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Optimization of Clutchless AMT Shift Control Strategy for Electric Vehicles

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Abstract

With the development of the economy, the number of cars in China is rapidly expanding, which has caused a certain degree of pollution to the environment. The emergence of electric vehicles has the good evasive effect on this issue. In order to shorten the shifting time of the electric clutchless automatic mechanical transmission (AMT) and reduce the shifting shock, the DC brushless drive motor, the clutchless and synchronizer-free AMT and the final drive are combined to establish the electric vehicle power transmission model of the drive motor and AMT controlled by the power transmission integrated controller. And the dynamic analysis of the picking phase, the shift process, and the torque reduction and torque recovery phases are carried out. Based on the dynamics of the shifting process, the implementation flow of the coordinated control of the shifting process is created. The classical PD control algorithm is used to optimize its control strategy and realize the optimal shift control of the clutchless AMT of electric vehicles. The experimental results show that the electric vehicle with the shift control strategy has a shifting time of 720 ms-750 ms in the static, low speed, medium speed and high speed state, and the impact degree is inside ±10 m·s−3 during the shifting process. This shows that the electric vehicle using the proposed shift control strategy has less time for shifting, high shifting quality, and smooth shifting process.

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Keywords: *Electric vehicle; Clutchless; AMT; Shift control; Strategy; Optimization*.

1. Introduction

In the face of increasingly severe energy and environmental problems, more and more countries regard the development of new energy vehicles as a national development strategy (Yang et al. 2017a). Under the trend of the country to vigorously develop green, energy-saving and environmentally friendly new energy vehicles, the in-depth study of the integrated drive technology of pure electric vehicle power system and the coordinated control of automatic shifting, and the development of automotive electric drive system are conducive to China's environmental protection and energy security. This provides the basis for the sustainable development of people, resources and the environment in the automotive industry.

The automated mechanical trans-mission (AMT) has the simple structure, low cost, and high transmission efficiency. It has the good application prospect in electric vehicles (Yang et al. 2017b). However, the shifting process relies on the sliding friction of the synchronizing ring, so the noise impact is large and the shifting time is long, which seriously affects the smoothness and ride comfort of the vehicle shifting and limits its application (Kang et al. 2017). In order to improve the efficiency of the electric drive system and meet the power requirements, the drive motor of the pure electric vehicle or the series hybrid electric vehicle usually matches the transmission (Wang et al. 2016a). Compared to automatic transmission (AT), continuously variable transmission (CVT) and dual clutch transmission (DCT), electronically controlled electric AMT does not require hydraulic or pneumatic power (Ren et al. 2017). AMT also has many shortcomings, such as the wear of the clutch friction disc, the power interruption during shifting, the contradiction between shifting time and shifting shock, but these problems do not affect its application performance on electric vehicles. Domestic and foreign scholars have done a lot of research on this (Zhou et al. 2016). Existing research can be divided into three categories depending on the structure of the AMT. In order to reduce the shift shock, the first type retains both the traditional AMT clutch and the synchronizer. Scholars have studied the two-speed rear mechanical automatic transmission (I-AMT). Through the feedback control of the clutch and the motor, shifting without power interruption is achieved (Su et al. 2016). In the I-AMT, the dry clutch is placed behind the AMT to eliminate power interruptions, but it inevitably causes energy loss (Izadkhast et al. 2016).In order to reduce the friction loss of the clutch, the control method of the jaw clutch is proposed. There is less research on the use of a synchronizer AMT for the pure

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electric vehicle because the AMT of this structure is complicated in structure and control, and it is not easy to achieve good results (Pelletier et al. 2016).The second type of study retained the synchronizer of the traditional AMT, but the clutch is removed. The reasons are:1. the motor has the characteristics of low speed and large torque, so the vehicle can be started directly by the motor drive. 2. The motor can be quickly switched between torque mode, free mode and speed mode to meet the shifting requirements. 3. Eliminating the clutch helps increase efficiency and reduces the weight and cost of the electric car. 4. The shifting power interruption caused by canceling the clutch can be compensated by shortening the shifting time (Hu et al. 2016a).The clutch is eliminated and the coordinated control of the drive motor and the shifting motor in the shifting process control becomes very important (Sarker et al. 2016). There are many studies on AMTs without clutches and synchronizers. Scholars have explored the feasibility of clutchless AMT for electric vehicle applications and proposed corresponding control methods. In order to shorten the synchronization time of the synchronizer and improve the service life of the synchronizer, scholars have proposed the constraint control method for the lock loop synchronizer. To improve the life of the synchronizer, the scholars designed the multivariable robust H-negative controller to evaluate the effect of closed-loop control based on noise and disturbance (Hannan et al. 2017). In order to improve the composite optimal control strategy for electric vehicle transmissions, a powertrain test rig including a high-performance electric dynamometer is established. The linear secondary regulator is used to actively compensate the torque of the driving motor, and the nonlinear time optimal control is used to track the execution Rotor position. The proposed control strategy can analyze the shift process and effectively improve the shift quality(CHAIBenben et al.2018).

