A Nonlinear Control Scheme for the Traction Problem in EVs with Unknown Parameters

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Abstract

This paper addresses the traction control problem for the electrical vehicles (EVs) driven by permanent magnet synchronous motor (PMSM). A robust nonlinear control law at the torque level is proposed firstly to cope with the unknown tire reaction force. A parameter estimation mechanism will be introduced to the adaptive control scheme of the system with unknown friction forces. Then, a new torque control strategy for PMSM with vector transformation is introduced to achieve the desired torque for the robust traction. It is shown that by using a kind of backstepping design approach, the goal of traction control can be achieved at electrical control level of the PMSM.

Keywords

traction control, PMSM, nonlinear system, backstepping

1. INTRODUCTION

The traction control system in a vehicle helps the driver to reduce or eliminate excessive slipping or sliding during vehicle acceleration and thus enhance the controllability and maneuverability of the vehicle. Usually, the slipping phenomenon between the road surface and tires is described by the slip ratio λ which is defined as follows [Johansson et al., 2003; Kiencke et al., 2000]

$$\lambda = (r\omega - v)/r\omega \tag{1}$$

where is the vehicle's longitudinal speed and ω is the rolling speed of the wheel. The typical traction control is to regulate the slip ratio around a constant value λ^* when the vehicle is driving on the specific road surface. Many researchers have paid their attention on such a traction control problem. Particularly, for EVs, there has been renewal of interest in this issue, since the electrical machine, as the driving power, has the fast and precise torque response property. Various design approaches to the traction control have been proposed at the driving torque level [Johansson et al., 2003; Sakai et al., 2000], and experimental results have been shown with the synchronous motor or induction motor [Shen, 2004].

On the other hand, the lack of understanding traction force is that the propulsive force is produced by friction between the rolling wheel and the surface upon which the vehicle moves. Although a number of studies on friction force are proposed for finding a proper mathematic model to describe the friction phenomena, such as [Armstrong et al., 1994] and [Canudas et al., 1995], the physical mechanism of the friction is still problematical. It's one of the main difficulties to deal with the traction control.

Evolution of the motor and driver technology makes the PMSM with vector control simpler to achieve the performance required by EVs traction problem relative to induction motor. And though the model of PMSM is simplified by using the dq transformation, the motor is still a coupled system. Due to this reason, height performance control of the PMSM is still a challenging problem.

In this paper, we propose a new design approach to the traction control algorithm for EVs driven by PMSM. At the beginning, a coordinate transformation is introduced by using the dynamics of the error S between the real slip-ratio and the set value, that is

$$S = (\lambda - \lambda^*) r\omega \tag{2}$$

With the new variable, the traction control problem is transformed to stabilize the error S. In order to adapt to the variation of road surface, the road condition is considered as the unknown parameters of the slip-ratio. And these unknown parameters are estimated by a nonlinear adaptive law. With such estimated values, a nonlinear control law for PMSM voltage is derived by the backstepping design procedure.

The remaining of this paper is organized as follows: a briefly review of the mathematics model of EV system with the dynamics of PMSM is given in section 2. In section 3, an adaptive nonlinear control law for the traction control is developed at the torque input level. And then the control law will be extended with the vector control techniques given in [Wang et al., 2004] to the motor control signal level in section 4. A design example and concluding remarks are given in the section 5 and 6, respectively.

2. PROBLEM FORMULATION

If we consider the traction problem in the longitudinal direction only, the dynamics of a car can be described by one wheel model shown in Figure 1 which is widely used in design procedure.

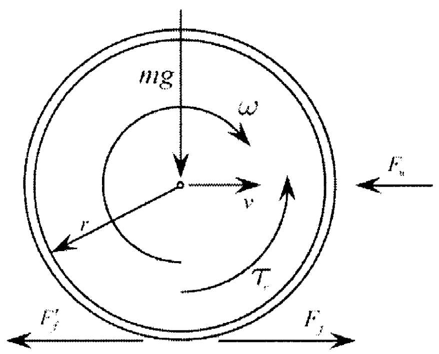

Fig. 1 One wheel system with friction force between road surface and tire

Based on Newton's motion laws, the dynamics of the wheel is given as

$$\begin{cases} m\dot{v} = F_f - F_w \\ J\dot{\omega} = \tau_e - rF_f - \sigma_w \omega \end{cases} \tag{3}$$

where m is the mass of the vehicle, J is the inertia of the driveline, r is the radius of the wheel. The dumping coefficient of mechanism in the vehicle driveline is σ_w. F_w is the token of resisting force which is in the reverse direction. If the vehicle is driving on a flat road, the resisting force is mainly produced by air resistance which has the form, F_w, $\sigma_i v$, where σ_i is a positive coefficient of air resistance [Johansson et al., 2003].

