Electric motor control for hybrid electric vehicles based on different driving cycles

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Abstract—this paper presents a comparison of different electric motor controls-PI control and sliding mode control for a hybrid electric vehicle based on fuel cell. The control needs to track a driving cycle, which represents the vehicle speed by time. Different driving cycles (standard and recorded) are simulated, and the study shows the impact of the different driving patterns on the electric motor control. The simulation results demonstrate that sliding mode control have better dynamic performance than PI control especially when load torque changes at high frequency.

Index Terms— Hybrid electric vehicles, Electric motor control, Sliding mode control, Permanent magnet synchronous motor (PMSM)

I. Introduction

Hybrid electric vehicles (HEVs) based on fuel cell are increasingly popular due to their lower fuel consumption and exhaust emissions compared to classical vehicles with internal combustion engines. In these days, permanent magnet synchronous motors (PMSM) are often used to drive the vehicles [1, 2]. The speed of HEVs is variable depending on the driving style and pattern.

Some prior studies put forward several control strategies for variable speed of PMSM. In [3], a nonlinear adaptive state feedback controller for PMSM is designed. The controller achieves exponential speed tracking with small control gains despite the uncertainties in motor dynamics. Under the condition of both speed and load torque changing exponentially, a novel controller [4] of PMSM servo system based on Active-Disturbance Rejection Controller (ADRC) is proposed. The ADRC position controller provides a transient process for the input signal, which results in fast response and no overshooting. The proposed control system produces better performance than PI control and is robust against the modeling uncertainty and the external disturbance in various operating conditions. However, all the papers mentioned before fail to respond to variable speed of real cases. Moreover, in view of the load torque changes, the robustness of the system should be considered in controller design.

This paper shows different PMSM control strategies for standard driving cycle and recorded cycle in which the speed and load torque change following the actual situation. In the first part, the model of the vehicle is presented. Then, the methodology used to create driving cycle from recorded data is explained using Global Positioning System (GPS) acquisition recorder. Finally, simulation results for various cycles with PI control and sliding mode control are shown, followed by a conclusion.

II. Hybrid Electric Vehicle Modelling and Driving Cycle Definition

A. Architecture

The hybrid electric vehicle considered in this study is based on a series hybrid architecture [5] with fuel cell and batteries. Fig. 1 shows the drivetrain topology including the energy management system. The energy of HEV is provided by battery or/and fuel cell which is controlled by a fuzzy logic controller. Since the batteries are directly linked to the DC-bus, only the fuel cell can be actively controlled [6]. The electric motor uses PMSM, connecting to the motor controller.

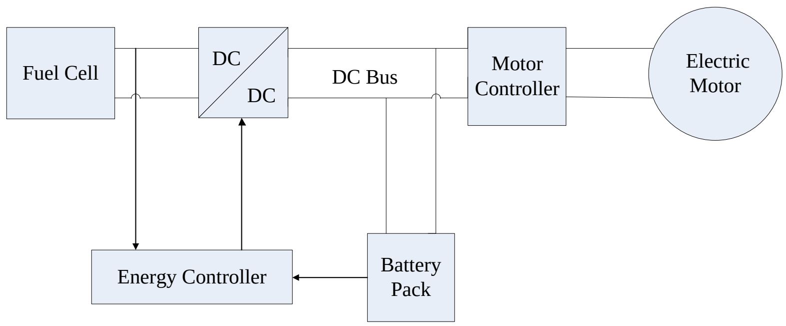


Fig. 1. Drivetrain topology of HEV based on fuel cell.

The speed and torque by time evolution described in the driving cycle are used as inputs in the motor controller and the output gives the reference power for the energy sources management.

B. Driving cycle recording

Several studies can be found in the literature using standard driving cycle as an input [7]. The aim of this work is to compare cycles, such as standardized European driving cycle (ECE) and recorded ones, and their impact on the control of PMSM motor. Real driving cycle has been recorded using a GPS recorder linked with GPRS transmission in order to measure GPS position, speed and altitude. Fig. 2 represents the principle of the GPS recorder system with a recorded driving cycle of 3 hours. The GPS records the position and altitude, then calculates the speed from the position and sends the datas to the PC through wireless network. The frequency of the measurement is set to 1 second, which is enough to obtain acceleration and deceleration phases without errors.

