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The Seamless Gear Shifting Control for Pure Electric Vehicle with 2-speed Inverse-AMT

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Abstract: This article deals with a 2-speed inverse automated manual transmission (I-AMT). The design of this transmission permits seamless gear shifting. In order to make the transmission output torque change smoothly during shift process, a control method is put forward. The control method contains a linear feedforward control for motor and clutch during the shift torque phase and a PID control for motor during the inertia phase. The principles of the control system are confirmed through test on an AMESim simulation model of the transmission system. The simulation results indicate that the control algorithm of the transmission system can improve the ride comfort and power performance of pure electric vehicle.

Keywords: electric vehicle; inverse-AMT; simulation; gear shifting control.

1. INTRODUCTION

Recently, with the development of battery technology Battlebury (1999); Han et al. (2001), electric vehicle has developed rapidly. Many car manufacturers have introduced pure electric vehicles into the market. The drive train system of pure electric vehicle has several structures, for example,

- traditional multiple-speed transmission with clutch;
- single-speed transmission without clutch;
- two independent motors and fixed gear transmission with drive shaft;
- in-wheel motor form Ehsani et al. (2010);
- Continuously Variable Transmission (CVT) Fitz and Pires (1991);
- Double Clutch Transmission(DCT) Lu (2010),

and so on. The nature of the torque/speed characteristic of traction motor is that if the speed of motor below the base speed it has the constant torque characteristic while exceeds the base speed it has the characteristic of constant power. This feature is usually described with the speed ratio x which is defined as the speed ratio of the maximum and the base speed. The application of multiple-speed or single-speed drive train depends on the nature characteristic of traction motor, that is to say, in a given motor rated power, if it has a wide range of constant power area, the single-speed transmission at low speed can produce enough high traction torque, otherwise, it must apply multiple-speed (more than two-speed) drive train system Ehsani et al. (2010). Pure electric vehicle is usually equipped with a single-speed transmission in order to reduce drive train size, minimize the cost and also improve the transmission efficiency. The efficiency of a multiple-speed transmission system is generally lower than the efficiency of the signal-speed transmission for the same vehicle Sorniotti et al. (2011). The vehicle equipped with CVT generally presents some issues such as slow launch enberge (2004), big fuel consumption, low efficiency, easy slippage and it is not suitable for quick acceleration Smik and Pfeiffer (1999). Despite the wide speed range of the traction motor, a 2-speed gearbox may be employed in order to increase the driving torque at low vehicle velocity, therefore, increase the maximum road gradient Sorniotti et al. (2011). 2-speed transmission system appears to be suitable for pure electric vehicle in consideration of dynamic performance and energy efficiency of passenger car Sorniotti et al. (2010).

In order to improve the shift performance of AMT, a lot of control methods have been put forward, such as maps, fuzzy control Tang et al. (2002), no-linear estimation Gao et al. (2011) and so on. The control of AMT always focuses on the cooperation control of clutch, synchronizer and internal combustion engine or traction motor. The gear shifting control of AMT is expected to meet the following requirements at the same time.

- minimizing clutch lockup time;
- minimizing friction losses;
- minimizing the jerk during the shifting process;
- ensuring smooth running of vehicle.

Driving torque interruption and significant dynamic oscillation of the transmission output torque always appear during the gear shifting process of AMT. This article mainly focuses on the gear shifting of 2-speed automated manual transmission. Several researches about gear shifting of 2-speed transmission have already been proposed Sorniotti et al. (2011), but the transmission output torque has a torque hole during the gear shifting process. In order to make the transmission output torque change smoothly during the gear shift process, this article puts forward a control method which control the engagement and disengagement of clutch, synchronizer and the torque and speed of traction motor accurately.

The rest of the paper is organized as follows. In Section 2, the structure diagram of pure electric vehicle drive train system is established. The control method is introduced in detail in Section 3. Then in Section 4, a complete drive train simulation model is set up and based on the simulation model, the proposed control strategy is tested and discussed in Section 5. At last, conclusion is given in Section 6.

