Analysis and Control of Shift Process for AMT without Synchronizer in Battery Electric Bus

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Abstract. A type of Automatic Mechanical Transmission (AMT) without clutch and synchronizer for pure electric bus is introduced in this paper. The shift process model of this type of AMT is created, and the factors that affect the shift process are analyzed. Based on this shift process model, the shift control strategy is designed. The field vehicle road tests results show that the strategy was able to meet the passenger comfort and vehicle power requirements, and verified the validity and correctness of the control strategy.

Introduction

Because of zero fuel consumption and emission, battery electric vehicle is thought to be the ideal solution for the energy crisis and global warming [1]. Battery electric vehicles can only have single-stage deceleration device. However, because of large load and frequent starts and stops, pure electric bus with only single-stage deceleration device, is difficult to meet the start-up and high torque requirements. Therefore, buses need the multi-speed transmission to match the vehicle [3].

A battery electric vehicle equipped with 3-speed automatic mechanical transmission (AMT) is present in the study. The AMT has a pneumatic actuator, no clutch and synchronizer. Through the use of AMT, pure electric cars can be automatically shifted by the driver's intentions to reduce driver’s fatigue and improve ride comfort.

The AMT in this study uses the non-synchronous design inside the gearbox. Therefore, this article attempts to model and analyst the shift characteristics without the synchronizer, as well as a key factor to affect the shift quality through the various stages of the shifting process, and then formulate the corresponding shift strategy.

AMT System Composition

Figure 1 shows the AMT system for battery electric vehicles. Battery electric bus is powered by a motor. Power gets through three gear transmission, driveshaft, and finally passes to the wheel. The AMT system consists of the gearbox, pneumatic actuator, TCU (transmission control unit) and a variety of sensors. TCU exchanges information with the vehicle controller (VMS), the motor controller (MCU) and the battery management system (BMS) via the CAN bus.

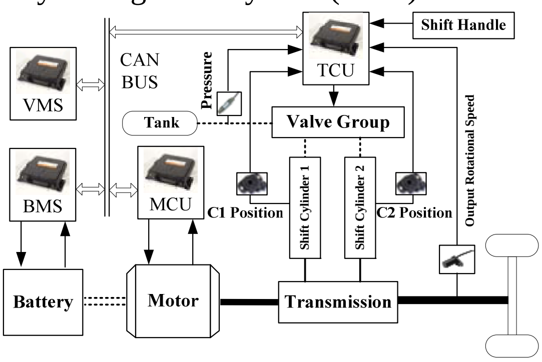

Figure.1 Schematic of AMT for Pure Electric Bus

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It can be seen from the Figure, AMT has no clutch. This design directly uses the low-speed torque of the motor to complete the start–up. In the shift process, TCU controls the motor quickly to enter the free mode, the motor gets into the non-excitation state, which will cut off the power between the power transmission and motor. Pneumatic actuator will pick off the gear at this time.

This AMT gearbox has no synchronizer. It uses the engaging sleeve to achieve the shift.

The actuator consists of two cylinders and solenoid valve, which the cylinder 1 is responsible for 2-N-3 shift action, cylinder 2 is responsible for 1-N shift action. Therefore, this AMT has no selection gear, directly uses the cylinder to shift.

Shift process modeling and analysis

The shifting process of the AMT can be divided into picking-off phase, speed adjustment phase, engaging gear phase and torque recovery phase. In order to establish an effective transmission system model, first the following assumptions:

1) The system consists of inelastic inertial components;
2) Each rotary member has only one degree of freedom;
3) Mechanical efficiency loss of transmission system converse to running resistance.

Based on the above assumptions, the system can be simplified as the equivalent of a discrete system. Shown in Figure.2, the kinematics and dynamics of the relationship of the electrical power transmission process:

$$\frac{T_c}{i_g} = T_m - J_m.\dot{\omega_m} \quad (1)$$

$$\frac{T_v}{i_o} = T_c - J_v.\dot{\omega_v} \quad (2)$$

Where, T_c is synchronizer torque; T_m is motor output torque; T_v is automobile driving resistance torque; J_m、J_v is respectively the moment of inertia converted to the transmission input shaft and output shaft ends; $\dot{\omega_m}$、$\dot{\omega_v}$ is respectively for transmission input shaft and output shaft speed ; i_g、i_o is respectively for the gearbox ratio and final drive ratio.