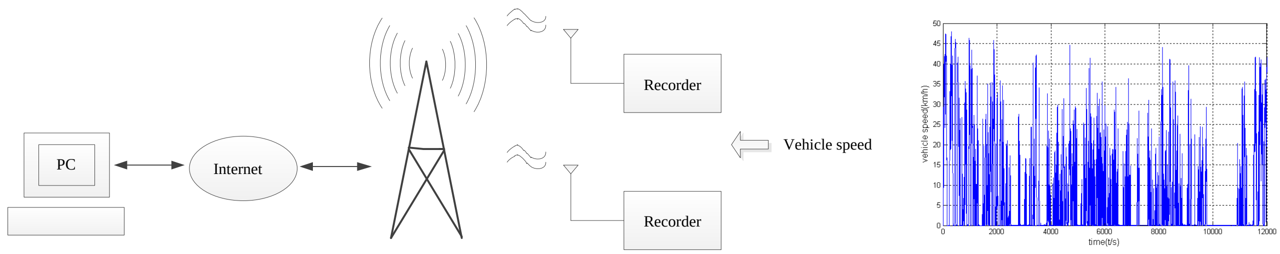


Fig. 2. Principle of the GPS recorder system.

C. Vehicle model

The Newton's second law is used to determine the instantaneous power demand of the vehicle at each step of the driving cycle [8]:

$$v(t) = \frac{P_v(t)}{F_t(t)} \tag{1}$$

$$F_t(t) = m_v(t)\frac{d}{dt}v(t) + F_a(t) + F_r(t) + F_g(t) + F_d(t) \tag{2}$$

where v is the vehicle speed, P_v is the instantaneous vehicle power, F_a is the drag force, F_r is the rolling friction, F_g is the force caused by gravity when driving on non-horizontal roads, F_d is the disturbance force that summarizes all other effects and F_t is the traction force which depends on speed, acceleration, and is used as an input of the motor controller.

III. Electric motor control

A. Electric motor model and parameters

A precise mathematical model of PMSM must be established to control the electric motor effectively. Fig. 3 shows the block diagram of PMSM system.

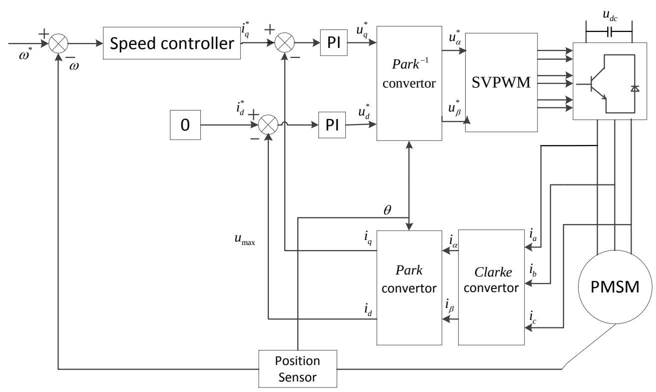


Fig. 3. Block diagram of PMSM system.

As can be seen from the PMSM in Fig. 3 the PMSM system is a double-loop system: the inner-loop is current-loop, and the outer-loop is speed-loop. In recent years, vector conversion is one of the most common schemes for the theoretical analysis of PMSM [9]. CLARK conversion and PARK conversion can convert three-phase variables in a-b-c frame to two-phase variables in d-q frame. In d-q frame, d-axis is vertical to q-axis.

According to Fig. 3, the mathematical model of PMSM can be concluded, which is expressed as:

$$\begin{cases} u_d = \dfrac{d\psi_d}{dt} - \omega_e \psi_q + R_S i_d \\ u_q = \dfrac{d\psi_q}{dt} + \omega_e \psi_d + R_S i_q \end{cases} \tag{3}$$

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{4}$$

where ω_e is motor electrical angular speed; i_d u_d and Ψ_d are current, voltage and flux linkage of d-axis respectively; i_q, u_q, and Ψ_q are current, voltage and flux linkage of q-axis respectively; R_s is the motor phase resistance; Ψ_f is the flux induced by magnets; Electromagnetic torque equation is

$$T_{em} = p_n(\psi_d i_d + \psi_q i_q) = p_n[\psi_f i_q + (L_d - L_q) i_d i_q] \tag{5}$$

where p_n is the number of pole pairs. Mechanical equation:

$$J\frac{d\omega}{dt} = T_{em} - T_L - \mathrm{R}_\Omega \omega \tag{6}$$

where J is the inertia; ω is the angular speed; R_Ω is the resistance coefficient; T_{em} is the electromagnetic torque; T_L is the load torque;

B. Control of the electric motor

In hybrid electric vehicle system, both reference speed and load torque vary with high dynamic, leading to huge external interferences which largely affect the performance of system. To solve the problem, sliding mode control is introduced [10, 11], which forces the state of the system to slide according to the pre-designed switching surface. In this way, the hybrid electric vehicle system is immune to parameter changes (such as resistance) and the outside interference, hence the accuracy and robustness of the system being improved. Two types of speed controller, PI controller [12] and sliding mode controller, are studied in this paper.