The control method of the drive motor in the shift process control is proposed by coordinating the control of the drive motor and the shifting motor to improve the shifting effect. These studies have proved that it is feasible to cancel the clutch in AMT, but the feasibility of canceling the synchronizer has not been further studied. In the third type of study, the synchronizer in the AMT was cancelled. Because the target gear is directly connected to the motor after the clutch is removed, the clutch is connected to the vehicle through the output shaft. The inertia of these two parts is relatively large. If AMT relies on the synchronizer to complete the synchronization, the synchronization time is longer and the synchronizer wears out faster (Moon & Moon 2016).The shifting of the clutchless, synchronizer-free AMT requires the drive motor to have precise and fast speed regulation. At present, there are few studies on the control of the AMT shifting process of the clutchless synchronizer in pure electric vehicles. The existing research proves the feasibility of clutchless and synchronizer-free AMT, and proposes corresponding control strategies. However, the shifting time of the clutchless synchronizer AMT is relatively long compared to other types of transmissions. How to shorten the shift time under the premise of ensuring a small impact is still worth studying. In this paper, the optimization of the shift control strategy for the clutchless AMT of electric vehicles is studied. These include the synchronous control of the speed of the drive motor before the gear shift, the control of the shift actuator and the coordinated control of the two to shorten the shift time and improve the vehicle dynamics.

2. MATERIALS AND METHODS

2.1. Power transmission model of electric vehicle

The electric vehicle power transmission system studied in this paper adopts the combination of DC brushless drive motor, AMT without clutch and synchronizer, and main decelerator. The drive motor and AMT are controlled by the power transmission integrated controller (Hu et al. 2016b). The biggest advantage of the integrated controller is that it uses a control core, which saves the communication time between the drive motor controller and the AMT controller, thus shortening the shift time. The structure of the power transmission system is schematically shown in Figure 1.

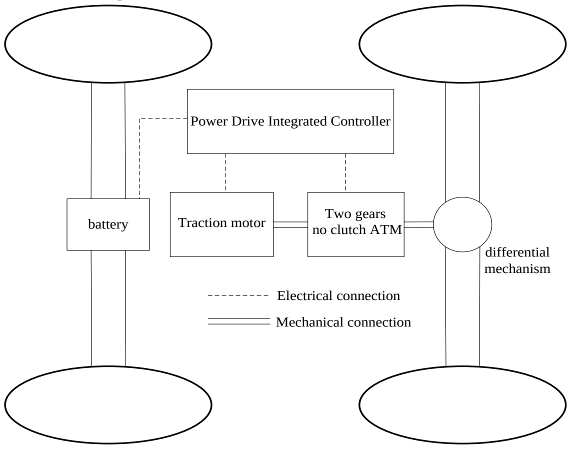

Figure 1. Structure diagram of power transmission system

The composition of the power transmission integrated controller of the pure electric vehicle is shown in Figure 2. The integrated controller calculates the appropriate target gear according to the accelerator pedal position, brake signal and vehicle speed, and completes the shift by coordinating the control of the drive motor and the shifting motor (Wang et al. 2016b). In the shifting process, the drive motor needs to perform multiple mode switching, and adjust the speed and torque in time to ensure that the shifting is smooth.

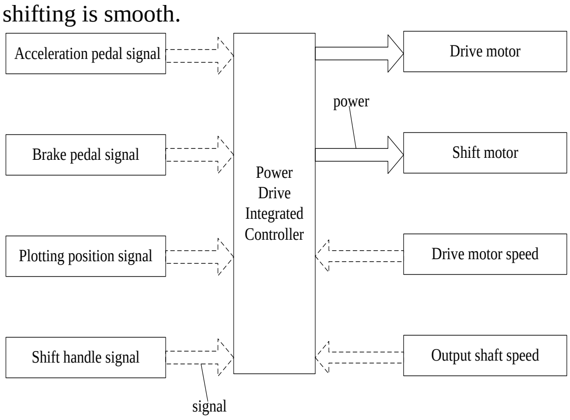

Figure 2. Integrated controller of electric vehicle power drive

2.2. Dynamic analysis of the shifting process

Figure 3 is the schematic diagram of the structure of the AMT. The shift actuator is a motor-drive mechanism that does not require hydraulic power, which improves the efficiency of the AMT. Figure 4 shows the dynamics of the entire vehicle transmission system.