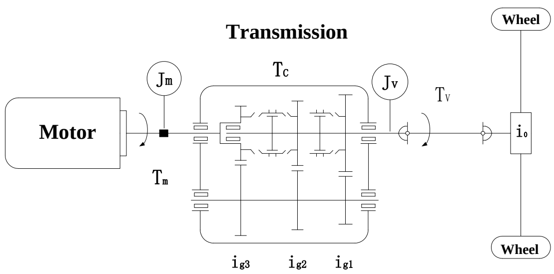

Figure.2 Model of Power train System for Pure Electric Bus

Disengagement phase.Figure.3 is mesh force model when picking neutral. F is the force of picking neutral; Fc is synchronous transmission force; Ff is friction resistance force between mesh gears; f is friction coefficient between the mesh gears.

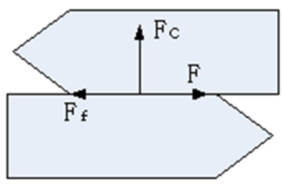

Figure.3 Force Model on Teethes in Shift to Neutral Phase

If the radius of mesh gear forcing point is for R:

$$F_f = F_c * f \quad (3)$$

$$F_c = T_c / \int dR \quad (4)$$

By formula (3) and formula (4) is:

$$F_f = T_c f / \int dR \quad (5)$$

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Because resistance force mainly comes from mesh gear friction force when picking neutral, formula (5) shows that in order to achieve the least resistance force when picking neutral, one should try to reduce Tc as much as possible. By formula (1) and formula (2) is:

$$T_c = \frac{J_m . T_v . \frac{i_g}{i_0} + J_v . T_m}{J_m . i_g + \frac{J_v}{i_g}} \tag{6}$$

The formula (6) shows, torque of synchronous transmission is the minimum when T_m is 0. So one should make motor not output torque.

Speed adjustment phase. Under the neutral gear condition, one should adjust the speed of the motor rapidly to make the input shaft speed meet the demand of next gear transmission ratio. The target speed range of the input shaft can be expressed as:

$$\Delta\omega_m = \left(i_{g2} - i_{g1}\right) \frac{u_a i_0}{0.377r} \tag{7}$$

In order to make shifting smooth and reduce shifting impact, the difference value of motor speed should be in a very small range after adjusting. As smaller the speed difference value is, the smaller impact and the higher the shifting comfort is. Specific speed difference value should be depending on the motor control precision.

Engagement phase. According to position difference, synchronizer can be divided into two states as "chamfer contact" and "crossed the chamfer" in the process of shift gear. Because the speed controlling in practice cannot ensure synchronization accurately, one should use synchronizer to eliminate the speed difference in the early stage of engaging gear. Figure 4 is the meshing force model in the synchronization process.

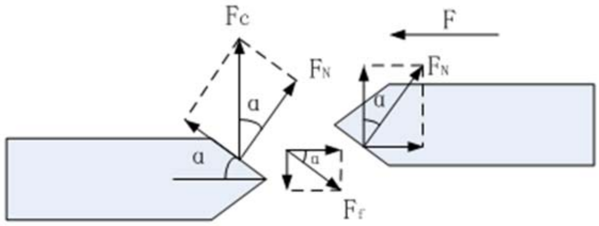

Figure.4 Force Model on teethes in Shift Gear Phase

$$F_N = F_c . \cos a \tag{8}$$

$$F_f = F_N . f \tag{9}$$

The force analysis model shows that F must satisfy follows so that gear can be picked on successfully:

$$F > F_N \sin a + F_f \cos a \tag{10}$$

$$F > \frac{T_c}{\int dR} \sin a \cos a + \frac{T_c}{\int dR} \cos a \cdot f \cdot \cos a \tag{11}$$

$$F > k i_g (T_m - J_m . \dot{\omega}_m) \tag{12}$$

As can be seen, decided whether in gear mainly two factors are the motor torque Tm and engaging set of angular velocity. In the initial design conditions are unchanged, for smooth shifting, on one hand, in the process of the gear motor torque Tm should be zero, so shifting phase also need to control the motor into the free mode; on the other hand, in order to reduce the gear sleeve of the angular velocity, requirements of motor speed after the actual speed and target synchronous speed difference must be as small as possible, in order to satisfy (11) condition.