When designing the sliding mode controller, state variable is set to $x_1 = \omega^* - \omega, x_2 = \frac{dx_1}{dt}$ (7) [13], then the output of the controller is i_q^*. When the viscous friction is ignored, the mathematical model of the system in phase space is

$$\begin{cases} \frac{dx_1}{dt} = x_2 \\ \frac{dx_2}{dt} = -\frac{p_n \psi_f}{J} + \frac{T_L}{J} \end{cases} \tag{8}$$

Since the speed is limited, the sliding mode switch function is: $s = cx1 + x2$, where c is a constant. Hence the output of sliding mode controller is

$$u(t) = \psi_1 x_1 + \psi_2 x_2 \tag{9}$$

where

$$\psi_1 = \begin{cases} \alpha_1, x_1 s > 0 \\ \beta_1, x_1 s < 0 \end{cases}, \psi_2 = \begin{cases} \alpha_2, x_2 s > 0 \\ \beta_2, x_2 s < 0 \end{cases} \tag{10}$$

With $K_c = p_n \psi_f$, the parameters of the controller should meet:

$$\begin{cases} \alpha_1 > 0, \beta_1 < 0 \\ \alpha_2 > \frac{cJ}{Kc}, \beta_1 < \frac{cJ}{Kc} \end{cases} \tag{11}$$

C. Simulation results based on different driving cycles

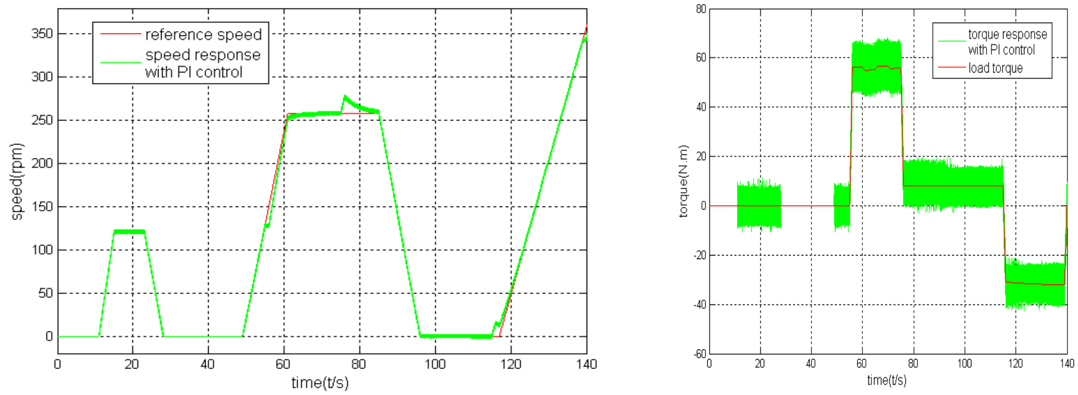
The dynamic model of electric motor presented in this paper is established based on Matlab/Simulink. Table 1 lists the parameters used in the simulation.

TABLE 1

MOTOR PARAMETERS IN SIMULTION

Symbol	Quantity	Value
P_n	Number of pole pairs	3
U_{dc}	Rated voltage(V)	280
J	Moment of inertia(Kg.m^2)	0.01046
R_s	Stator resistance(Ω)	0.26
L_d	Inductance of d-axis(H)	0.0014
L_q	Inductance of q-axis(H)	0.0014
Ψ_f	Flux induced by magnets	0.19

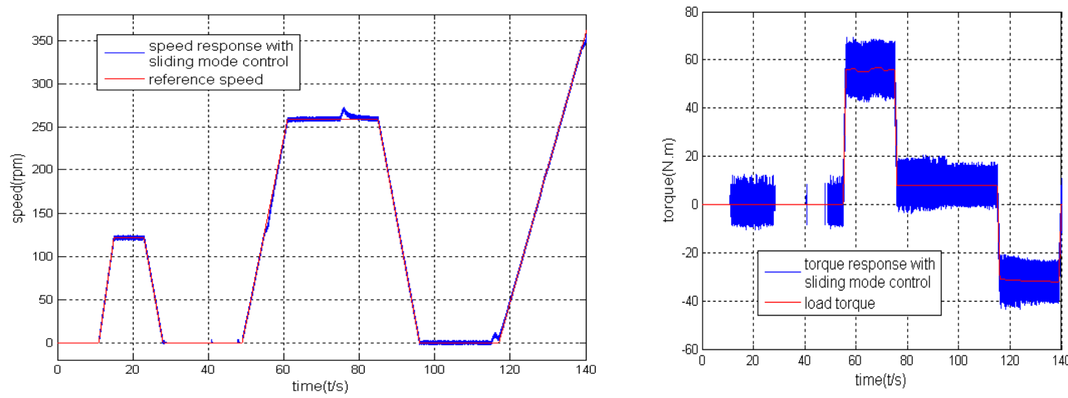
A first simulation is run on standardized ECE driving cycle. Fig. 4 and Fig. 5 emphasis a part of the cycle and show the electric motor speed and torque response compared to the inputs.