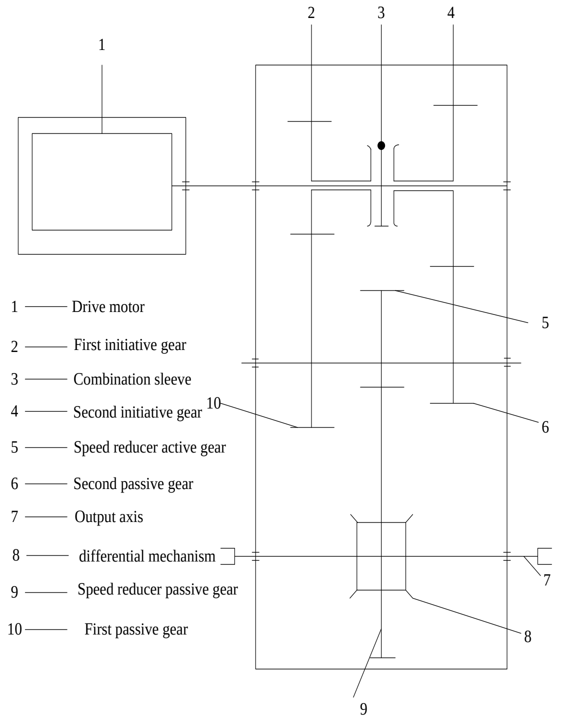

Figure 3. AMT structure diagram

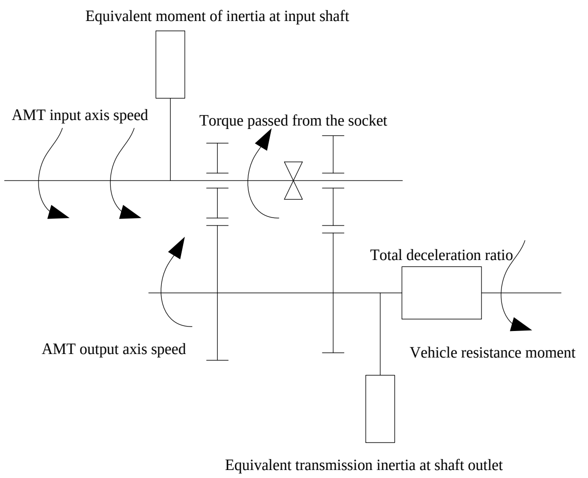

Figure 4. Dynamic model of vehicle transmission system

2.2.1. Force analysis during the picking stage

During the picking phase, the force analysis of the meshing teeth is shown in Figure 5.

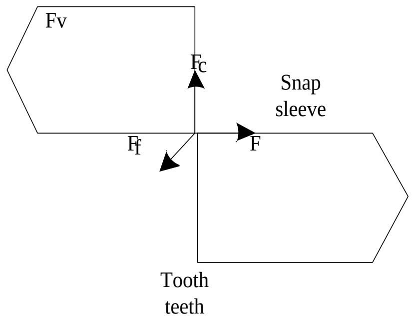

Figure 5. Stress analysis of meshing teeth in extraction stage

When picking up the gear, the resistance F mainly comes from the friction F_f between the engaging ring gear and the joint sleeve. The expression is

$$F_f = \mu F_V = \mu T_c / R \tag{1}$$

where μ is the tooth surface friction factor; F_V is the contact surface positive pressure; T_c is the torque transmitted by the joint sleeve; R is the joint sleeve indexing circle radius.

The torque T_c transmitted by the sleeve is:

$$\begin{cases} T_c = \left(T_m - J_m \dot{\omega}_m - c_{in}\omega_m\right) i_g \\ T_V = \left(T_c - J_v \dot{\omega}_{out} - c_{out}\omega_{out}\right) i_0 \end{cases} \tag{2}$$

where T_m is the traction motor torque; J_m is the equivalent moment of inertia of the AMT input; ω_m is the angular velocity of the input shaft. c_{in} is the rotational damping coefficient of the input shaft; i_g is the current gear ratio; T_V is the equivalent resistance torque of the whole vehicle. J_v is the equivalent moment of inertia of the AMT output; ω_{out} is the angular velocity of the AMT output shaft; c_{out} is the rotational damping coefficient of the output shaft; i_0 is the main reduction ratio.

When AMT is not in neutral, ω_m and ω_{out} satisfy the following equation:

$$\omega_m = i_g \omega_{out} \tag{3}$$

From the Equations (1), (2) and (3):

$$F = \frac{\mu\left(i_g i_0 J_V T_m + i_g^2 J_m T_V\right)}{R\left(i_0 i_g^2 J_m + i_0 J_V\right)} \tag{4}$$

In the Equation (2), c_{in} and c_{out} are relatively small, and they are ignored in the derivation of the Equation (4). When the actual output torque T_m of the motor is 0, F_f is the smallest, and the pick is the lightest. Therefore, it is necessary to reduce the output torque T_m of the drive motor to 0 before the lift, that is, to switch the drive motor from the torque mode to the free mode.

2.2.2. Force analysis of the gear shift process

In the gear stage, the force analysis of the meshing teeth is shown in Figure 6, and in Figure 6, F_h is the longitudinal force of the contact surface.

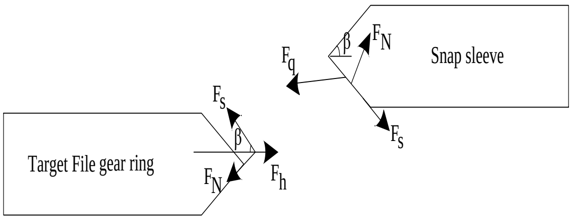

Figure 6. Stress analysis of meshing teeth when hanging

At the beginning of the gear, the engaging teeth are in contact with the end of the target gear, and the resistance F_q of the fork is as follows.

$$F_q = F_N \sin(\beta) + F_s \cos(\beta) \tag{5}$$

where F_N is the contact surface positive pressure; β is the tooth end chamfer angle; F_s is the contact surface friction.