In the model (3), F_f notes the friction force between the contacting surface which can be considered as the product of the normal tire reaction force mg and the adhesion coefficient $\mu(\lambda)$, that is $F_f = mg\mu(\lambda)$. The adhesion coefficient $\mu(\lambda)$ depends on the tire-road conditions and the value of the slip-ratio λ. Figure 2 shows a set of typical μ-λ curves [Johansson et al., 2003]. In this paper, we use the following model for F_f with positive constants c_1, c_2 and c_3 which are depended on the road condition and unknown in the design [Kiencke et al., 2000].

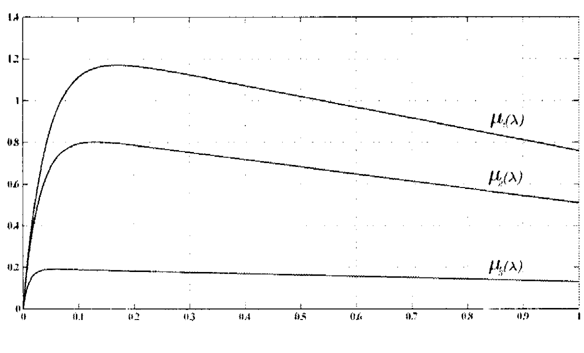

Fig. 2 Typical μ-λ curves for different road conditions

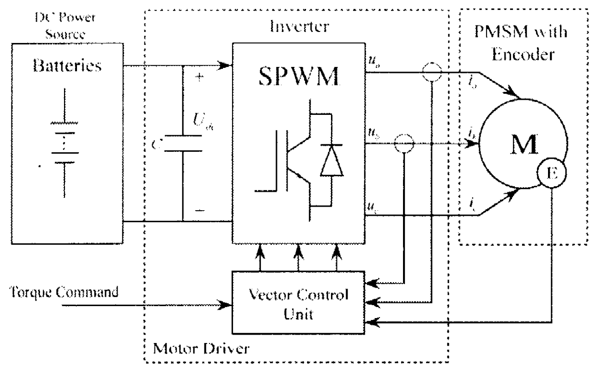

Fig. 3 The system structure of PMSM with driver

$$F_f = mg[c_1(1 - e^{-c_2\lambda}) - c_3\lambda] \tag{4}$$

For EVs which are driven by PMSM, τ_e is the traction torque acting on the wheel which is produced by PMSM. A sketch of PMSM system with driver is shown in Figure 3.

As is well-known, the dynamic of PMSM in dq frame is described as [Leonhard, 1996]

$$\begin{bmatrix} \dot{i}_d \\ \dot{i}_q \\ \dot{\omega}_m \end{bmatrix} = \begin{bmatrix} -R/L & P_m\omega_m & -K_{ed}/L \\ -P_m\omega_m & -R/L & K_{eq}/L \\ 0 & K_I/J_m & D_m/J_m \end{bmatrix} \begin{bmatrix} i_d \\ i_q \\ \omega_m \end{bmatrix} + \frac{1}{L}\begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} u_d \\ u_q \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix}\tau_l \tag{5}$$

where i_d, i_q are the current of the d-axis and q-axis respectively, R, L are the resistor and induction of stator wind respectively, P_m is number of pole pairs, J_m is the inertia of the rotor included in the inertia J of the whole driveline, ω_m is the speed of the rotor which has a the transmission ratio n of the wheel speed, that is $\omega_m = n\omega$. K_{ed}, K_{eq} are the coefficients of counter electromotive force, τ_l is the external disturbance, u_d, u_q are the control voltages of the d-axis and q-axis. The electromagnetism torque has linear relationship with the current of q-axis, i.e. $\tau_e = nK_T i_q$, where K_T is the torque coefficient. The rotor dynamic is also included in the equation (5). It's easy to achieve the following result given in [Wang et al., 2004]. If i_d, i_q and ω_m are measurable, set