(a) speed response

(b) torque response

Fig. 4. Response of ECE cycle with PI control.



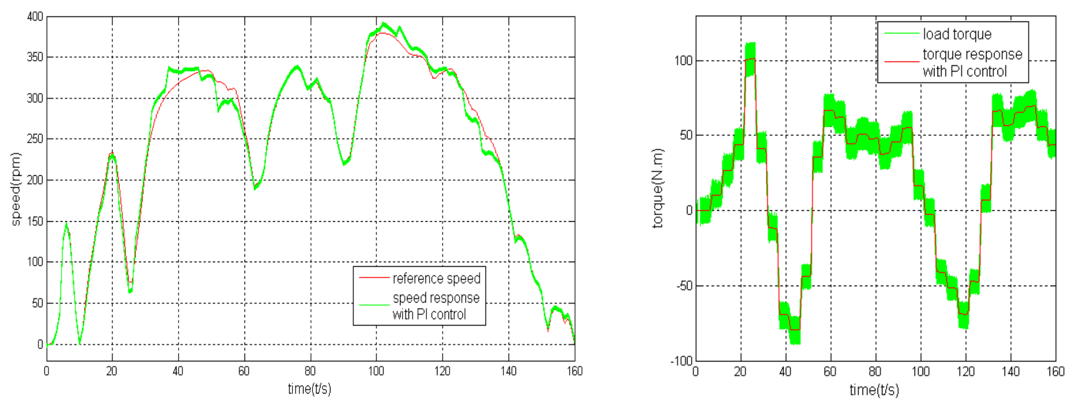
(a) speed response

(b) torque response

Fig. 5. Response of ECE cycle with sliding mode control.

Simulation results for the PI control show that the speed tracking error is higher when the load torque increases dramatically but still reasonable in Fig. 4(a). Fig. 5(a) shows the sliding mode control effects have smaller tracking error than that of PI control when torque changes greatly. As can be seen from Fig. 4(b) and Fig. 5(b), the response torques for both PI control and sliding mode control can track the load torque. However, the torque ripples are inevitable since currents are adjusted all the time.

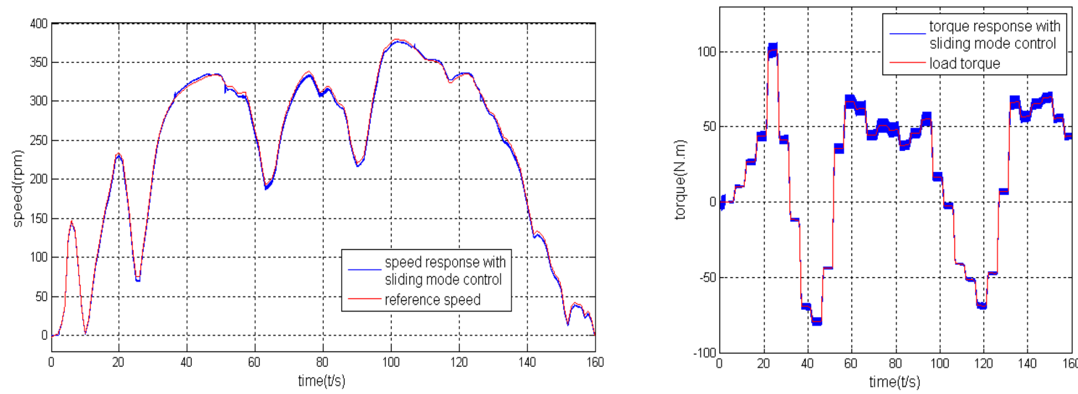
A second simulation is run on a recorded driving cycle with the GPS recorder described in section II.B. Fig.6 and Fig.7 also emphasis a part of the cycle and show the motor speed and torque response compared to the inputs.



(a) speed response

(b) torque response

Fig. 6. Response of the recorded cycle with PI control.



(a) speed response (b) torque response

Fig. 7. Response of the recorded cycle with sliding mode control.

In recorded driving cycle, the tracking error of sliding mode control is much smaller Fig. 7 (a) than PI controller Fig. 6 (a) when comparing speed responses. Moreover, the amplitude of torque ripple decreases greatly when the sliding mode control is used, which can be easily observed in Fig. 6(b) and Fig. 7(b).

IV. Conclusion

This paper compared two PMSM controls applied to HEV driving cycle. The proposed sliding mode control has excellent dynamic performance compared to PI control even when the reference speed and load torque changes at high frequency. Moreover, the selection between recorded driving cycle and standardized one has a huge impact on the results comparison of PMSM control. The high dynamic variations of speed and torque on the recorded driving cycle emphasis the results of the sliding mode control over PI control. Otherwise, in ECE cycle, where the acceleration/deceleration phases are slow, the difference between sliding mode and PI are not so relevant.

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