F_N and F_s meet the following equation:

$$\begin{cases} F_s = \mu_2 F_N \\ F_c + F_s \sin(\beta) = F_N \cos(\beta) \end{cases} \tag{6}$$

$$F_c = T_c / R \tag{7}$$

where μ_2 is the frictional contact coefficient of the tooth end contact surface; F_c is the force transmitted by the joint sleeve.

From (5), (6) and (7):

$$F_q = \frac{T_c\left[\sin(\beta) + \mu_2 \cos(\beta)\right]}{R\left[\cos(\beta) - \mu_2 \sin(\beta)\right]} \tag{8}$$

In order to ensure that the target gear is successfully engaged, the resistance F_q of the fork is as small as possible, that is, T_c is as small as possible. It can be seen from Equation (2) that T_c depends on the output torque T_m of the drive motor and the difference in rotational speed between the sleeve and the engagement ring gear. The smaller the speed difference and T_m are, the smaller the T_c is. Therefore, when the gear is engaged, the drive motor should stop the torque output and control the difference in rotational speed between the clutch sleeve and the engagement ring gear as small as possible.

According to the above description, that is, the clutch output torque at the synchronization point is driven by the friction torque. The transition to static friction torque is prone to sudden changes in torque. This results in a large longitudinal impact of the vehicle and affects the smooth start.

2.2.3. Dynamics analysis of the torque reduction and recovery phases

From the force analysis in the picking stage, it can be seen that the drive motor should be switched from the torque mode to the free mode before the picking. After the gear is completed, the drive motor needs to be restored from free mode to torque mode. Switching between torque mode and free mode should establish appropriate control strategies to avoid large shocks.

The impact j of a pure electric vehicle can be expressed as:

$$j = \frac{da}{dt} = \frac{d^2 u_a}{dt} \tag{9}$$

where a is the acceleration; u_a is the vehicle speed. The longitudinal acceleration of the vehicle is

$$a = \frac{T_m i_g i_0 \eta_T - T_V}{\delta m r} \tag{10}$$

where η_T is the transmission efficiency; δ is the rotation mass conversion factor; m is the vehicle mass; r is the wheel radius.

From (9) and (10):

$$j = \frac{1}{\delta m r} \frac{d\left(T_m i_g i_0 \eta_T - T_V\right)}{dt} \tag{11}$$

Since the shifting time is very short, it can be assumed that the running resistance torque of the vehicle remains unchanged during the shifting process, and then Equation (11) can be simplified as:

$$j = \frac{i_g i_0 \eta_T}{\delta m r} \frac{dT_m}{dt} \tag{12}$$

It can be known from Equation (12) that the impact degree of the pure electric vehicle is proportional to the first derivative of the motor output torque. The more intense the output torque of the motor changes, the greater the impact will be. The impact is inversely proportional to the height of the AMT gear. In order to ensure that the impact of the torque reduction and recovery phases is as small as possible, sudden changes in the motor output torque should be avoided. In the low gear, the motor torque drops and the recovery rate should be less than that in the high gear.

2.3. Optimizing the control method of the shifting process

2.3.1. Shift coordination control

During the shifting process of the electric vehicle, a series of dynamic changes have occurred in the transmission system, such as the alternation of the motor load condition and the no-load condition, and the transmission gear shift. For the clutchless AMT electric drive system, the key to shifting is the coordinated control of the drive motor, transmission and shift actuator.

According to the specific control method in the automatic shifting process, the shifting process can be divided into three stages: unloading, synchronous gearing and loading.

During the driving process of the car, the integrated controller continuously collects the driving status information of the car. Combined with the driver's operating intention, the shifting module analyzes and judges that when the shifting condition is reached, the integrated controller issues the shift signal, and the control system enters the shifting process.

In the unloading phase, the motor controller controls the drive motor to operate in the torque mode to unload the drive motor. When the output torque of the motor to be driven reaches the unloading target torque TE1*, the motor controller controls the driving motor to be switched from the torque mode to the free mode, so that the shifting actuator performs the lifting operation without any impact under the condition of no load. In the synchronous gearing phase, the motor controller controls the drive motor to switch from free mode to speed mode. The drive motor is regulated to reduce the difference in rotational speed between the main and driven parts of the synchronizer. When the driving motor speed reaches the target speed n*, the motor controller controls the driving motor to switch from the speed mode to the free mode, so that the shifting actuator completes the gearing operation smoothly and without impact under no load conditions. During the loading drive phase, the motor controller controls the drive motor to switch from free mode to torque mode. The output torque of the drive motor is loaded to the target torque TE2* required by the power system. At this time, the shift actuator is maintained at the current position, the vehicle is normally driven according to the driver's operation intention, and the entire shifting process ends. Based on the dynamics of the shifting process, the coordinated control implementation process of the shifting process is shown in Figure 7.

