4, q_5\} \in Q$, where q_1, q_2, q_3, q_4, q_5 indicate the electric drive state, the engine starting state, the torque coordination state, the hybrid driving state, and the engine driving state, respectively. The states of the respective operating modes are shown in Table 1, and the switching relationship between these different modes are shown in Figure 1. As can be seen from Figure 1, the five different operating modes $\{q_1, q_2, q_3, q_4, q_5\}$ correspond to different operating states of the engine, motor and clutch; and there are eight switching states $\{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8\}$ between the five operating modes.

Table 1. States of the operating mode.

Working State	Engine	Clutch	Motor	Description
electric drive	off	separation	work	motor drives vehicle separately
engine start	work	separation	work	motor drives vehicle separately and the engine starts
torque coordination	work	sliding friction	work	motor and engine jointly drive the vehicle, and clutch is in sliding friction
hybrid drive	work	combined	work	motor and engine jointly drive the vehicle, and clutch is fully integrated
engine drive	work	combined	off	engine drives vehicle separately

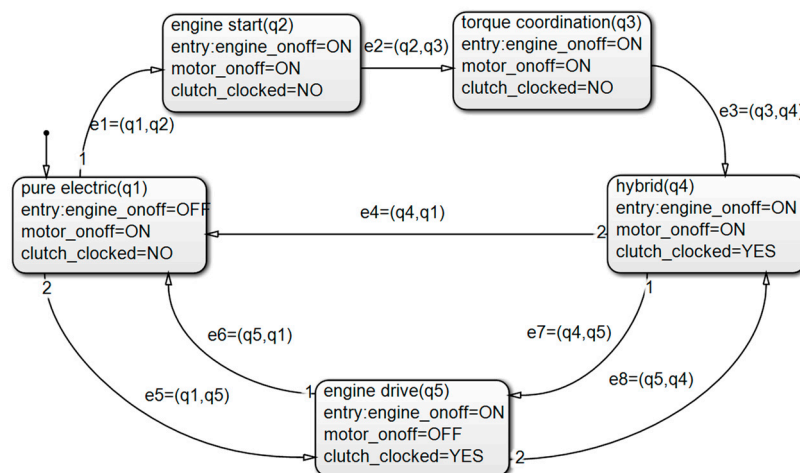


Figure 1. Working mode switching of hybrid power system.

Continuous state variables $x = \{\omega_e, \omega_m\} \in X$, which represents engine speed and motor speed, respectively. The set of input variables includes a continuous variable set and a discrete variable

set, wherein the continuous input variables $u_c = \{T_e, T_m\} \in U_C$ are engine torque and motor torque, respectively; and $u_d = \{u_1\} \in U_D$ is the discrete input variables, in which u_1 represent clutch engagement states (YES/NO). The output variable set includes a continuous output variable set and a discrete output variable set, wherein the continuous output variables $y_c = \{v, SOC, \omega_e, \omega_m\} \in Y_C$ are the vehicle velocity, the state of charge of the battery, the engine speed and the motor speed, and the discrete output variable $y_d = \{hybrid|yes : no\} \in Y_D$, indicating whether the vehicle is running in the hybrid drive state. $Init \subseteq Q \times X$ is the initial state of the system, and $Init = \{q_0, x_0\}$ is the starting set for the control system. $f : Q \times X \times U \rightarrow R^n$ is the differential or difference equation for state variables and input variables, related to the current discrete state, continuous variable state, and input variables. For each discrete state $q \in Q$, the invariant set associated with x and u in the current discrete state is specified by $Inv : Q \rightarrow 2^{X \times U}$. For a HEV, it is equivalent to defining constraints on continuous state variables and input variables in each discrete state. For the hybrid system of a HEV, the corresponding invariant set is shown as follows.

$$Inv(q) \rightarrow \begin{cases} \omega_e = 0, \omega_m < \omega_{mmax}, u_1 = Clutch_NO \mapsto q = q_1 \\ \omega_e = \omega_{idle}, \omega_m < \omega_{mmax}, u_1 = Clutch_NO \mapsto q = q_2 \\ \omega_e < \omega_{emax}, \omega_m < \omega_{mmax}, u_1 = Clutch_NO \mapsto q = q_3 \\ \omega_e < \omega_{emax}, \omega_m < \omega_{mmax}, u_1 = Clutch_YES \mapsto q = q_4 \\ \omega_e < \omega_{emax}, \omega_m = 0, u_1 = Clutch_YES \mapsto q = q_5 \end{cases} \quad (12)$$

