EVS24
Stavanger, Norway, May 13-16, 2009

The control algorithm of active synchronization of motor in shifting process for electric vehicles

Hong Fu[1], Guangyu Tian, Quanshi Chen
State Key Laboratory of Automotive Safety and Energy, Tsinghua University, Beijing 100084, P. R. China
[1]*corresponding author, fuh06@mails.tsinghua.edu.cn*

Abstract

As for the propulsion system of electric vehicle, integrated motor and multi-gearbox is a suitable choice because of its low cost and improved performance, but the shifting process should be well controlled to ensure the shifting quality. This paper presents a control algorithm of active synchronization of motor. Based on electromagnetic equations of asynchronous motor, the model of field oriented control system is set up to demonstrate transient process. Then the dynamic model of integrated powertrain is presented to analyze properties during shifting. During active synchronization, the switch of control state of asynchronous motor is realized by S-Function and reference value is given considering acceleration consistency and torque shock. At the same time, corresponding torque and speed profiles of motor are presented. Next simulation models are developed to verify the effectiveness of the proposed control system. The simulation results illustrate that fast response and small speed error are achieved using active synchronization, which ensures reduced power loss and shifting comfort for electric vehicles. In addition, this control algorithm is beneficial not only for the removal of clutch, and structure simplification of the gearbox concerning non-synchronizer. By comparing with model without active synchronization, the proposed control algorithm is suitable for integrated powertrain applied to electric vehicles.

Keywords: powertrain, asynchronous motor, transmission, electric drive

1 Introduction

Electrical machine propulsion systems play an important role for efficient operation of electric vehicles, especially battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs). In order to achieve required performance, various configurations of electric drive systems have been developed [1]-[2]. When taking cost and reliability into consideration, integrated motor and multi-gearbox is a suitable choice for the propulsion system [3]-[4]. In addition, the clutch can be removed from the integrated system during automatic shifting if the propulsion motor is well controlled. Similar to automatic manual transmission without clutch [5], a reasonable control algorithm of motor should be developed to attain required torque and speed. Generally, a torque-based control scheme is applied to the driving process. But in case of shifting, speed becomes primary objective concerning fast response and negligible impact. The state switch and active synchronization of motor are necessary for such an integrated system. Therefore, this paper presents a control algorithm of active synchronization of motor, taking the switch between different states and transient properties of motor into consideration.

The remaining sections are organized as follows: Section 2 describes the electromagnetic model of asynchronous motor and dynamic model of driveline in case of different phases in shifting process. In Section 3, the active synchronization is analyzed and the profiles of torque and speed are presented. Section 4 performs simulation using MATLAB/Simulink models. The results demonstrate the effectiveness and applicability of the proposed control method. Finally, conclusion is given in Section 5.

2 Model Description

The integrated powertrain system is shown in Fig.1. An asynchronous motor is used for propulsion and it is coupled directly with a multi-gearbox. The control of power is realized by the motor controller, which also switches the motor state and accomplishes active synchronization. The function of the gearbox controller is to switch gear ratios and communicate with the motor controller.

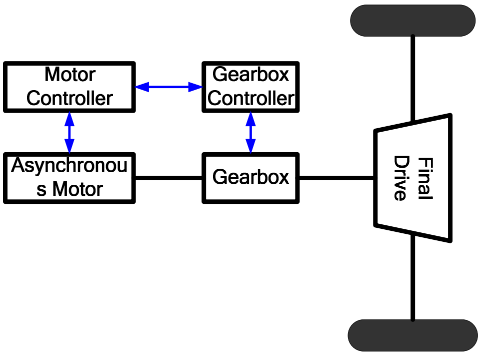

Figure 1: Powertrain schematic diagram

2.1 Asynchronous motor model

In order to analyze the transient response, field oriented control algorithm is applied to asynchronous motor. The electromagnetic equations [6] are as follows:

$$\begin{cases} u_{sd} = R_s i_{sd} + p\psi_{sd} - \omega_s \psi_{sq} \\ u_{sq} = R_s i_{sq} + p\psi_{sq} + \omega_s \psi_{sd} \\ 0 = R_r i_{rd} + p\psi_{rd} - (\omega_s - \omega_r)\psi_{rq} \\ 0 = R_r i_{rq} + p\psi_{rq} + (\omega_s - \omega_r)\psi_{rd} \end{cases} \quad (1)$$