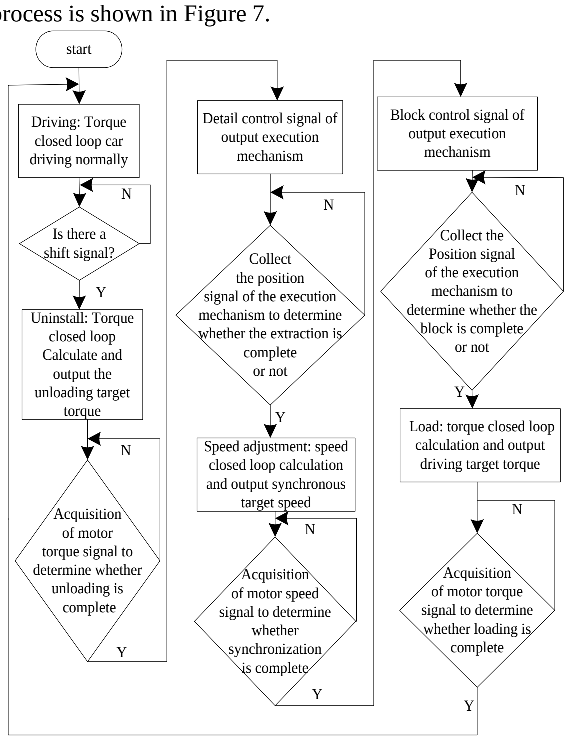

Figure 7. Coordinated control flow of gear shifting process

Analysis of the shifting process shows that the shifting coordinated control system compensates for the effect of clutchless in the power transmission system by accurately controlling the speed and torque of the drive motor, and smoothly completes the shifting. Therefore, in the entire shift coordination control system, the control of the drive motor is extremely important. The adjustment level of motor speed and torque determines the speed and smoothness of the shifting process. Therefore, on the basis of the integrated electric drive of the motor-transmission, the corresponding control strategy is established for the speed and torque of the drive motor at each stage, and the reliability of the system automatic shift coordination control strategy and the shift quality of the whole vehicle are improved.

2.3.2. Optimization of shift control strategy

In the automatic shifting process of AMT without clutch, for the adjustment of the output characteristics of the drive motors in each stage, when the normal driving, unloading and loading phases of the vehicle are the torque adjustment of the motor, the speed adjustment is in the synchronization phase.

In the whole shifting process, not only the torque and the rotational speed of the drive motor are precisely adjusted, but also the drive motor needs to be switched between the torque adjustment and the rotational speed adjustment. The entire control link is automatically coordinated by the integrated controller. The output characteristics of the drive motor are temporarily not controlled by the accelerator pedal.

The shifting process of the electric vehicle AMT without clutch is realized by using the working mode of the electric vehicle power motor and the control shifting actuator. There are three main types of actuators, namely, electronically controlled hydraulic, electronically controlled pneumatic and electronically controlled. The electric control electric type is selected as the DC motor drive of the electric vehicle. This type of DC motor drive uses the master chip to generate PWM to control the speed and matrix of the motor. It can use the sensor to adjust the PWM wave according to the position change of the shift selector to control this.

The shifting quality of the clutchless two-speed AMT system is to change the transmission ratio of the transmission to meet the purpose of changing the transmission speed and torque of the vehicle. The evaluation of its quality mainly depends on two aspects. One is the time to shift gears. How to achieve fast and smooth shifting needs to take into account the ECU operating rate, actuator response, shifting speed, coordinated control of the power motor and the efficiency of the transmission. The second is the impact of shifting. The vehicle's longitudinal acceleration rate of change can be used to identify it.

First, the maximum change rate $(dT/\mathrm{dt})\max$ of the power motor matrix needs to be confirmed. When the real-time rate of change is less than this premise, its state value is reduced to 0, which can switch between the torque mode and the free mode. In the speed regulation of the power motor, if n_1 is the target speed value after the speed regulation, n_2 is the mechanical automatic transmission intermediate shaft speed, and Δn is the speed correction amount, then the following equation can be given.

$$n_1 = i_g n_2 + \Delta n \tag{13}$$

Since the speed before and after synchronization are increased, correction is required. It is found that adjusting the value of the axial force change rate can achieve the effect of reducing the synchronous impact.

In order to ensure the control of the selection action and shifting, the classical PD control algorithm can be adopted. Within this algorithm, the shift position sensor's deviation from the current position value and the target position value is $e(t)$. The shift actuator motor drive voltage $U(t)$ and its relationship are as follows,

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$$U_{(t)} = K_p e(k) + K_d \left[e(k) - e(k-1) \right] \tag{14}$$

After the end of the gear, the driver's purpose will be automatically recognized by the controller, and then the target torque of the power motor will be completed, so that it will take the least time to increase the target torque, and the free mode to torque mode can be changed.