$E \subset Q \times Q$ is a set of discrete events corresponding to each discrete state. Of course, it is not possible to switch between any two states. For each $e = (q, q') \in E$, the discrete events in this paper are shown as $\{e_1, e_2, e_3, e_4, e_5, e_6, e_7, e_8\}$ in Figure 1. $R : E \times X \times U \rightarrow 2^X$, for discrete events $e = (q, q') \in E$, and $x \in X$, and $u \in U$, formulate the default value after state switching of the continuous state variables x , also known as mutation function. $\Phi : Q \times X \rightarrow 2^U$, an allowable input field is specified for each state, that is, an input scope is defined. Under each operating state of the HEV, the current maximum working capacity limit and the physical limitations that exist impose constraints on the input variables. For a real system of HEV, the input T_e and T_m are limited by the power battery, the motor, the generator, and the engine, so they have a range of allowable values. And the permissible input is the input corresponding to this tolerance [19].

3. Energy Management Strategy of HEV Based on Hybrid System Theory

From the perspective of theoretical research, the core of EMS of HEVs is the working mode selection problem and power allocation control problem of the power system of HEVs. The difficulty lies in how to find a feasible algorithm or method to realize the coordination of the sub-components of HEVs and the optimal allocation of energy. It can be seen from the above analysis that the core of the control strategy of the multi-energy source power control system of a HEV with hybrid system characteristics is how to obtain the optimal control input U and the discrete events of state switching E , so that the control effect of the hybrid system is the most excellent.

The structure of the HEV power system is complex and diverse. In order to achieve different control requirements, different control strategies are needed for control. At present, the best fuel economy, lowest emissions, lowest drive system cost and best drive performance are often used as control targets. The goal of energy management strategy for parallel hybrid vehicles is to achieve smooth switching between operating modes under the premise of ensuring fuel economy and emissions, and to obtain better driving performance, that is, to optimize the overall efficiency of HEVs.

3.1. EMS of HEV without Considering Torque Coordination

The rule-based energy management strategy has the advantages of simple and efficiency, minor calculation, and strong practicability. This paper uses this strategy to make the energy of a parallel HEV meet the optimal allocation. The core of the strategy is described as follows, and the corresponding control logic rules are shown in Table 2.

- (1) When the demand torque of the HEV is small and the state of charge (SOC) of the battery is high, the engine is turned off, and the electric drive mode is adopted;
- (2) When the SOC of the battery is too low or the demand torque is large, the engine is started, and the engine driving mode or the hybrid driving mode is adopted. According to the output torque of the motor and engine in Table 2, the motor operates in the maximum torque to use the electrical energy as much as possible, and the remaining demand torque is provided by the engine when the hybrid driving mode is adopted in the case of high-speed driving, acceleration and climbing. It is easy to understand that when the SOC is too low, in order to prevent the battery from being over-discharged, sometimes the vehicle is driven only by the engine, and the battery operates in the SOC maintenance mode.
- (3) When the SOC of the battery is low, the battery pack needs to meet the instantaneous input power requirement to achieve the regenerative braking.

Table 2. Control logic rules based on determining rules *.

$T/\text{State of Charge (SOC)}$	$\text{SOC} < \text{SOC}_{\min}$	$\text{SOC}_{\min} \leq \text{SOC} \leq \text{SOC}_{\max}$	$\text{SOC} > \text{SOC}_{\max}$
$0 < T_r \leq T_{m\max}$	$T_m = 0$ $T_e = T_r$	$T_m = T_r$ $T_e = 0$	$T_m = T_r$ $T_e = 0$
$T_r > T_{m\max}$	$T_m = 0$ $T_e = T_r$	$T_m = T_{m\max}$ $T_e = T_r - T_{m\max}$	$T_m = T_{m\max}$ $T_e = T_r - T_{m\max}$

* T_r is the vehicle demand torque of the hybrid electric vehicle (HEV); T_m is the output torque of motor; T_e is the output torque of engine; $T_{m\max}$ is the maximum instantaneous output torque of motor; SOC_{\min} and SOC_{\max} indicate the setting lower and upper limit value of the SOC of power battery, respectively.

According to the logic rules in Table 2, the switching process of the operation states of the HEV in control strategy is as shown in Figure 2. The corresponding switching conditions are shown in Table 3.