$$\begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = L_s i_{sq} + L_m i_{rq} \\ \psi_{rd} = L_r i_{rd} + L_m i_{sd} \\ \psi_{rq} = L_r i_{rq} + L_m i_{sq} \end{cases} \quad (2)$$

$$T_e = \frac{3}{2} p_n \frac{L_m}{L_r}(i_{sq}\psi_{rd} - i_{sd}\psi_{rq}) \quad (3)$$

$$J\frac{d\omega_m}{dt} = T_e - T_L \quad (4)$$

where u_{sd}, u_{sq} are the stator voltages; i_{sd}, i_{sq} are the stator currents; Ψ_{sd}, Ψ_{sq} are the stator flux linkages; i_{rd}, i_{rq} are the rotor currents; Ψ_{rd}, Ψ_{rq} are the rotor flux linkages. All of them are physical quantities at d-q reference frame. R_s is the stator resistance; L_s is the stator inductance; R_r is the rotor resistance; L_r is the rotor inductance; L_m is the mutual inductance; p_n is the pairs of poles; J is the rotor inertia; ω_s is the stator electrical angular frequency; ω_r is the rotor electrical angular frequency; ω_m is the mechanical angular frequency; T_e is the electromagnetic torque; T_L is load; p is the differential operator.

According to equations (1)-(4) and the transformation between different reference coordinates, the field oriented control system diagram is shown in Fig. 2.

In the field oriented control system, we have

$$\frac{\psi_{rd}}{u_{sd1}} = \frac{L_m / R_s}{\sigma\tau_s\tau_r s^2 + (\tau_s + \tau_r)s + 1} \quad (5)$$

$$\frac{T_e}{u_{sq1}} = \frac{p_n L_m \psi_{rd} / R_s L_r}{\sigma\tau_s s + 1} \quad (6)$$

where τ_s is the stator time constant, $\tau_s=L_s/R_s$; τ_r is the rotor time constant, $\tau_r=L_r/R_r$; σ is the coefficient, $\sigma=1-L_m^2/(L_s \cdot L_r)$.

The complementary voltages are

$$U_{sd2} = -\omega_s \sigma L_s i_{sq} \quad (7)$$

$$U_{sq2} = \omega_s(\sigma L_s i_{sd} + \frac{L_m}{L_r}\psi_{rd}) \quad (8)$$

Then the control input voltages are

$$U_{sd} = U_{sd1} + U_{sd2} \quad (9)$$

$$U_{sq} = U_{sq1} + U_{sq2} \quad (10)$$

The function of state switch is to accomplish the switch between torque control and speed control, which is for the requirement of active synchronization.

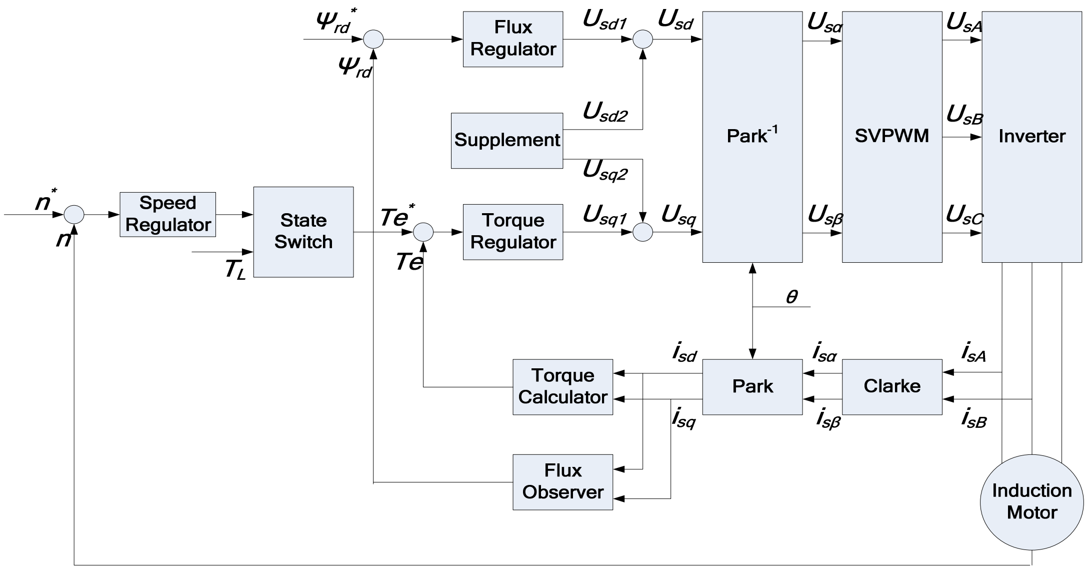

Figure 2: Field oriented control of asynchronous motor

2.2 Driveline model

The driveline can be simplified as inertia model for analysis, as shown in Fig. 3.