$$u_d = K_{ed}\omega_m - LP_m i_q + v_d \tag{6}$$

$$u_q = LP_m i_d - K_{eq}\omega_m + v_q \tag{7}$$

then the i_d and i_q are decoupled. Because the electromagnetism torque only relates with i_d, i_q should be set to zero. With the PI controller, $v_d = -i_d(K_{dp} + K_{di}/s)$, i_d can be regulated to zero.
From the above discussion, the traction control problem is to find a proper traction torque τ_e to stabilize the variable S and use the control voltage v_q to achieve the torque requirement with the measurement of v, ω, i_d and i_q, i.e., find a algorithm $v_q(v, \omega, i_d, i_q)$ to make the error $|S| \to 0$.

3. ROBUST TRACTION CONTROL LAW

Consider the traction control system given in (3), the dynamics of S is

$$\begin{aligned}\dot{S} &= (1-\lambda^*)r\dot{\omega} - \dot{v}\\ &= -\sigma_i S/m + (\sigma_i/m - \sigma_w/J)(1-\lambda^*)r\omega + r(1-\lambda^*)\tau_e/J\\ &\quad -[m(1-\lambda^*)r^2/J+1]g\mu(\lambda)\end{aligned} \tag{8}$$

If we consider the variable S as the output of the system, the following proposition gives the zero dynamics of the car speed v with the respect to $S = 0$.

Proposition 1. The zero dynamics of the car speed v with the respect to the output $S = 0$ is stable with the car speed $v > 0$ and $v \to v^*$ where

$$v^* = mg\mu(\lambda^*)/\sigma_i \tag{9}$$

Proof. $S = 0$ implies that $\lambda = \lambda^*$ when the vehicle is driving on the road. With the similar derivation given in [4], we choose a positive definite function

$$V_1(v) = \frac{1}{2}(v - v^*)^2 \tag{10}$$

then we have the time derivation of $V_1(v)$

$$V_1(v) = -\sigma_i(v - v^*)^2/m < 0, \forall v \neq v^* \tag{11}$$

This implies that we can focus our attention on the dynamics of the state S in the following design procedure.
Choose the driving torque as

$$\begin{aligned}\tau_e^* = -\frac{J}{r(1-\lambda^*)}&\{K_1 S + (\sigma_i/m - \sigma_w/J)(1-\lambda^*)r\omega\\ &+ g[m(1-\lambda^*)r^2/J+1][MS/r\omega - \mu(\lambda^*)]\}\end{aligned} \tag{12}$$

where K_1 is any given positive number and M satisfies the following Lipschitz property

$$|\mu(\lambda) - \mu(\lambda^*)| \leq M|\lambda - \lambda^*| \tag{13}$$

where $\mu(\lambda^*) > 0$ is a constant for the specific road surface.
With such driving torque, the stability of the closed loop is achieved in the sense of Lyapunov. Define a Lyapunov function

$$V_3 = \frac{1}{2}S^2 \tag{14}$$

The time derivative of V_1 is

$$\begin{aligned}\dot{V}_3 &= S\dot{S}\\ &= -(\sigma_i/m + K_1)S^2 - g[m(1-\lambda^*)r^2/J+1]MS^2/r\omega\\ &\quad -g[m(1-\lambda^*)r^2/J+1][\mu(\lambda)-\mu(\lambda^*)]S\\ &\leq -(K_1 + \sigma_i/m)S^2 \leq 0\end{aligned} \tag{15}$$

From the above discussion, we have proved the following proposition:

Proposition 2. For the dynamics of the error S given in (8), if all the parameters are known, the feedback controller at torque level given in (12) can stabilize the state S as $t \to \infty$.
In fact, the parameters, such as $\theta = [\sigma_i\ \sigma_w\ M\ \mu(\lambda^*)]^T$, in proposition 2 are not known exactly. It is necessary to derive an adaptive law to estimate these parameters. We denote the estimates for the unknown parameters of immeasurable signals by $\hat{\theta}$, where $\hat{\theta} = [\hat{\sigma}_i\ \hat{\sigma}_w\ \hat{M}\ \hat{\mu}(\lambda^*)]^T$, and using these estimates we modify the feedback controller (12) as