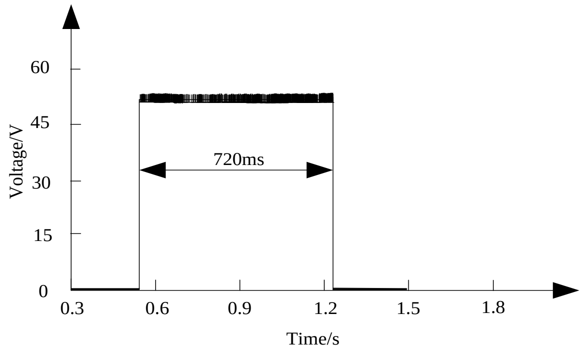
3. RESULTS

In order to verify the effect of the shift control method in this paper, the actual vehicle test under typical working conditions was carried out. The shifting quality is mainly measured by the shifting time and the difference in rotational speed between the AMT output shaft and the target gear when the target gear is engaged. According to the previous theoretical and experimental data analysis, we know that the point that is prone to impact during the starting process is the clutch synchronization point. Before the synchronization point is the second stage of the starting process, and after the synchronization point is the third stage of the starting process. In the second stage, the dynamic friction torque transmitted by the clutch is determined by the pressing force between the clutch master and driven parts. In the third stage, the static friction torque transmitted by the clutch is equivalent to the motive torque. To ensure that the vehicle starts smoothly, the dynamic friction torque output by the clutch should be equal to the engine output torque before the synchronization point. Therefore, the control of the second stage can be divided into two stages before and after: increasing the coupling speed of the clutch in the first half to shorten the start time as the goal; reducing the torque transmitted by the clutch in the second half to suppress the impact at the synchronization point.

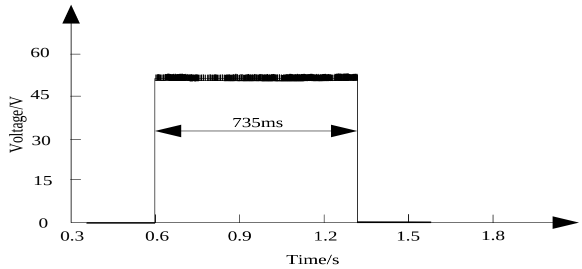
CRUISE software is developed by AVL List. Its modular modeling ideas and graphical modules make it easy to build a complete vehicle model. Its complete solver ensures the accuracy and speed of calculation of the entire vehicle model. Improve more advanced control modules such as the transmission program (GB Program) module, transmission control (GB Control) module and calculation optimization functions such as automatic transmission shift law optimization (GSP), DOE functions, etc. to optimize the automatic transmission simulation The field has played a greater role. The use of CRUISE software to build a commercial vehicle AMT vehicle model and the use of GSP function modules to optimize its shifting rules are of great significance for accelerating vehicle development and speeding up transmission calibration.

3.1. Static shift

The static shift time is mainly determined by the AMT shift motor speed, the gear ratio of the shift actuator and the stroke between the high and low gears. The static shift time reflects the shortest shift time determined by the AMT mechanical structure. The shift time can be obtained by measuring the terminal voltage of the shifting motor. The shift time at rest is shown in Figure 8.



(a) Low block to high block



(b) High block to Low block

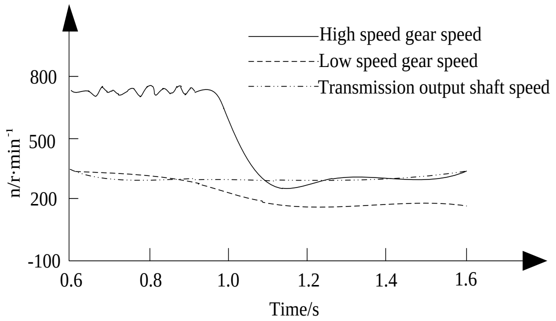
Figure 8. Voltage waveform at the end of the shift motor during parking shift

It can be seen from Figure 8 that in the static situation, when the electric vehicle is changed from the low speed gear to the high speed gear, the voltage changes at 0.5 s, and the voltage value is 0 at 1.22 s. The entire shifting process time is 720 ms. In the static situation, when the electric vehicle is changed from the high speed gear to the low speed gear, the voltage changes at 0.6 s, and the voltage value is 0 at 1.35 s. The entire shifting process time is 735 ms.

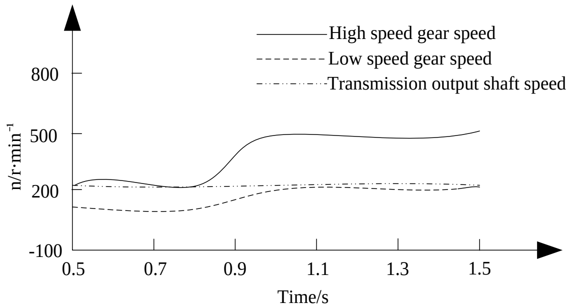
3.2. Shifting during driving

In the first stage, the clutch is quickly combined to eliminate the gap between the master and the driven parts within a short time; in the second stage, the clutch's coupling speed is controlled to make the clutch smoothly enter the combined state; in the third stage, the clutch continues to slowly couple, which can be pursued High vehicle acceleration, shortening the start time. In the fourth stage, when the speed difference between the clutch master and driven parts is reduced to Δn, the combination of clutches is controlled according to the change in engine speed: if the engine speed is increased or maintained.