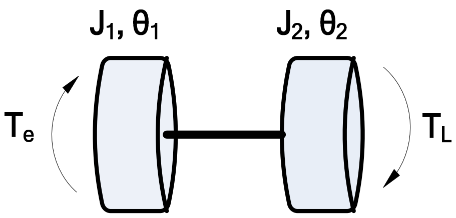

Figure 3: The driveline inertia model

where J_1 is the equivalent inertia of motor and gearbox input shaft; J_2 is the equivalent inertia of gearbox output shaft and vehicle; θ_1 is the rotor mechanical angle; θ_2 is the gearbox output shaft angle.

The dynamic equations have different forms in various phases of the shifting process.

Before disengaging gears

$$(J_1 + J_2 / i_g^2)\ddot{\theta}_1 = T_e - T_L / i_g i_0 \tag{11}$$

where, i_g is the recent gear ratio; i_0 is the final drive ratio.

After gears are disengaged, the motor switches to speed control, then

$$J_1\ddot{\theta}_1 = T_e \tag{12}$$

$$J_2\ddot{\theta}_2 = -T_L / i_0 \tag{13}$$

During the synchronizing process

$$J_1\ddot{\theta}_1 = \frac{-T_s sign(\omega_1 / i_{g(n\pm1)} - \omega_2)}{i_{g(n\pm1)}} \tag{14}$$

$$J_2\ddot{\theta}_2 = T_s sign(\omega_1 / i_{g(n\pm1)} - \omega_2) - T_L / i_0 \tag{15}$$

where T_s is the friction torque during synchronizing process; ω_1 is the mechanical angular frequency of rotor; ω_2 is the angular frequency of gearbox output shaft; $i_{g(n\pm1)}$ is objective gear ratio.

When shifting is completed and gears are engaged

$$(J_1 + J_2 / i_{g(n\pm1)}^2)\ddot{\theta}_1 = T_e - T_L / i_{g(n\pm1)} i_0 \tag{16}$$

3 Motor Active Synchronization

At the beginning of shifting, the torque of motor should be reduced to disengage gears in the absence of clutch. The duration time is required to be short to reduce the power loss and prevent the unexpected power stall.

When the gears are disengaged, control objective is switched to motor speed. Assuming the velocity of the electric vehicle almost has no change in shifting process, the objective motor speed can be expressed as the following equation.

$$n_1^* = \frac{n_{1\_g}}{i_g} i_{g(n\pm1)} \tag{17}$$

where n_1^* is the objective motor speed; $n_{1\text{-}g}$ is the motor speed before shifting.

In the condition of

$$n_2 i_{g(n\pm1)} - n_1 \le \Delta n \tag{18}$$

where n_1 is the actual motor speed; n_2 is the output speed of gearbox; Δn is the required speed error.

The gears are engaged and the control mode is switched to torque control again. In order to achieve a good shifting quality [7], equation (19) is set up.

$$\ddot{\theta}_g = \ddot{\theta}_{g(n\pm1)} \quad (19)$$

Then equation (20) is derived

$$\frac{T_{e\_g} i_g - T_L}{J_1 i_g^2 + J_2} = \frac{T_{e\_g(n\pm1)} i_{g(n\pm1)} - T_L}{J_1 i_{g(n\pm1)}^2 + J_2} \quad (20)$$

where T_{e_g} is the motor torque before shifting; $T_{e\_g(n\pm1)}$ is the objective motor torque.

In the case of $J_2 >> J_1$, we obtain

$$\frac{T_{e\_g(n\pm1)}}{T_{e\_g}} = \frac{i_g}{i_{g(n\pm1)}} \quad (21)$$

Finally, the shifting process can be described as Fig. 4 (taking upshifting for example).