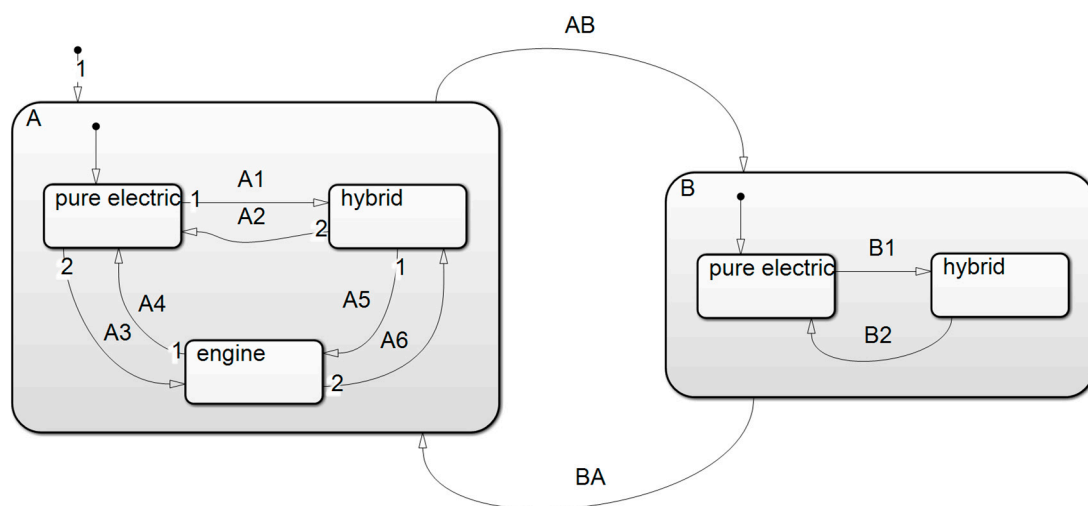


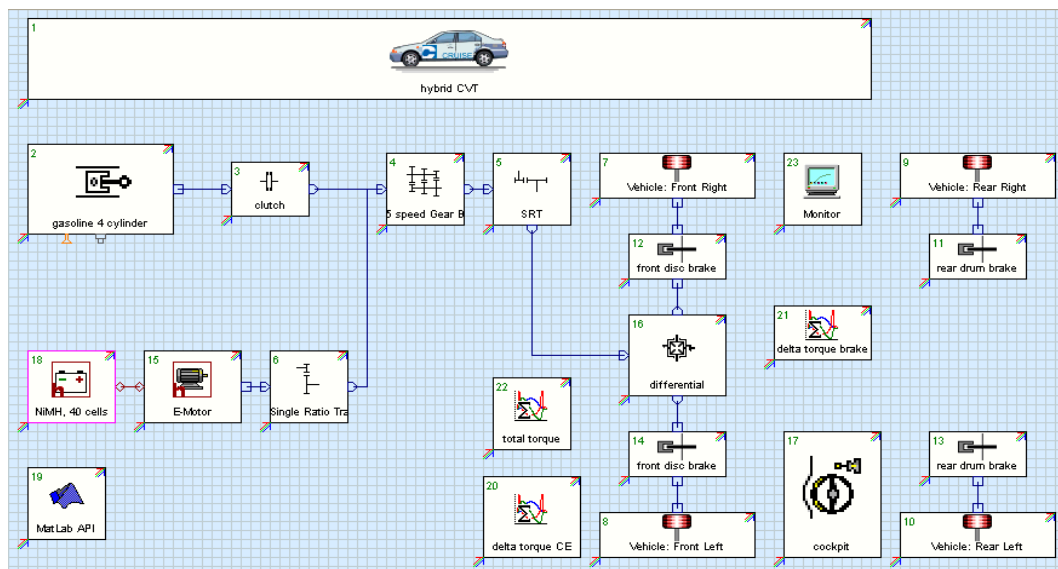
Figure 2. The state switching of the rule-based control strategy of the hybrid electric vehicle (HEV) without torque coordination.

In AVL Cruise, the vehicle model of the parallel HEV is built. AVL Cruise is a flexible vehicle driveline simulation solution, supporting a wide range of applications, including the analysis of the powertrain concept in the office environment as well as real time applications [7]. With this simulation software, we can accurately and reliably predict the energy management of a vehicle concept. Find the best balance between efficiency, emissions, performance and drive quality [20,21].

Table 3. The operating state and switching conditions of the rule-based control strategy without the torque coordination.