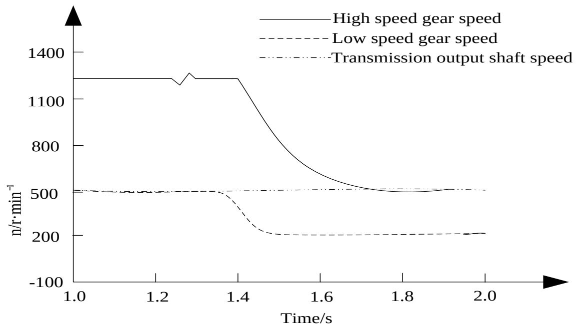
Keep the same, and the throttle opening of the engine increases, continue to engage the clutch or maintain its current position; otherwise, slowly release the clutch to the semi-engagement point position; Phase 5, after synchronization, the clutch is quickly engaged until the end. Figure 9 shows the rotational speed of each part of the AMT when shifting at low, medium and high vehicle speeds. The shift time depends mainly on the speed of the car. The higher the speed is, the greater the difference in rotational speed between the sleeve and the target gear is, and the longer it takes to match the speed is. Therefore, shifting at different speeds can reflect the effect of the shift control strategy.



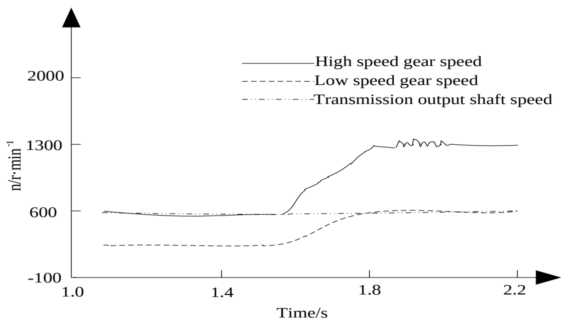
(a) At low speed Low block to high block



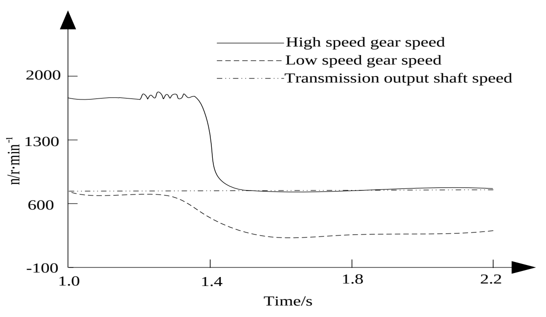
(b) At low speed high block to Low block



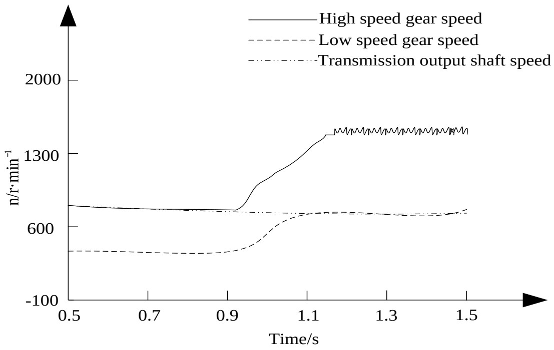
(c) Medium speed Low block to high block



(d) Medium speed high block to Low block



(e) At high speed Low block to high block

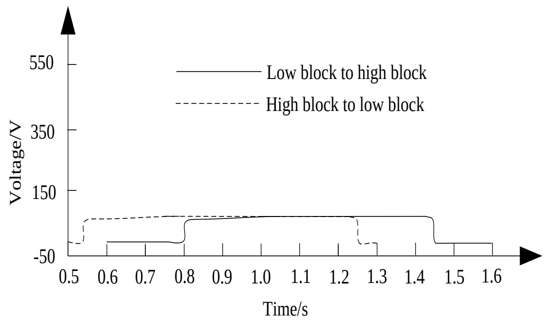


(f) At high speed high block to Low block

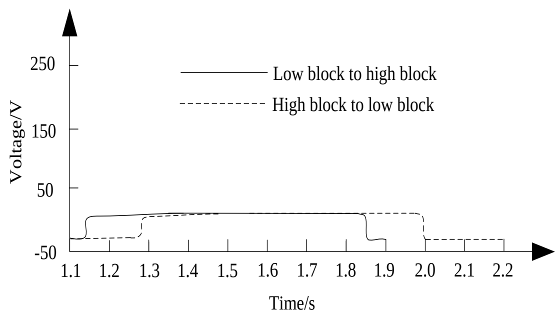
Figure 9 . Shift speed curve at different speeds

As can be seen from Figure 9, the shift motor does not stop during the shifting process, whether it is low speed, medium speed or high speed. This shows that the drive has been completed before the clutch reaches the neutral cut-off point. The effectiveness of the shifting of the clutchless AMT control strategy is verified.