2. STRUCTURE DIAGRAM

The structure diagram of pure electric vehicle drive train system is illustrated in Fig. 1. The first gear is engaged by synchronizer, while the second gear connects to a dry clutch. This structure of drive train is different from traditional automated manual transmission. The transmission is located between traction motor and clutch, so it is called Inverse Automated Manual Transmission (I-AMT) Liang et al. (2012).

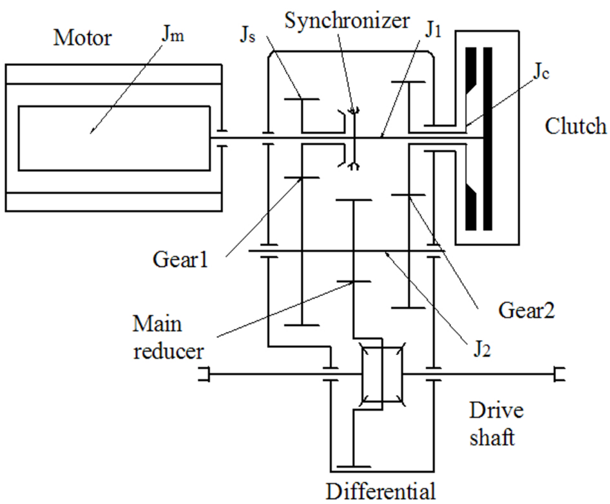

Fig. 1. The structure diagram of drive train

As mentioned above, the gear shifting of the 2-speed transmission for pure electric vehicle Sorniotti et al. (2011) is well addressed, but it has a torque hole of the transmission output torque. This article proposes a control method which can avoid this situation. The transmission output torque changes smoothly during the gear shift process.

The gear shift process is divided into the torque phase and the inertia phase. During the torque phase of upshift, the output torque of the traction motor is transferred from synchronizer to clutch, while in the inertia phase the torque transferred by synchronizer becomes zero and the clutch is synchronized. The downshift is approximately regarded as a reverse process of the upshift. The downshift starts from the inertia phase where the synchronizer is synchronized, then into the torque phase where the torque is transferred from clutch to synchronizer. During the shift process, coordinated control of the clutch, synchronizer and motor is the key to realize smooth shift and keep the transmission output torque change smoothly.

3. CONTROL ALGORITHM

As proposed, the gear shift process is divided into the torque phase and the inertia phase. During the torque phase the focus is put on the precise control of the torque transferred by clutch and the output torque of motor. In order to precisely control the output torque of motor and the torque through clutch a feedforward control is adopted. During the inertia phase, a PID (Proportion Integrative Derivative) controller is adopted to control motor speed to follow a reference speed to complete the synchronization of clutch. The control effect of gear shift is shown in Fig. 2.

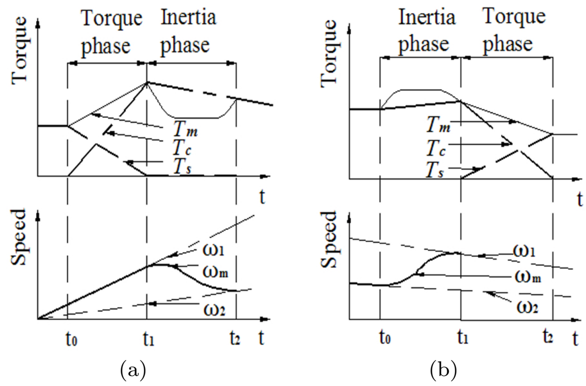

Fig. 2. The simplified diagram of upshift and downshift process in conditions of constant torque demand: (a) upshift process, (b) downshift process.

ω_1 - the first driving gear speed; ω_2 - the second driving gear speed; ω_m - Motor speed; t_0 - start time of gear shift; t_1 - phase change time; t_2 - end time of gear shift; T_m - Motor output torque; T_c - Torque through clutch; T_s - Torque through synchronizer.

The control algorithm of power-on upshift process is described in detail as follows.