Code	Starting State	Switching Condition	Final State
AB	A ($SOC \leq SOC_{max}$)	$T_r > 0, SOC > SOC_{max}$	B ($SOC > SOC_{max}$)
B1	electric drive	$T_r > T_{mmax}$	hybrid drive
B2	hybrid drive	$T_r \leq T_{mmax}$	electric drive
BA	B ($SOC > SOC_{max}$)	$T_r > 0, SOC \leq SOC_{max}$	A ($SOC \leq SOC_{max}$)
A1	electric drive	$T_r > T_{mmax}, SOC > SOC_{min}$	hybrid drive
A2	hybrid drive	$T_r \leq T_{mmax}, SOC > SOC_{min}$	electric drive
A3	electric drive	$SOC < SOC_{min}$	engine drive
A4	engine drive	$T_r \leq T_{mmax}, SOC > SOC_{min}$	electric drive
A5	hybrid drive	$SOC < SOC_{min}$	engine drive
A6	engine drive	$T_r > T_{mmax}, SOC > SOC_{min}$	hybrid drive

As shown in Figure 3, according to the configuration, the parallel hybrid drive system structure is a torque-coupled and single-shaft hybrid drive system with the transmission behind the motor (E-motor). The torque and speed transmitted by the engine (Gasoline 4 cylinder) and the motor to the drive axle are adjusted by the gearbox (5 speed Gear Box), thus, the engine and the motor must have the same speed range. At the same time, the motor plays multiple functions such as driving the vehicle, starting the engine, and generating the regenerative braking power. The models of motors, engines, and power batteries (NiMH, 40 cells) in AVL Cruise are mainly based on the look-up table method, for the computational efficiency can be greatly improved by this method. In practice, the characteristic curves of these components can be obtained through experiments, and then modeled in the vehicle model by look-up table method in AVL Cruise. The transmission system of the HEV is mainly composed of a clutch, two single ratio transmissions (SRTs), a differential, and a 5-speed gearbox. Co-simulation of the control strategy in Matlab and the vehicle model in AVL Cruise is realized through the MATLAB API interface.

**Figure 3.** The vehicle model built in AVL Cruise.

The control strategy is established in the Matlab/Simulink, and the mode switching process is simulated. Among them, the power battery in the model uses a nickel-hydrogen battery. Considering the service life of the power battery, the value range of the SOC of the HEV power battery pack is set to [0.3, 0.8], that is $SOC_{min} = 0.3$, $SOC_{max} = 0.8$. The T_{mmax} in the control variable is related to the speed and power of the motor. The size of T_{mmax} is determined according to the external characteristic curve

of the motor in the model. When the vehicle is running at low velocity, the motor works in the constant torque zone, $T_{m\max}$ is large and maintains; at high velocity, the motor works in the constant power zone, and $T_{m\max}$ decreases as the speed of motor increases.

In the design of the control strategy, we first ensure that the motor runs at maximum torque, and then, if the motor cannot meet the demand torque or $SOC < SOC_{\min}$, the engine works. This minimizes engine operation and improves fuel economy and emissions. The simulation results in AVL Cruise are presented in Section 4 along with the results of the control method.

As the improvement of specific indicators such as fuel economy and fuel consumption of HEV are not paid much attention in this paper, in fact, the optimization of driving performance during the switching process of HEV driving mode is more concerned. Therefore, the specific parameters of battery, motor and engine, etc. of the HEV model in AVL Cruise are not given any more for the simplicity of the article.

3.2. EMS of HEV Considering Torque Coordination

In this section, the above control method is improved, and the torque coordination process is considered in the pure electric drive mode to hybrid drive mode.

According to the control logic rules in Table 2, the torque coordination process is added in the operation state switching in the control strategy of the HEV, as shown in Figure 4. The corresponding switching conditions are shown in Table 4. Compared with the control process without considering torque coordination shown in Figure 2, the proposed method in this paper adds the two processes of engine starting and torque coordinated control.

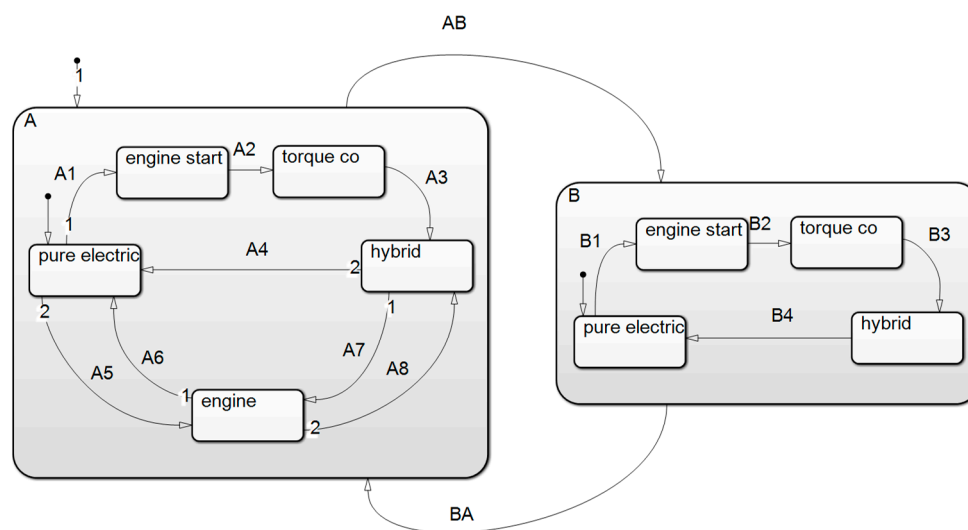


Figure 4. The state switching of the rule-based control strategy of the HEV with torque coordination.