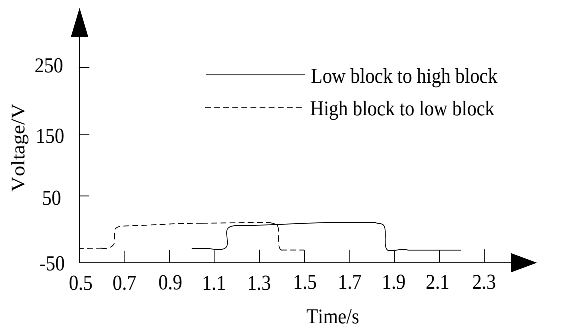
Figure 10 shows the shifting time for low, high and low gears at low, medium and high speeds.



(a) Shift time at low speed



(b) Shift time at medium speed



(c) Shift time at high speed

Figure 10. Shift time at different speeds

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The low gear shifts of low, medium and high speeds are 723 ms, 725 ms and 729 ms, respectively, and the shift times of high gears and low gears are 742 ms, 749 ms and 751 ms respectively. This shows that the clutchless AMT shift control strategy studied in this paper can significantly shorten the shift time of electric vehicles.

The impact degree is the rate of change of the longitudinal acceleration of the vehicle, which is an important indicator reflecting the smoothness of the shifting process. According to the subjective feelings of passengers, countries have set corresponding standards for the impact value, and the German recommended value is 10 m•s^{-3}. The impact value of electric vehicles at different speeds is shown in Table 1.

Table 1. Impact value of electric vehicles at different speeds

Time/s	At low speed/ m•s^{-3}		Medium speed/ m•s^{-3}		At high speed/ m•s^{-3}	
	Low block to high block	high block to Low block	Low block to high block	high block to Low block	Low block to high block	high block to Low block
0.5						
0.6						8.9
0.7	-3.6	0				2.5
0.8						1.7
0.9						3.5
1.0		-0.5			2.4	-2.8
1.1	-0.7		-0.3	-9	3.5	-0.8
1.2			-4.9		-1.8	3.2
1.3		0		-8.7	2.9	1.9
1.4				5.1	-3.4	2.5
1.5			0	-4.2	2.8	-3.5
1.6	0.3			3.4	-3.4	
1.7				-2.8	6.7	
1.8				4.2	0.5	
1.9			3.1	7.6	-2.4	
2.0				5.4	3.4	
2.1				-1.9	-5.6	
2.2				2.6		

It can be seen from Table 1 that the electric vehicle using the clutchless AMT control strategy proposed in this paper has the shock degree of ±10 m•s^{-3} during shifting with low speed, medium speed and high speed. This shows that the clutchless AMT control strategy can meet the requirements of shift smoothness.

The test results show that, in the static situation, the whole process time of the electric vehicle from the low speed to the high speed is 720 ms, and the process time from the high speed to the low speed is 735 ms. At low, medium and high speeds, the time required for the low gear to shift to the high gear is 723, 725, 729 ms, and the time for the high gear to the low gear is 742, 749, 751 ms. Whether it is low speed, medium speed or high speed, the shifting motor does not stop during the shifting process. The electric vehicle using the clutchless AMT control strategy proposed in this paper has the shock degree of ±10 m•s^{-3} during shifting with low speed, medium speed and high speed. This shows that the shift control strategy of this paper has a good effect in shortening the shift time and reducing the shift impact. At the same time, it verifies the effectiveness of the clutchless AMT control strategy proposed in this paper.

4. DISCUSSION

(1) For the shifting process control of the electric vehicle without clutch AMT, the DC brushless drive motor, the AMT without the clutch and the synchronizer, and main decelerator are combined to establish the power transmission model of the electric vehicle controlled by the power transmission integrated controller. The integrated controller of the power traditional model has only one control core, which can save the communication time between the drive motor controller and the AMT controller, thereby shortening the shift time.

(2) Through the process of shifting coordinated control, the shifting coordinated control strategy compensates for the effect of no clutch in the power transmission by accurately controlling the speed and torque of the drive motor, and smoothly completes the shift. Therefore, the control of the drive motor is extremely important in the entire shift coordination control system. The adjustment of the speed and torque of the motor determines the speed and smoothness of the shifting process. On the basis of the integrated electric drive system of the motor-transmission, the speed and torque of the drive motor at each stage are given corresponding control strategies in order to improve the reliability of the coordinated control strategy of the system automatic shift and the shift quality of the whole vehicle.

5. CONCLUSIONS

In this paper, based on the dynamic model of the integrated electric drive system of the motor-transmission, the automatic shifting principle of the clutchless AMT electric drive system is analyzed, and an automatic shift control strategy based on the classical PD control algorithm is developed. The effectiveness of the strategy is verified by experiments. The experimental results show that the automatic shift coordination control strategy developed in this paper can accurately control the speed and torque of the drive motor. The shifting mechanism can be coordinated, and the absolute value of the shifting impact is within the range of ±10 m•s^{-3}, which is in line with the standard. It can smoothly complete the automatic shifting of the clutchless AMT drive system. The shift time is short, about 730ms. It is the effective strategy which improves shift performance.

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