$$\begin{aligned}\tau'_e &= -\frac{J}{r(1-\lambda^*)}\{K_1 S + (\hat{\sigma}_i/m - \hat{\sigma}_w/J)(1-\lambda^*)r\omega\\ &\quad + g[m(1-\lambda^*)r^2/J+1][\hat{M}S/r\omega - \hat{\mu}(\lambda^*)]\}\\ &= \tau_e^* - \frac{J}{r(1-\lambda^*)}\phi(S,\omega)\tilde{\theta}\end{aligned} \tag{16}$$

where $\tilde{\theta}$ notes the error between the estimates and real value, i.e. $\tilde{\theta} = \hat{\theta} - \theta$, and the function $\phi(S, \omega)$ is

$$\phi(S,\omega) = \begin{bmatrix}(1-\lambda^*)r\omega/m\\ -(1-\lambda^*)r\omega/J\\ gS[m(1-\lambda^*)r^2/J+1]/r\omega\\ -g[m(1-\lambda^*)r^2/J+1]\end{bmatrix}^T \tag{17}$$

The following proposition gives an adaptive law such that the closed loop coordinated by S, $\hat{\sigma}_i$, $\hat{\sigma}_w$, $\hat{M}$ and $\hat{\mu}(\lambda^*)$ is Lyapunov stable and $S \to 0$.

Proposition 3. Consider the dynamic of S with the feedback controller (16). Let the adaptation law be

$$\dot{\hat{\theta}} = S\Gamma\phi^T(S,\omega) \tag{18}$$

Then for any given initial condition $\hat{\theta}(0)$ the parameter estimates are bounded and $S \to 0$.

Proof. The dynamic of the closed loop with feedback controller (16) is

$$\begin{aligned}\dot{S} &= -(\sigma_i/m+K_1)S-[m(1-\lambda^*)r^2/J+1]g\mu(\lambda)\\ &\quad -g[m(1-\lambda^*)r^2/J+1][MS/r\omega-\mu(\lambda^*)]-\phi(S,\omega)\tilde{\theta}\end{aligned} \tag{19}$$

Introduce the Lyapunov function candidate

$$V_2 = \frac{1}{2}S^2+\frac{1}{2}\tilde{\theta}^T\Gamma^{-1}\tilde{\theta} \tag{20}$$

where $\Gamma = \{\gamma_1, \gamma_2, \gamma_3, \gamma_4\}$. Along the trajectories of the closed loop, the time derivative of V_2 is

$$\begin{aligned}\dot{V}_2 &= S\dot{S}+\tilde{\theta}^T\Gamma^{-1}\dot{\tilde{\theta}}\\ &\le -(\sigma_i/m+K_1)S^2-S\phi(S,\omega)\tilde{\theta}+\tilde{\theta}^T\Gamma^{-1}\dot{\tilde{\theta}}\end{aligned} \tag{21}$$

Note that for the constant parameters $\dot{\tilde{\theta}} = \dot{\hat{\theta}}$, substitute the adaptive law given in (18), we have

$$V_2 = S\dot{S}+\tilde{\theta}^T\Gamma^{-1}\dot{\tilde{\theta}} \le -(\sigma_i/m+K_1)S^2 \le 0 \tag{22}$$

4. BACKSTEPPING PROCEDURE FOR CONTROL VOLTAGE

In this section, the backstepping procedure is used to realize the required torque produced by PMSM. Consider the decoupled dynamics of PMSM system

$$\begin{bmatrix}\dot{i}_d\\ \dot{i}_q\end{bmatrix} = \begin{bmatrix}-R/L & 0\\ 0 & -R/L\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\frac{1}{L}\begin{bmatrix}v_d\\ v_q\end{bmatrix} \tag{23}$$

From the former discussion, we can choose a simple *PI* controller to regulate the current i_d to zero. If the electromagnetic torque is regarded to be in direct proportion to the current i_q, we introduce a new variable to express the error between the electromagnetic torque and the required torque, that is