The control strategy is still verified in the vehicle model built in Figure 3. Among them, the value range of the SOC in the control variable and the determination of $T_{m\max}$ are the same as in the previous section. The values of the parameters in the engine starting process and the torque coordination process are taken as reference to the experimental data in [22].

The switching process from electric drive mode to hybrid drive mode is as follows: when $SOC \leq SOC_{\max}$, the vehicle is running in the A state. When $SOC > SOC_{\min}$ and $T_r \leq T_{m\max}$, the vehicle works in electric drive mode, and the system is driven by the electric motor alone; if $T_r > T_{m\max}$ and $SOC > SOC_{\min}$, the engine enters the starting state, in which the clutch is not interlocked, and the vehicle is still driven by the electric motor alone; then, the clutch will enter the sliding friction for torque coordination, when the engine speed increases until the difference with the motor speed on the two sides of the clutch is lower than a given threshold which is taken as 191 r/min ($\omega_m - \omega_e \leq 191$). This process is the most important stage in coordinating motor torque, clutch torque and engine torque.

In addition, when the speed difference between the two sides of the clutch is zero, that is $\omega_m - \omega_e \leq 0$, the clutch is locked, and the vehicle is jointly driven by the engine and the motor in the hybrid drive mode, furthermore, if $T_r \leq T_{mmax}$ and $SOC > SOC_{min}$, the hybrid drive mode is switched to the electric drive mode; and if $SOC < SOC_{min}$, regardless of whether the vehicle is running in the electric drive mode or the hybrid drive mode, the motor will stop working, and the vehicle is separately driven by the engine. When the vehicle is driven by the engine alone, if $T_r \leq T_{mmax}$ and $SOC > SOC_{min}$, the operation mode is switched to the electric drive mode. If $T_r > T_{mmax}$ and $SOC > SOC_{min}$, the operation mode is switched to the hybrid drive mode. The mode switch process when the vehicle is running in the B state is the same.

Table 4. The operating state and switching conditions of the rule-based control strategy with the torque coordination.

Code	Starting State	Switching Condition	Final State
AB	A ($SOC \leq SOC_{max}$)	$T_r > 0, SOC > SOC_{max}$	B ($SOC > SOC_{max}$)
B1	electric drive	$T_r > T_{mmax}$	engine start
B2	engine start	$\omega_m - \omega_e \leq 191$	torque coordination
B3	torque coordination	$\omega_m - \omega_e \leq 0$	hybrid drive
B4	hybrid drive	$T_r \leq T_{mmax}$	electric drive
BA	B ($SOC > SOC_{max}$)	$T_r > 0, SOC \leq SOC_{max}$	A ($SOC \leq SOC_{max}$)
A1	electric drive	$T_r > T_{mmax}, SOC > SOC_{min}$	engine start
A2	engine start	$\omega_m - \omega_e \leq 191$	torque coordination
A3	torque coordination	$\omega_m - \omega_e \leq 0$	hybrid drive
A4	hybrid drive	$T_r \leq T_{mmax}, SOC > SOC_{min}$	electric drive
A5	electric drive	$SOC < SOC_{min}$	engine drive
A6	engine drive	$T_r \leq T_{mmax}, SOC > SOC_{min}$	electric drive
A7	hybrid drive	$SOC < SOC_{min}$	engine drive
A8	engine drive	$T_r > T_{mmax}, SOC > SOC_{min}$	hybrid drive

4. Results and Verification

The simulation experiment and verification adopted the co-simulation method of AVL Cruise software and Matlab. The power system of the HEV, the vehicle model, and the driver model, etc. are realized in AVL Cruise, and the algorithm of EMSs is realized in Matlab. In AVL Cruise, a simulation comparison of the EMSs with and without the torque coordination control is shown in Figure 5, from the clutch engagement, the output torque of engine, the output torque of motor, vehicle demand velocity and current velocity, vehicle acceleration, and vehicle jerk.

It can be seen from Figure 5a–c that compared with the method without considering the torque coordination, the fluctuations caused by the clutch torque, the engine output torque and the motor output torque are significantly reduced in the process of switching from the electric drive mode to the hybrid drive mode when considering the torque coordinated, thereby the proposed method reduced the sudden change of the torque during the switching process.