When the engaging sleeve chamfering speed over the complete synchronization, time = 0, mainly for the meshing gear drag friction force, the force is far less than the gear force, it can be rapidly engage a gear, the gear process completed.

Torque recovery phase. The completed engagement need to control the motor torque while at the same time to ensure smooth from shock recovery in the shortest possible time. Usually to the analysis and evaluation of the degree of impact as a smooth shift indicators, the rate of change of the vertical acceleration of the impact of degree j concept vehicles in the shifting process, namely:

$$j = \frac{da}{dt} = \frac{d^2u}{dt^2} \tag{13}$$

Torque recovery process time is very short, so ignore the resistance changes of this process are:

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$$j = \frac{d^2u}{dt^2} = \frac{i_g i_0 \eta_T}{\delta nr}\frac{dT_q}{dt} \quad (14)$$

Seen the impact of the size and the rate of change of torque is proportional to, so in the formulation of the shift the process of torque control strategy of the recovery phase, passengers can withstand the impact of degree as boundary conditions to calculate the gear torque recovery control slope. From (13) can be seen that the relatively high gear low gear to restore torque to slow.

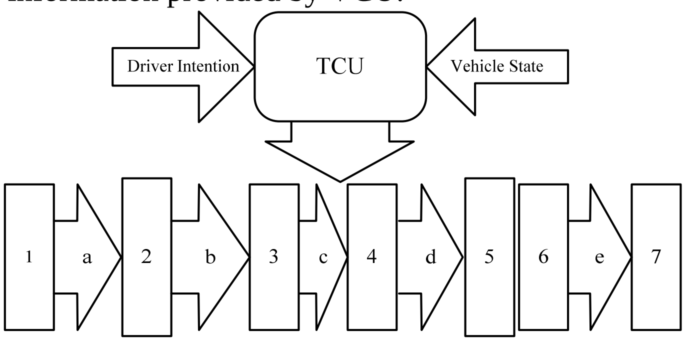
Shift control strategy

Actuator control. Pneumatic electromagnetic valve group comprises 5 switching valves. V5 is open valve and the total control valve. On the one Hand V5 controls the on-off of the gas circuit, on the other hand, in the V4, V3power, make the C1 in a neutral position. V1 is also open valve. When V2 has no power, C2 is in the neutral position. V2, V3, V4 is closed valve. When they are in the power-on state, transmission engages respectively 1st, 2nd and 3td gear. Table 1 shows control logic of pneumatic electromagnetic valve.

Table 1 Control Logic of Pneumatic Electromagnetic Valve

Cylinder Action	Electromagnetic Valve				
	V1	V2	V3	V4	V5
N-1 Gear	1	1	0	0	1
1-N Gear	0	0	0	0	1
N-2 Gear	0	0	1	0	1
2-N Gear	0	0	0	0	1
N-3 Gear	0	0	0	1	1
3-N Gear	0	0	0	0	1

Multi-controller coordinating control. The shift process of the AMT is multi controller coordinating control. The controller of an electric control system by CAN bus network communication, MCU, TCU respectively and VCU communication. VCU is responsible for collecting vehicle state, forward CAN messages, arbitration vehicle control; MCU is responsible for collecting motor state, speed, torque and other information, in response to the VCU torque request and control request; TCU is responsible for collecting handle information, through VCU to motor speed adjustable torsion, sending the request as well as the implementation of structural control, required, motor vehicle information provided by VCU.



a. Shift permission; b. Motor free mode; c. Neutral gear; d. Synchronization; e. Engagement
1. Shift process start; 2.Free mode request; 3.Picking off gear; 4.Motor Adjusting speed; 5. Free mode request; 6.Picking up gear; 7.Torque recovery