3.1 Torque phase

During the torque phase, the primary shaft of the transmission has a moment of inertia J_1, which rotates together with the motor shaft (with inertia J_m and the acceleration level $\ddot{\theta}_m$), and the torque balance equation of the primary shaft is:

$$T_m - T_c - T_s = (J_m + J_1)\ddot{\theta}_m \tag{1}$$

The torque balance equations of the first driving gear (with inertia J_s) and the driven plate of clutch (with inertia J_c and the acceleration $\ddot{\theta}_c$) are:

$$T_c - T_{g2} = J_c\ddot{\theta}_c \tag{2}$$

$$T_s - T_{g1} = J_s\ddot{\theta}_m \tag{3}$$

T_{g1} and T_{g2} are the torque through the first and second gear respectively.

The second shaft of transmission has the inertia J_2 and the acceleration level $\ddot{\theta}_2$, the transmission output torque is:

$$T_{out} = (T_{g1}i_1\eta_1 + T_{g2}i_2\eta_2 - J_2\ddot{\theta}_2)i_0\eta_0 \tag{4}$$

Where i_1, i_2 and i_0 are the first, second gear and main reducer ratio respectively, η_1, η_2 and η_0 are the efficiency of the first, second gear and main reducer respectively. T_{out} is the transmission output torque.

By combing (1), (2), (3), (4) and using the definition of the gear ratios and the related kinematical relationships ($\ddot{\theta}_c = i_2\ddot{\theta}_2$, $\ddot{\theta}_m = i_1\ddot{\theta}_2$) the equation of the transmission output torque is obtained:

$$T_{out} = T_m i_1 \eta_1 i_0 \eta_0 + T_c i_0 \eta_0 (i_2\eta_2 - i_1\eta_1) - A(t) \quad (5)$$

Where $A(t) = \frac{i_0\eta_0\ddot{\theta}_m}{i_1}\ [(J_m + J_1 + J_s)i_1^2\eta_1 + J_2 + J_c i_2^2\eta_2]$.

3.2 Inertia phase

During the inertia phase of the power-on upshift process, it needs to complete the synchronization of clutch. In order to reduce the sliding friction of clutch to realize the synchronization of clutch as soon as possible, it needs to control the motor speed precisely. Moreover, a PID controller is adopted to control the motor speed to follow a reference speed which is stored in a profile. Because the lock-up of clutch tends to cause a sudden change of transmission output torque, the rotational acceleration of motor shaft should be equal to that of the driven plate of clutch at the synchronization point.

In this phase $T_s = 0$, the transmission output torque is decided entirely by the torque through clutch. The dynamic equation of the inertia J_s is:

$$T_{g1} = J_s\ddot{\theta}_2 i_1 \quad (6)$$

$$T_{out} = (T_{g2}i_2\eta_2 - T_{g1}i_1\eta_1 - J_2\ddot{\theta}_2)i_0\eta_0 \quad (7)$$

By combing equations (2), (6), (7) the transmission output torque is obtained:

$$T_{out} = T_c i_2 \eta_2 i_0 \eta_0 - B(t) \quad (8)$$

Where $B(t) = \frac{i_0\eta_0\ddot{\theta}_c}{i_2}[J_s i_1^2\eta_1 + J_2 + J_c i_2^2\eta_2]$.

In order to make sure that the transmission output torque changes smoothly during the shift gear process, it needs to control the torque through the clutch in the torque phase and the inertia phase change linearly, also with the motor output torque during the torque phase. According to the transmission output torque T_{out0} (in the time t_0), T_{out2} (in the time t_2) and the motor output torque T_{m0} (in the time t_0), the change characteristics of the torque through clutch and the motor output torque can be obtained.