$$e = nK_T i_q - \tau'_e \tag{24}$$

where τ'_e is given in (16). Then, the dynamics of e is

$$\begin{aligned}\dot{e} &= nK_T\dot{i}_q-\dot{\tau}'_e\\ &= nK_T(v_q-Ri_q)/L+\frac{J}{r(1-\lambda^*)}\{(\dot{\hat{\sigma}}_i/m-\dot{\hat{\sigma}}_w/J)(1-\lambda^*)r\omega\\ &\quad +g[(1-\lambda^*)r^2m/J+1][S\dot{\hat{M}}/r\omega-\dot{\hat{\mu}}(\lambda^*)]+c(\hat{\theta},\omega,S)\mu(\lambda)\\ &\quad -b(\hat{\theta},\omega)(\tilde{\sigma}_i/m-\tilde{\sigma}_w/J)(1-\lambda^*)r\omega-b(\hat{\theta},\omega)(\sigma_i/m+K_1)S\\ &\quad +a(\hat{\theta},\omega,S)[nK_Ti_q-\sigma_w\omega]+b(\hat{\theta},\omega)r(1-\lambda^*)e/J\\ &\quad -b(\hat{\theta},\omega)g[(1-\lambda^*)r^2m/J+1][\hat{M}S/r\omega-\hat{\mu}(\lambda^*)]\}\end{aligned} \tag{25}$$

where $b(\hat{\theta},\omega)$, $a(\hat{\theta},\omega,S)$ and $c(\hat{\theta},\omega,S)$ are given by

$$b(\hat{\theta},\omega) = g[(1-\lambda^*)r^2m/J+1]\frac{\hat{M}}{r\omega}+K_1 \tag{26}$$

$$\begin{aligned}a(\hat{\theta},\omega,S) &= \frac{1}{J}\{(\hat{\sigma}_i/m-\hat{\sigma}_w/J)(1-\lambda^*)r\\ &\quad -g[(1-\lambda^*)r^2m/J+1]\frac{MS}{r\omega^2}\}\end{aligned} \tag{27}$$

and

$$\begin{aligned}c(\hat{\theta},\omega,S) &= -b(\hat{\theta},\omega)[(1-\lambda^*)r^2m/J+1]g\\ &\quad -a(\hat{\theta},\omega,S)rmg\end{aligned} \tag{28}$$

With the dynamics of variable e, the control voltage v_q and the adaptive law for unknown parameters can be derived by using the similar procedure as proposition 3. The result can be summarized as the following proposition.

Proposition 4. For the dynamics of the error S given in (8), if we choose the control voltage v_q and the adaptive law $\dot{\hat{\theta}}$ as follows

$$\begin{aligned}v_q &= \Theta_i i_q+\Theta_s S+\Theta_w\omega+\Theta_e e\\ &\quad +\frac{LJ}{nrK_T(1-\lambda^*)}\{g[(1-\lambda^*)r^2m/J+1]\dot{\hat{\mu}}(\lambda^*)\\ &\quad -\hat{M}\,|\,c(\hat{\theta},\omega,S)S\,|\,\mathrm{sgn}(e)/r\omega\\ &\quad +a(\hat{\theta},\omega,S)rmg\hat{\mu}(\lambda^*)\}\end{aligned} \tag{29}$$

and

$$\dot{\hat{\theta}} = S\Gamma\phi^T(S,w)-\frac{Je}{r(1-\lambda^*)}\Gamma\Phi^T(S,\omega,\hat{\theta},e) \tag{30}$$

where the coefficients Θ_i, Θ_s, Θ_w, Θ_e and the regulation function $\Phi^T(S,\omega,\hat{\theta},e)$ are given as follows

$$
\begin{aligned}
\Theta_i &= R - \frac{LJ}{r(1-\lambda^*)} a(\hat{\theta},\omega,S) \\
\Theta_s &= -\frac{LJ}{nrK_T(1-\lambda^*)}\{(1-\lambda^*)^2 r^2 / J^2 - b(\hat{\theta},\omega)(\hat{\sigma}_i / m + K_1) \\
&\quad + \frac{g}{r\omega}[(1-\lambda^*)mr^2 + J][\dot{\hat{M}} - b(\hat{\theta},\omega)\hat{M}]\} \\
\Theta_w &= -\frac{LJ}{nrK_T(1-\lambda^*)}[(\dot{\hat{\sigma}}_i / m - \dot{\hat{\sigma}}_w / J)(1-\lambda^*)r - a(\hat{\theta},\omega,S)\hat{\sigma}_w] \\
\Theta_e &= -[\frac{LK_2}{nK_T} + \frac{Lb(\hat{\theta},\omega)}{nK_T}]
\end{aligned}
\tag{31}
$$

and

$$
\Phi^T(S,\omega,\hat{\theta},e) = \begin{bmatrix} [S-(1-\lambda^*)r\omega]b(\hat{\theta},\omega)/m \\ a(\hat{\theta},\omega,S)\omega + b(\hat{\theta},\omega)(1-\lambda^*)r\omega/J \\ -|c(\hat{\theta},\omega,S)S|\,\mathrm{sgn}(e)/r\omega \\ -c(\hat{\theta},\omega,S) \end{bmatrix} \tag{32}
$$

then the dynamics of the error S is stable. And by the proposition 1, the car speed will converge to a constant value v^*, the whole system included the car and PMSM is stable.