It can be clearly seen in Figure 5d,e that the current vehicle velocity following the required vehicle velocity is also significantly improved.

As can be seen from Figure 5e,f, the acceleration of the vehicle is the ratio of the amount of change in vehicle velocity to the time at which this change occurs, that is recorded as $\Delta v / \Delta t$. It is the physical quantity that describes how fast the velocity of an object changes. When the vehicle is running, the driver's job is to control the speed of the vehicle, and the change in speed (acceleration), however, the change in acceleration (jerk) will have a great effect on drivability and comfort [23,24]. In the mode switching process, the driving comfort is evaluated by the jerk generated by the acceleration change. That is, the evaluation index is the jerk, which is expressed by the change rate of acceleration; the smaller the jerk, the better the comfort of mode switching, and the recommended value of China is 17.64 m/s^3 , which was the biggest jerk that people can endure [24,25].

It can be seen from Figure 5f,g that when considering the torque coordination control, the acceleration fluctuation of the vehicle is obviously reduced, the vehicle jerk is also obviously improved, and it is within the recommended range of jerk in China. Under the premise of satisfying the dynamical performance of the vehicle, the sudden change of the torque during the mode switching is effectively suppressed, and the driving comfort of the vehicle is improved.

In summary, the simulation results verify that the designed energy management strategy with torque coordination control can make the HEV switch from electric drive mode to hybrid drive mode with better availability and effectiveness.

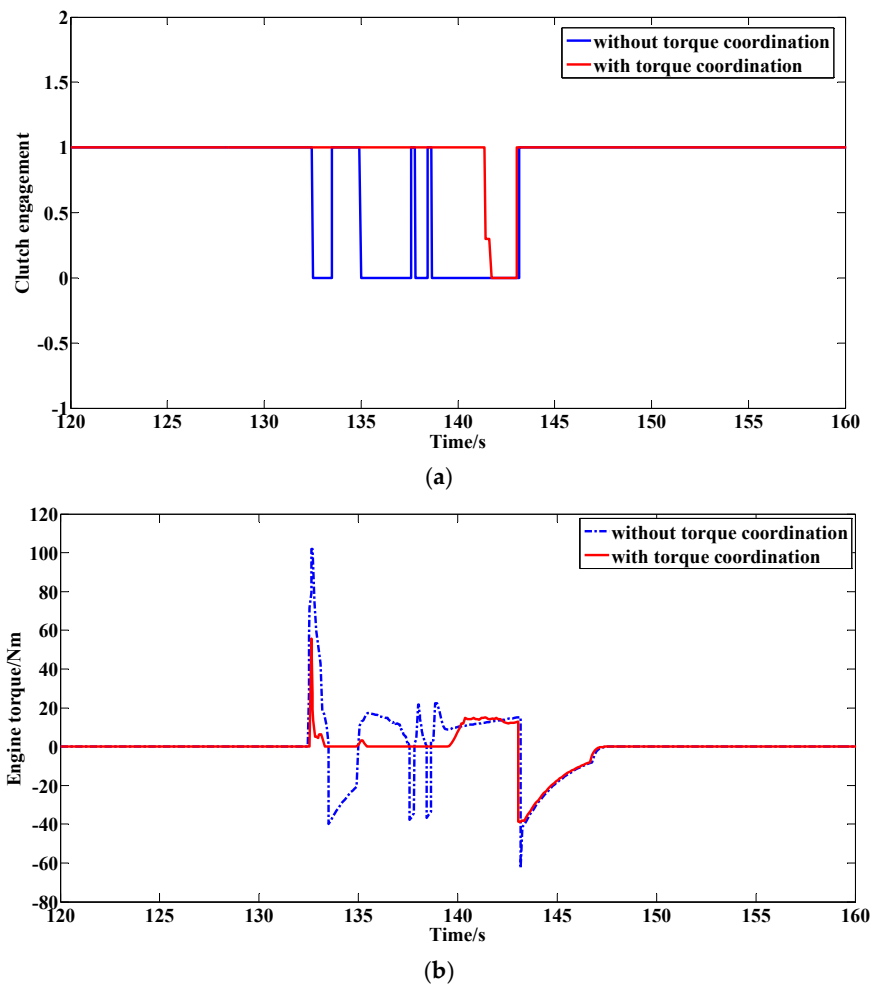


Figure 5. Cont.