In the torque phase the control law of the clutch and the motor output torque are

$$T_c = \frac{T_{out0}(t_2 - t_1) + T_{out2}(t_1 - t_0) + B(t_1)(t_2 - t_0)}{i_0\eta_0 i_2\eta_2(t_1 - t_0)(t_2 - t_0)} (t - t_0) \quad (9)$$

$$\begin{aligned} T_m = &\frac{[A(t_1)i_2\eta_2 - B(t_1)(i_2\eta_2 - i_1\eta_1)](t - t_0)}{i_0\eta_0 i_1\eta_1 i_2\eta_2(t_1 - t_0)} \\ &+[\frac{T_{out0}(t_2 - t_1)i_1\eta_1 + T_{out2}(t_1 - t_0)i_1\eta_1}{i_0\eta_0 i_1\eta_1 i_2\eta_2(t_1 - t_0)(t_2 - t_0)} - \frac{T_{m0}}{t_1 - t_0}] \\ &(t - t_0) + T_{m0} \end{aligned} \quad (10)$$

In the inertia phase the control law of the clutch is:

$$\begin{aligned} T_c = &\frac{(T_{out2} - T_{out0})t + [B(t_1) - B(t_2)](t - t_1)}{i_0\eta_0 i_2\eta_2(t_2 - t_1)} \\ &+\frac{T_{out0}t_2 - T_{out2}t_0}{i_0\eta_0 i_2\eta_2(t_2 - t_0)} \end{aligned} \quad (11)$$

The motor output torque is determined by the PID controller which provides motor torque demand. In the test conditions the equation of motor torque demand can be obtained as follows:

$$T_m = k_p\varepsilon(t) + k_i\int_{t_1}^{t_2}\varepsilon(\tau)d\tau + k_d\frac{d}{dt}\varepsilon(t)dt \quad (12)$$

Where $\varepsilon(t)$ is the speed difference between motor speed and the reference speed; k_p, k_i and k_d are the coefficient of the proportion, integrative and derivative respectively.

The value of k_p, k_i and k_d must be adjusted accurately to control the motor speed to strictly follow the reference speed. In the test conditions, the value of k_p, k_i and k_d are shown as follows:

k_p =500; k_i =1; k_d =0.2.

The downshift starts from torque phase. It needs to increase the motor speed to meet the speed of the first gear and complete the synchronization of synchronizer, then into the inertia phase. The control method of downshift is similar to upshift.

4. SIMULATION MODEL

The proposed control method is tested on a complete drive train model which is constructed by AMESim. The simulation model is illustrated in Fig. 3.

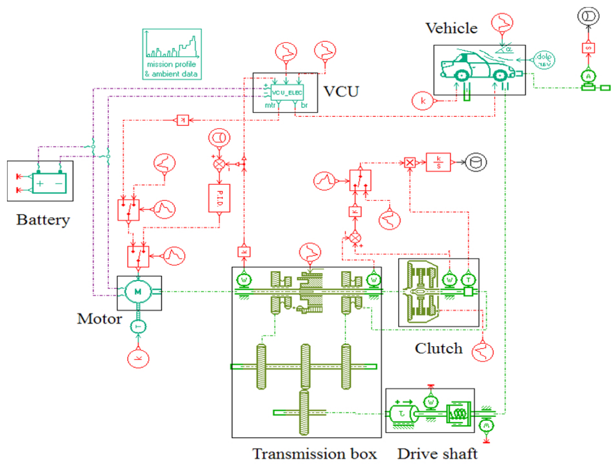

Fig. 3. The simulation model of pure electric vehicle

The external characteristic of traction motor is shown in Fig. 4. The torque of the traction motor is the function of speed and voltage. It contains an electric motor/generator with its converter. The output torque and power losses can be determined either by using data files or characteristic parameters. This model is bidirectional (motor/generator) and independent from the technology of the motor and its converter. Static operating conditions in the linear domain of the motor are considered. This model can be used for dynamic simulations if the establishing time of the current is fast enough compared to the dynamics of the other systems.