Proof. Introduce a Lyapunov function candidate

$$
V_4 = \frac{1}{2}S^2 + \frac{1}{2}e^2 + \frac{1}{2}\tilde{\theta}^T \Gamma \tilde{\theta} \tag{33}
$$

Substitute the feedback controller (29) into the dynamics of error S, the time derivative of V_4 is

$$
\begin{aligned}
\dot{V}_4 &= -(\sigma_i / m + K_1)S^2 - S\phi(S,\omega)\tilde{\theta} + \tilde{\theta}^T \Gamma^{-1}\dot{\tilde{\theta}} - K_2 e^2 \\
&\quad + \frac{Je}{r(1-\lambda^*)}\{c(\hat{\theta},\omega,S)[\mu(\lambda) - \mu(\lambda^*)] + b(\hat{\theta},\omega)\tilde{\sigma}_i \frac{S}{m} \\
&\quad - c(\hat{\theta},\omega,S)\tilde{\mu}(\lambda^*) - b(\hat{\theta},\omega)(\tilde{\sigma}_i / m - \tilde{\sigma}_w / J)(1-\lambda^*)r\omega \\
&\quad - \frac{\hat{M}}{r\omega}|c(\hat{\theta},\omega,S)S|\,\mathrm{sgn}(e) + \omega a(\hat{\theta},\omega,S)\tilde{\sigma}_w\}
\end{aligned}
\tag{34}
$$

in the other hand, use the Lipschitz property given in (13)

$$
\begin{aligned}
V_4 &\le -(\sigma_i / m + K_1)S^2 - S\phi(S,\omega)\tilde{\theta} + \tilde{\theta}^T \Gamma^{-1}\dot{\tilde{\theta}} - K_2 e^2 \\
&\quad + \frac{Je}{r(1-\lambda^*)}\{-\frac{\tilde{M}}{r\omega}|c(\hat{\theta},\omega,S)S|\,\mathrm{sgn}(e) \\
&\quad - c(\hat{\theta},\omega,S)\tilde{\mu}(\lambda^*) + b(\hat{\theta},\omega)\tilde{\sigma}_i \frac{S}{m} + a(\hat{\theta},\omega,S)\omega\tilde{\sigma}_w \\
&\quad - b(\hat{\theta},\omega)(\tilde{\sigma}_i / m - \tilde{\sigma}_w / J)(1-\lambda^*)r\omega\} \\
&= -(\sigma_i / m + K_1)S^2 - S\phi(S,\omega)\tilde{\theta} + \tilde{\theta}^T \Gamma^{-1}\dot{\tilde{\theta}} - K_2 e^2 \\
&\quad + \frac{Je}{r(1-\lambda^*)}\tilde{\theta}\Phi^T(S,\omega,\hat{\theta},e)
\end{aligned}
\tag{35}
$$

Substitute the adaptive law (30)

$$
V_4 = -(\sigma_i / m + K_1)S^2 - K_2 e^2 \le 0 \tag{36}
$$

Based on LaSalle invariant set theorem, the close loop is stable and $S \to 0$.

A few general remarks are in order. First, from the proposition 1, the zero dynamics of system (3) determines that the car speed will converge to a constant v^*. It implies that the car speed is determined by the set value of λ^* as $S \to 0$. This means the car can not accelerate or decelerate arbitrarily with the set point control of λ when it's running on the specific road condition.

On the other hand, although the model of friction between the road surface and the tires may not be in the form of (4), the above results are still available so long as the Lipschitz property of the friction is true. However, the model given in (4) is a continuous model which guarantees the Lipschitz property is true.