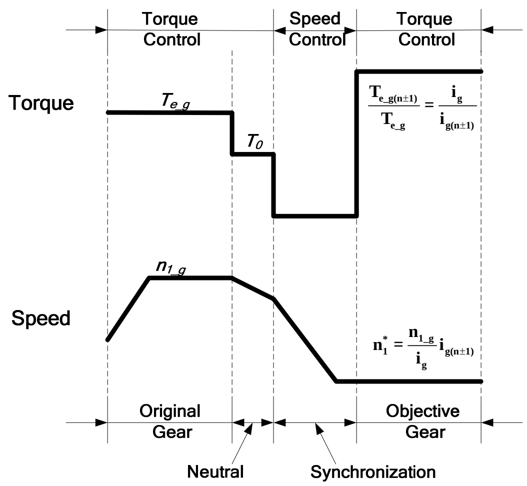

Figure 4: Torque and speed profiles of motor in shifting process

4 Simulation Results

Based on MATLAB/Simulink, the simulation model of the proposed control system is developed, and the state switch is realized by S-Function. The parameters of the asynchronous motor are shown in Table 1 and the sampling time $T_s = 10\mu s$.

Table 1: The parameters of the asynchronous motor

Parameters	Value
Power (kW)	30
DC Voltage (volt)	380
Stator Resistance (ohm)	0.0109
Stator Inductance (mH)	1.2500
Rotor Resistance (ohm)	0.0080
Rotor Inductance (mH)	1.2500
Mutual Inductance (mH)	1.2000
Rated Speed (rpm)	3600
Number of poles	4
Inertial (kg·m^2)	0.379

We assume the shifting begins at $t=0.5$ *sec* and torque and speed responses are shown in Fig. 5 and Fig. 6, which present the upshifting and downshifting between 2nd and 3rd gears, respectively. We have i_{g2}=2.722, i_{g3}=1.516 and final drive ratio i_0=3.292.

As shown in Fig. 5 and Fig. 6, the duration time is 250 ms for upshifting and 330 ms for downshifting. The profiles of the torque and speed meet the requirements of the desired ones as in Fig.4. We can see that after the period of 50 ms the motor torque T_e is reduced to 0 to disengage gears. Then the active synchronization of motor takes action. And also the absolute value of T_e becomes the maximum to ensure the fast response of n_1. In case of upshifting, it takes about 170 ms to synchronize the speed of the input and output shaft of the gearbox. We can see that n_1 varies from 2040 rpm to 1070 rpm. While the synchronization time is 250 ms for downshifting and n_1 varies from 1500 rpm to 2660 rpm. When the speed error meets requirement, the power is retrieved. In addition, synchronizers can be considered to remove from powertrain because of negligible speed error and small impact.

This paper also builds up the shifting model without motor active synchronization for comparison. The simulation results are shown in Fig. 7 and Fig. 8. For upshifting, there is a large speed gap of n_2 (from 459 rpm to 953 rpm) after completing shifting, which brings the wear of synchronizer. Meanwhile, the synchronizing time is far longer than that with active synchronization. In the case of downshifting, the maximum value of motor torque is applied during synchronizing. Even though there is almost no change on duration time, we cannot neglect the intense torque overshoot and obvious speed gap when gears are engaged.