The resistive forces of vehicle consist of three parts: the climbing resistance F_{cl}, the aerodynamic drag F_{aero} and

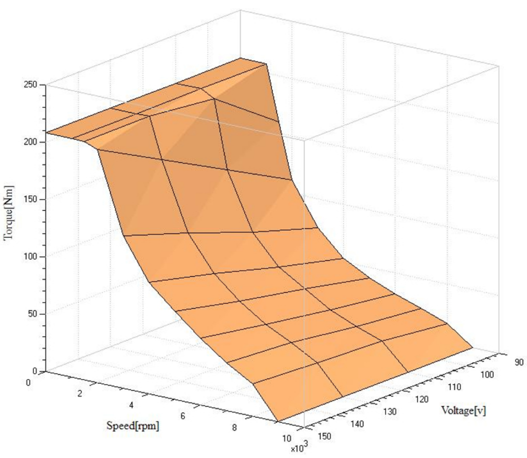

Fig. 4. The external characteristic of motor

the rolling friction force F_{roll}. The climbing resistance F_{cl} is given by:

$$F_{cl} = Mg\sin(\alpha) \tag{13}$$

The aerodynamic drag F_{aero} is calculated as follows:

$$F_{aero} = \frac{1}{2}\rho C_D A(v + v_w)^2 \tag{14}$$

The rolling friction force is regarded as constant given by:

$$F_{roll} = Mg(f + kv) \tag{15}$$

The values of parameters used in the simulation model are list in Table 1.

Table 1. The values of parameters of simulation model

U	Battery terminal voltage	300	v
i_0	Main reducer gear ratio	3.943	
i_1	Gear 1 ratio	2.28	
i_2	Gear 2 ratio	0.9	
J_c	Inertia of clutch	0.05	kgm^2
T_{cmax}	Maximum friction torque	300	Nm
I_d	Inertia of drive draft	0.1	kgm^2
C_{ds}	Friction coefficient of drive shaft	0.03	$\frac{\mathrm{Nm}}{(\mathrm{rev/min})}$
K_{ds}	Stiffness of drive shaft	50	$\frac{\mathrm{Nm}}{\mathrm{degree}}$
C_s	Damp of drive shaft	10	$\frac{\mathrm{Nm}}{(\mathrm{rev/min})}$
M	Vehicle mass	1500	kg
ρ	Air density	1.2	$\mathrm{kg/m}^3$
A	Front area	2.08	m^2
C_D	Aerodynamic drag coefficient	0.36	
f	Road friction coefficient	0.0106	
I_w	Wheel inertia	0.7	kgm^2
W_w	Tyre width	185	mm
W_d	Wheel rim diameter	0.381	m
k	Proportional friction coefficient	3.63×10^{-7}	$1/(m/s)$
v_w	Wind velocity	0	m/s
α	Road slope grade	0 / 9.5	degree
g	Acceleration of gravity	9.8	$\mathrm{m/s}^2$

5. SIMULATION RESULTS AND DISCUSSION

The power-on upshift and downshift process are tested on the proposed AMESim simulation model in the conditions of medium constant torque demand. The jerk (change rate of carbody longitudinal acceleration) is given to represent the ride comfort performance of vehicle. The friction work of clutch W is calculated as following equation.

$$W = \int_0^{t_f} T_c \Delta\omega dt \tag{16}$$

Where t_f is the engagement or disengagement time of clutch, $\Delta\omega$ is the speed difference of clutch.

The power-on upshift and downshift simulation results are shown in Fig. 5 and Fig. 6 respectively.

5.1 Power-on upshift process

During the torque phase (from 7 to 7.4s), the rotary speed of motor doesn't change greatly. While during the inertia phase (from 7.4 to 7.9s), the rotary speed changes intensively because of the clutch slip, the speed of traction motor is controlled to follow the reference speed with a PID controller and the clutch is synchronized gradually, meanwhile, the clutch torque is controlled precisely. Because of the speed regulation of the motor, the motor torque reduces significantly, thus the load of the traction motor decreases. After the clutch is locked up, the transmission output torque is determined by the traction motor torque. So it needs to control the traction motor torque to keep the transmission output torque change smoothly.

5.2 Power-on downshift process

The power-on downshift is simulated on a road with slope grade and the motor torque demand is the same as the upshift. The car runs from flat road to a slope. Due to the increase of the driving resistance, it should shift down to increase the traction torque. At first the clutch is released to a certain degree (from 32 to 32.2s), during this phase the transmission output torque is remained unchanged. The downshift process starts from the inertia phase (from 32.2 to 32.6s), when the synchronizer is synchronized the inertia phase finishes and the torque phase begins (from 32.6 to 33s), until the clutch is disengaged completely. The control method of downshift is similar to the upshift.