5. SIMULATION RESULTS

Figure 4 shows the result of a simulation where the adaptive control law given in proposition 3 is used to control a EV which runs through two kinds of road surface. The physical parameters of the vehicle are chosen as follows:

$$
M = 400[kg], J = 20[kg \cdot m^2], r = 0.3[m], \sigma_i = 196, \sigma_w = 0.1
$$

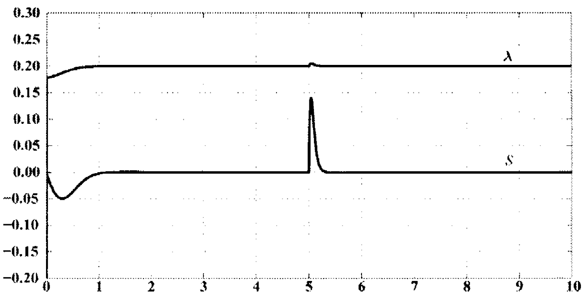

Fig. 4 The slip-ratio λ and the error S

The road condition is changed from μ_1 to μ_2 at the time $t = 15$[sec], where μ_1 describes dry asphalt with the parameters

$$
c_1 = 1.2801, c_2 = 23.99, c_3 = 0.52
$$

and μ_2 represents the snow road with

$$
c_1 = 0.1946, c_2 = 94.129, c_3 = 0.0646
$$

And the objective value λ^* is set to be 0.2.

The slip-ratio is changed as the road condition varies. With the feedback control law, the slip-ration converges

to the set value and the error S is stabilized.
The controller parameters are chosen as $K_1 = 30$ and the adaptation gains $\gamma_i = 10$ ($i = 1, 2, 3, 4$). The state of the car is shown in Figure 5. And Figure 6 shows the estimated values $\hat{\theta}$ which are converge to the constant numbers when the system is in the steady state.

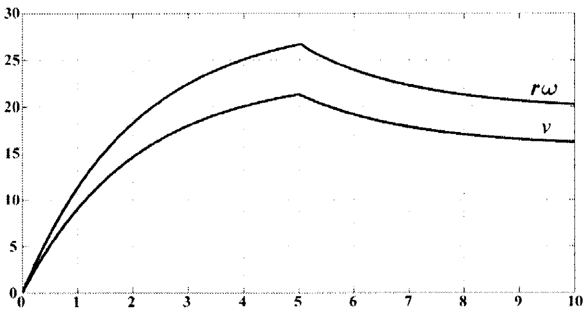

Fig. 5 The car speed v and wheel speed $r\omega$

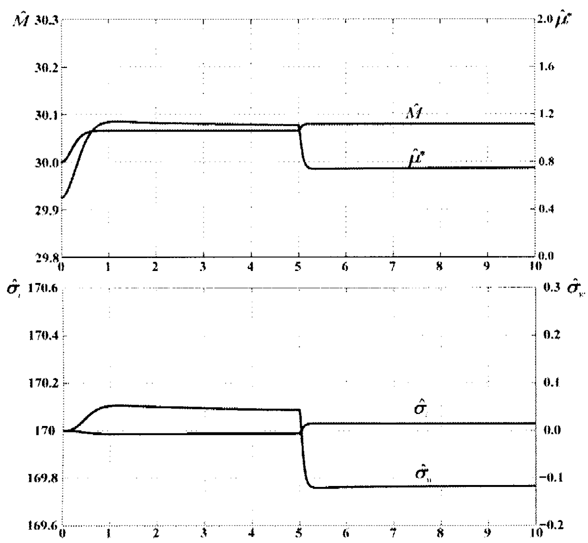

Fig. 6 The estimated values of the parameter $\hat{\sigma}_l$, $\hat{\sigma}_w$, $\hat{M}$ and $\hat{\mu}(\lambda^*)$.

6. CONCLUSION

We present a new method to design the traction control law for EV which is driven by PMSM. Using the controller, the slip ratio of the vehicle can be stabilized to a set value. And the parameters related to the road and the vehicle are estimated by the adaptation law such that feedback controller achieves more compatibility to deal with the unknown road conditions. From the view of application, the control voltage of the PMSM drive is derived, and with such an algorithm we can design the real driver for PMSM. Furthermore, simulation results imply such the closed loop is effective with the designed controller.

Acknowledgment

This work was supported in part by Nissan Diesel Co., Japan, and the author wish to thank Dr. M. Sasaki (Nissan Diesel Co.) and Mr. Y. Oguri (Sophia University) for the creative discussion with them on this research.

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