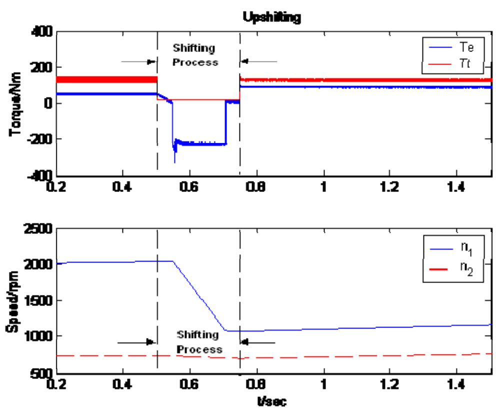

Figure 5: The upshifting process with motor active synchronization

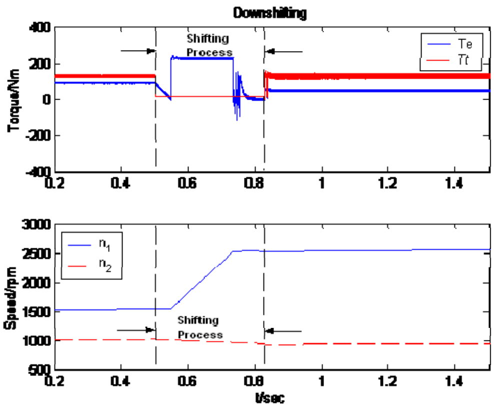

Figure 6: The downshifting process with motor active synchronization

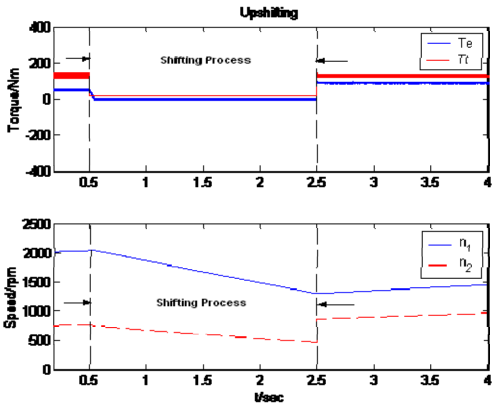

Figure 7: The upshifting process without motor active synchronization

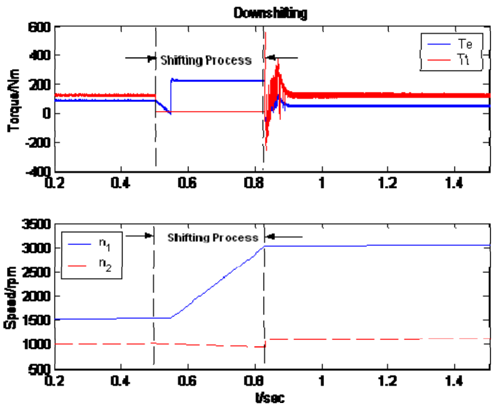

Figure 8: The downshifting process without motor active synchronization

5 Conclusion

This paper presented a control algorithm of active synchronization of motor in shifting process for electric vehicles, which can be applied to the integrated electric drive powertrain without clutch. The asynchronous motor is adopted for propulsion and the electromagnetic model is set up. Field oriented control scheme is used to analyze transient process. For the requirement of active synchronization, the state switch is added to motor control system. Then the dynamic model of driveline is built up and the different forms in various phases of the shifting process are presented. Motor active synchronization is elaborated and motor torque and speed profiles are shown. The simulation results demonstrated the effectiveness and applicability of the proposed control design. By comparing with the model without active synchronization, the proposed shifting control algorithm results in faster responses and reduced speed error. That will ensure the decrease of power loss and driving comfort for electric vehicles. Moreover, motor active synchronization is not only useful for the removal of clutch, non-synchronizer also can be considered due to controllable speed error of gears. Therefore, the proposed control algorithm of active synchronization can be applicable effectively to the shifting control of powertrain for electric vehicles.

References

[1] L.C. Chang, *Recent development of electric vehicles and their propulsion systems*, IEEE Aerospace and Electronic Systems Magazine, ISSN 0885-8985, 8(1993), 3-6

[2] M. Zeraoulia, D. Diallo, *Electric motor drive selection issues for HEV propulsion systems: A comparative study*, IEEE Vehicle Power and Propulsion Conference, ISBN 0780392809, (2005), 280-287

[3] P.E. Resele, O. Bitsche, *Advanced fully automatic two-speed transmission for electric automobiles*, SAE Special Publications, ISSN 0099-5908, (1995), 9-13

[4] B. Eberleh, Th. Hartkopf, *A high speed induction machine with two speed transmission as drive for electric vehicle*, International Symposium on Power Electronics, Electrical Drives, Automation and Motion, ISBN 1424401941, (2006), 249-254

[5] M. Pettersson, L. Nielsen, *Gear Shifting by Engine Control*, IEEE Transactions on Control Systems Technology, ISSN 1063-6536, 8(2000), 495-507

[6] D.W. Novotny, T.A. Lipo, *Vector control and dynamics of AC drives*, ISBN 0-19-856439-2, New York, Oxford University Press, 1996

[7] A. L. Ge, et. al., *The dynamic closed loop control in automatic shifting process*.

Automotive Engineering, ISSN 1000-680X, 16(1994), 276-282

Authors

Hong Fu is Ph. D candidate at the Department of Automotive Engineering, Tsinghua University, P.R. China. Her research interests include various aspects of integrated powertrain control of EVs, especially motor and transmission control.

Guangyu Tian received his Ph.D. degree in mechanical engineering in 1995 from Tsinghua University, P.R. China. Now he is the associate professor at the Department of Automotive Engineering of Tsinghua University. His current research area is system integration and vehicle control of PHEVs and FCEVs.

Quanshi Chen is the professor at the Department of Automotive Engineering, Tsinghua University, P.R. China. He is a member of Society of Automotive Engineers of China. His current research area is battery control and propulsion integration for PHEVs and FCEVs.