It can be seen from the simulation results that the max jerk of the upshift and downshift are $1.78\mathrm{m/s}^3$ and $2.7\mathrm{m/s}^3$ respectively, and the friction work of clutch are 8873J and 12183J, they are all within acceptable limits.

6. CONCLUSIONS

Based on the 2-speed Inverse Automated Manual Transmission (I-AMT), this paper proposes out a method of gear shifting control to make the transmission output torque change smoothly during the gear shifting process. The key technologies are precise speed and torque control of motor, and also the precise control of engagement and disengagement of clutch and synchronizer. The control method is tested on a complete drive train simulation model. The results indicate that the control method can make the transmission output torque change smoothly and without significant dynamic oscillation during the gear shifting process, improve the ride comfort and power performance of pure electric vehicle.

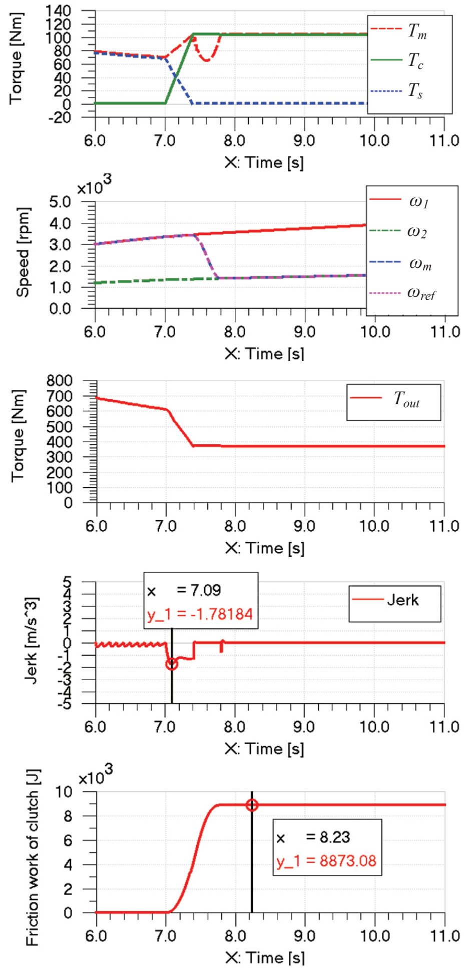

Fig. 5. The simulation results of upshift process. ω_{ref}-the reference motor speed.

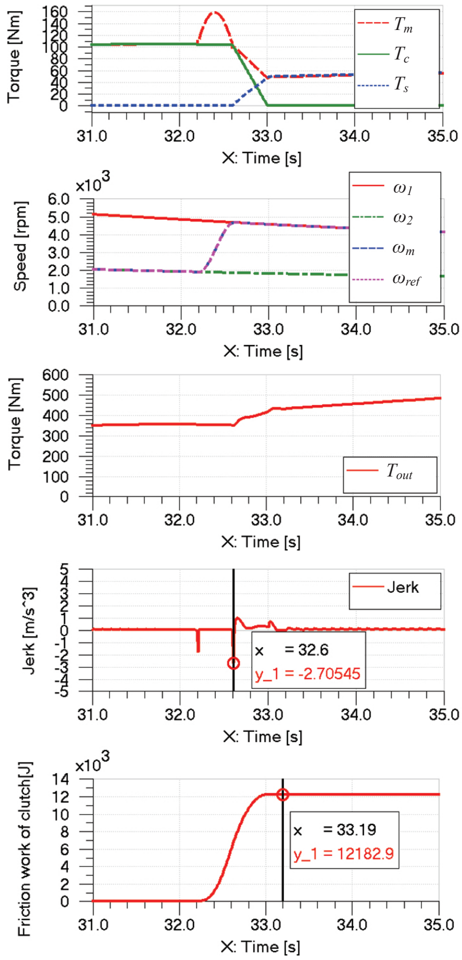

Fig. 6. The simulation results of downshift process.

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