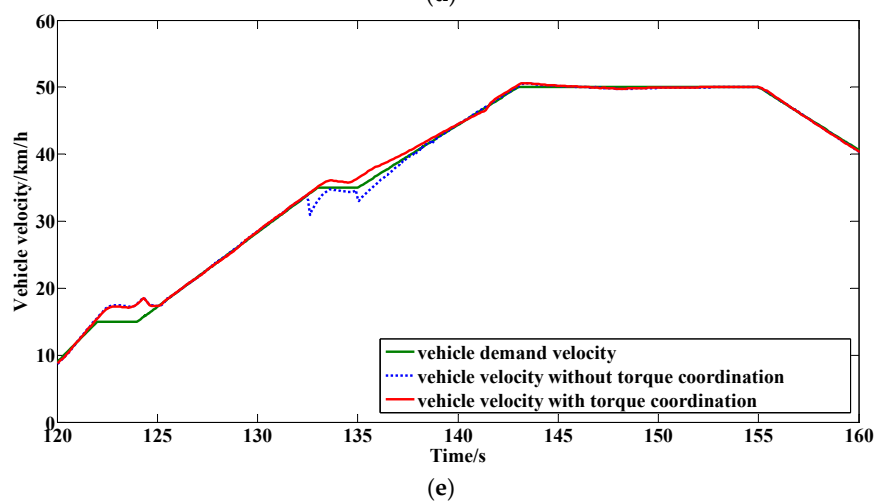
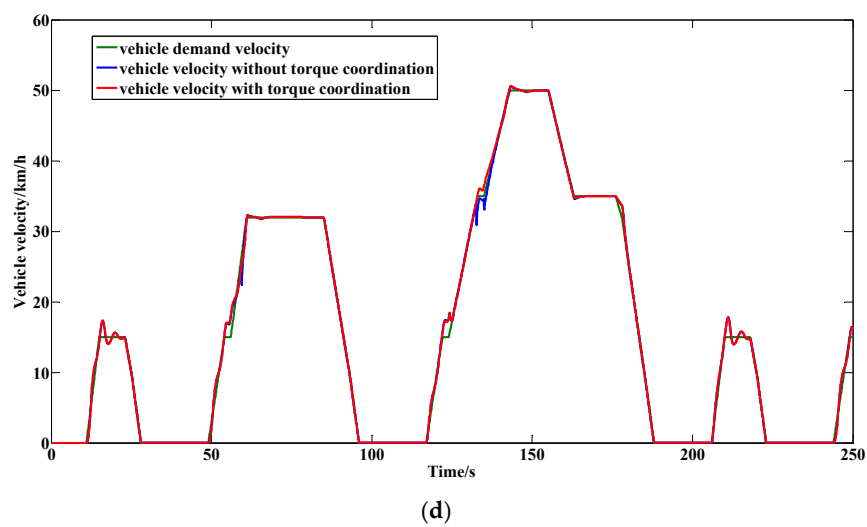
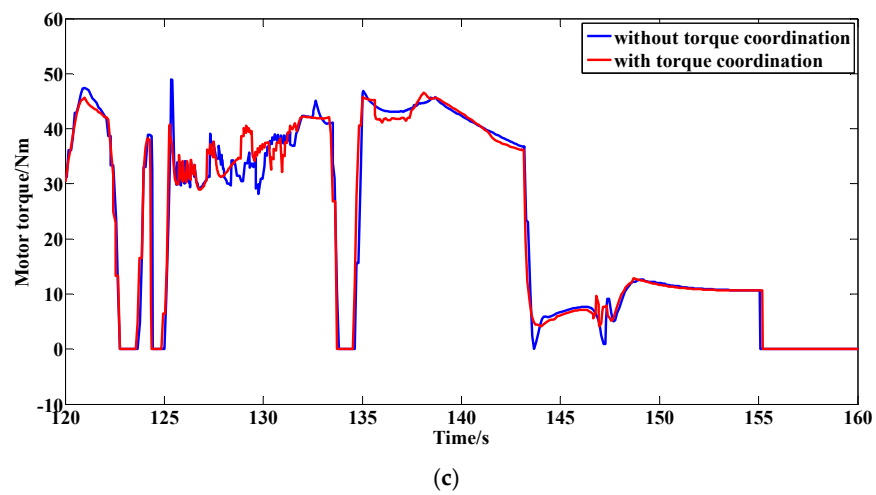


Figure 5. Cont.