Figure.5 Shift Control Process of AMT for Pure Electric Bus

Shift control process. Figure.5 shows the pure electric bus AMT shift control process of [5]. Normal running, TCU judging driver intention, according to vehicle running state, makes shift decision. The shift to the following stages: ①Request shift phase. TCU issued to the VCU shift request, permission, TCU gained control of motor vehicle; ②Free mode. TCU requested motor in free mode, cut off the motor power; ③Pick stage. TCU controlled cylinder pick up gear; ④Motor stage. TCU emit target speed motor, motor speed control mode of TCU into the real-time judgment, speed difference, when the speed difference in the allowable range, to enter the next stage; ⑤Picking the gear stage. In order to prevent the motor in the control state still output torque request,

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TCU motor in free mode, at the same time, the control cylinder gear; ⑥The restoring torque phase. In ensure the impact degrees under the premise, TCU to MCU a torque request, motor in torque mode; and when the torque is restored to the driver request torque, shift process ends, handing over the vehicle control TCU.

Vehicle experiments

Figure.6 shows the vehicle1litres 2shift experiment curve, from which we can see that in the process of shifting motor work mode, the motor speed, cylinder position, the rotation speed of the output shaft, the impact degree and the gear change process. Diagram of the marked shift of the 6 phases.

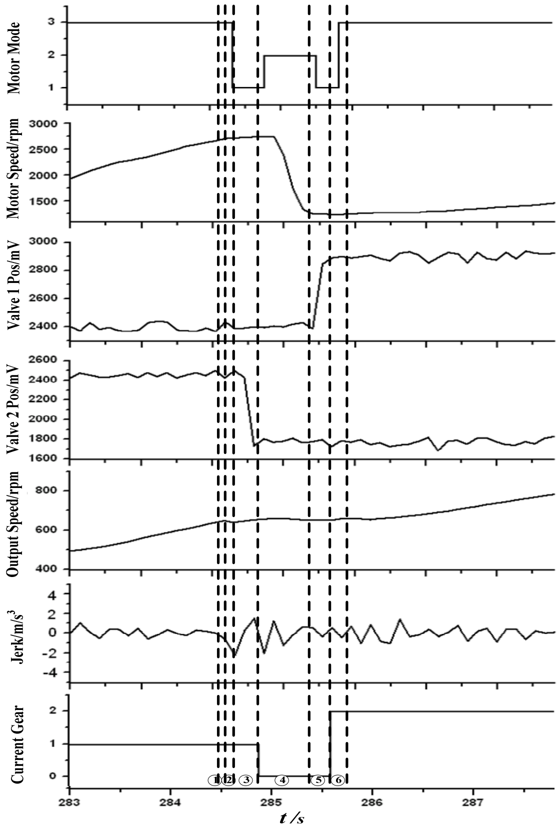

Figure.6 Curves of Vehicle Shift 1-2 Process

Table 2 Analysis of Shift Gear Duration

Number	Stage	Time(ms)
①	Request shift	40
②	Motor free mode	60
③	Picking neutral	180
④	Adjusting speed	420
⑤	Engaging gear	160
⑥	Restore torque	130

Shift time is a comprehensive index for evaluating shift quality. The time of different stages in shift process is as shown in table 2. The shift time from first gear to second gear is 0.89s, which satisfies the technical requirements of less than 1s. In the whole shift process, time of adjusting speed accounts for about 47.2% of the total time. It shows that the control of motor speed has great affect on the shift quality in the shift process. Time of disengage and engage gear accounts for about 38.2%, which mainly depends on factors such as the synchronous speed, the efficiency of shift actuators; time of torque recovery is dependent on the driver request torque and the vehicle speed.

The speed difference directly affects the vehicle shift quality: the smaller the speed difference is, the shorter the shift time and the smaller the impact will. The bigger the speed difference is, the

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bigger the impact as well as the worse comfort will. In addition, from the impact of the curve can be observed: the shifting process of impact is very small, and achieves the expected effect.

Conclusion

The AMT is already in the experiment on the bus and the bus has run more than 2500 kilometers. The results showed that battery electric vehicle equipped AMT with this shift strategy effectively shortened the shifting time, reduced shifting impact, and improved the ride performance and comfort. Therefore, the development of AMT shifting technology on battery electric vehicle has great importance for the progress of China's hybrid vehicle technology and industrialization.

Acknowledgment

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