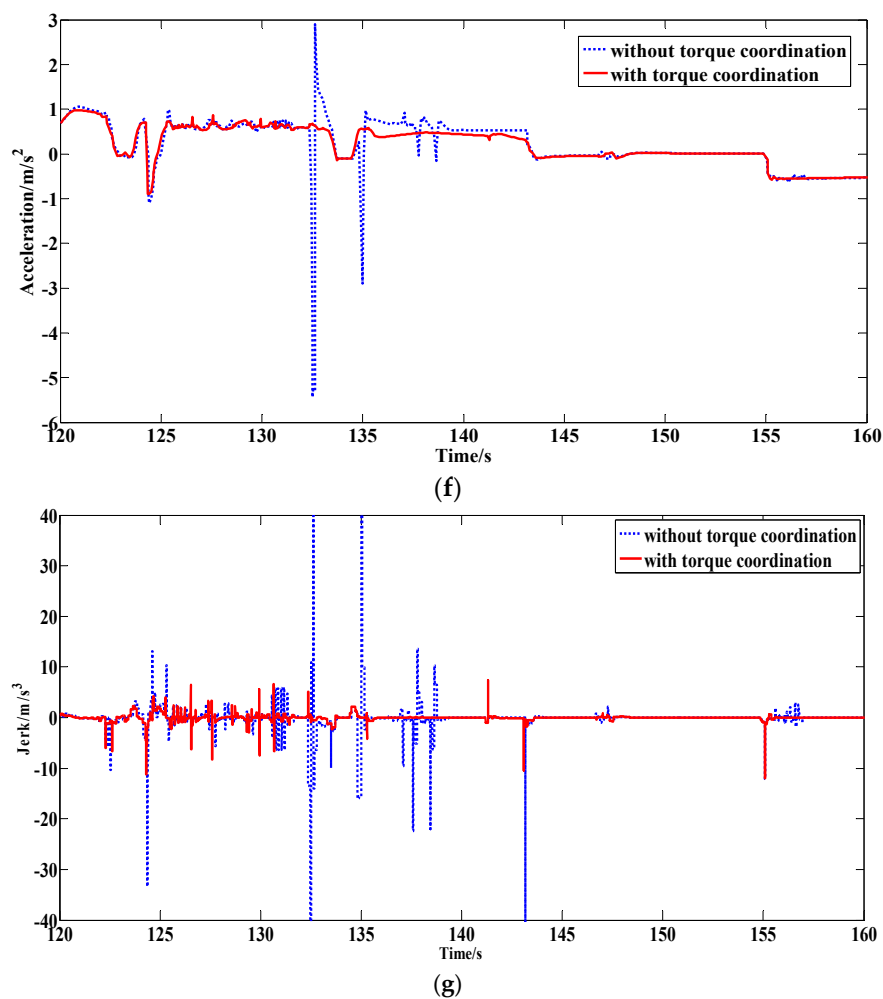


Figure 5. Simulation results and comparison curve of energy management strategy (EMS) with and without the torque coordination control: (a) Clutch engagement over time; (b) Output torque of engine; (c) Output torque of motor; (d) Vehicle demand velocity and current velocity; (e) Vehicle demand velocity and current velocity (amplification); (f) Vehicle acceleration; (g) Vehicle jerk.

5. Conclusions

The dynamical control system of the HEV has both continuous variable dynamical system characteristics and discrete event dynamical system characteristics. In order to reduce the vibration caused by mode switching of HEV and achieve smooth switching, the hybrid input/output automation model of power control system of a parallel HEV is established based on the theory of the hybrid dynamical system. And the interaction between continuous variables dynamical subsystems and discrete events is also studied. Taking the switching from electric drive mode to hybrid drive mode for example, the torque coordination is considered, and the performance is compared with the method without considering the torque coordination by using a rule-based control strategy. The simulation results in AVL Cruise show that, on the premise of ensuring the fuel economy and the emission, the mode switching process by considering the torque coordination control has the smaller torque fluctuation, the smoother mode switching and the better driving comfort. It should be pointed out that the research in this paper is based on the specific structure (a parallel hybrid architecture or vehicle) under the specific control strategy (rule-based), in fact, there are other parallel hybrid architectures with different functioning, in which these control procedures in this paper will be not completely common to all of them, instead, the control strategy should be adjusted according to the specific architecture.

However, in the design of energy management strategies, it is very important to consider the addition of torque coordination control in the mode switching process.

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Abbreviations

HEV	hybrid electric vehicle
BEV	battery electric vehicle
EV	electric vehicle
EMS	energy management strategy
HDS	hybrid dynamical system
HIOA	hybrid input and output automaton
DEDS	discrete event dynamical system
CVDS	continuous variable dynamical system
SOC	state of charge
T_r	vehicle demand torque of the HEV
T_m	output torque of motor
T_e	output torque of engine
T_{mmax}	maximum instantaneous output torque of motor
SOC_{min}	setting lower limit value of the SOC of power battery
SOC_{max}	setting upper limit value of the SOC of power battery
w_e	engine speed
w_m	motor speed
u_d	discrete input variables
u_1	engagement states (YES/NO) of clutch
v	vehicle velocity
y_c	continuous output variables
y_d	discrete output variable

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