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論 文
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Design of a Speed Controller for the Separately Excited DC Motor in Application on Pure Electric Vehicles

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Abstract - In this paper, an robust adaptive backstepping controller is proposed for the speed control of separately excited DC motor in pure electric vehicles. A general electric drive train of PEV is conceptually rearrange to major subsystems as electric propulsion, energy source, and auxiliary subsystem and the load torque is modeled by considering the aerodynamic, rolling resistance and grading resistance. Armature and field resistance, damping coefficient and load torque are considered as uncertainties and noise generated at applying load torque to motor is also considered. It shows that the backstepping algorithm can be used to solve the problems of nonlinear system very well and robust controller can be designed without the variation of adaptive law. Simulation results are provided to demonstrate the effectiveness of the proposed controller.

Key Words : Separately excited DC motor, Pure electric vehicles, Adaptive backstepping, Speed controller, Load torque

1. INTRODUCTION

The continued sluggish development of pure electric vehicles (PEV) results from a lack of significant developments in battery technology and it still exhibit some limitations in battery capacity. Nevertheless, the research on PEV will be explosively performed in the future since it has many advantages over the conventional internal combustion engine vehicle such as an absence of emissions, high efficiency, independence from petroleum, and quiet and smooth operation. Much research on PEV is recently focused on how to design the control structures for the propulsion system containing an electric motor as well as the battery problems.[1]~[3]

DC motor drives are still widely used in many industries which needs appropriately speed control in a wide range such as rolling mills, paper machine, and unwinding/rewinding machines. In a separately excited DC motor (SEDCM) drive system, linear control techniques are easily applied to the system represented by linear equations in the armature control region. However, system nonlinearities begin to appear once the motor is operated in the field-weakening region due to the electromagnetic torque being a product of field and armature current, the back electromotive force being a product of field current and speed, and magnetic saturation.[4]~[6]

Recent advances in nonlinear control system resulted in the development of more sophisticated controller based on the variable structure control, feedback linearization, backstepping techniques[7]~[9]. Especially, backstepping is a newly developed nonlinear control technique, which provides a systematic framework for the design of regulation strategies suitable for a large class of state linearizable nonlinear systems exhibiting constant, but unknown parameter values.

In this paper, robust speed controller based on backstepping technique will be designed to restrain the effect of parameter variations and load torque disturbances in PEV. Simulation results will be show that the proposed controller is feasible for the wide speed control of SEDCM for PEV.

2. Problem Formalization

A general electric drive train of PEV is conceptually illustrated in Fig. 1. The drive train consists of three major subsystems as electric propulsion, energy source, and auxiliary subsystem. Based on the control inputs from accelerator and brake pedals, the vehicle controller provides proper control signals to the electronic power converter, which functions to regulate the power flow between the electric motor and energy source. There are a variety of

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possible PEV configurations due to the variations in electric propulsion characteristics and energy sources.

The choice of electric propulsion systems for PEV mainly depends on a number of factors, including driver expectation, vehicle constraints, and energy source. Driver expectation is defined by a driving profile, which includes the acceleration, maximum speed, climbing capability, braking, and range. Vehicle constraints, including volume, and weight, depend on vehicle type, vehicle weight, and payload. The energy source relates to battery, fuel cell, ultra-capacitor, flywheel, and various hybrid sources.

DC motor drives have been widely used in applications requiring adjustable speed, good speed regulation, and frequent starting, braking and reversing. Various DC motor drives have been widely applied to different electric traction applications because of their technological maturity and control simplicity. Of those three kinds of DM motors, such as series, shunt and separately excited DC motor, SEDCM is most often used in that different speed can be obtained by changing the armature and field voltage. The significant feature of SEDCM configuration is its ability to produce high starting torque at low operation speed.

Assuming the magnetization curve is taken as linear one, SEDCM is characterized by the following three differential equations.

$$\frac{d}{dt}i_a = \frac{1}{L_a}(u_a - E - R_a i_a) \quad (1)$$
$$\frac{d}{dt}i_f = \frac{1}{L_f}(u_f - R_f i_f)$$
$$\frac{d}{dt}\omega = \frac{1}{J}(T_e - B\omega - T_L)$$

where, $E = Ki_f\omega$ is the back electromotive force and $T_e = Ki_f i_a$ the developed torque (K is motor constant). i_a and i_f are armature and field currents, u_a and u_f armature and field voltages, respectively, and ω is the rotational speed of motor. R_a and R_f are armature and field resistances, L_a and L_f armature and field inductances, respectively. J, B and T_L are rotor inertia, damping coefficient and load torque, respectively.

It clearly shown in Equation 1 that the dynamic model of SEDCM is highly nonlinear by the terms of $Ki_f\omega$ (product of field current and rotational speed), $Ki_f i_a$ (product of field current and armature current). Practically, the load torque (T_L) and the armature/field resistance (R_a,

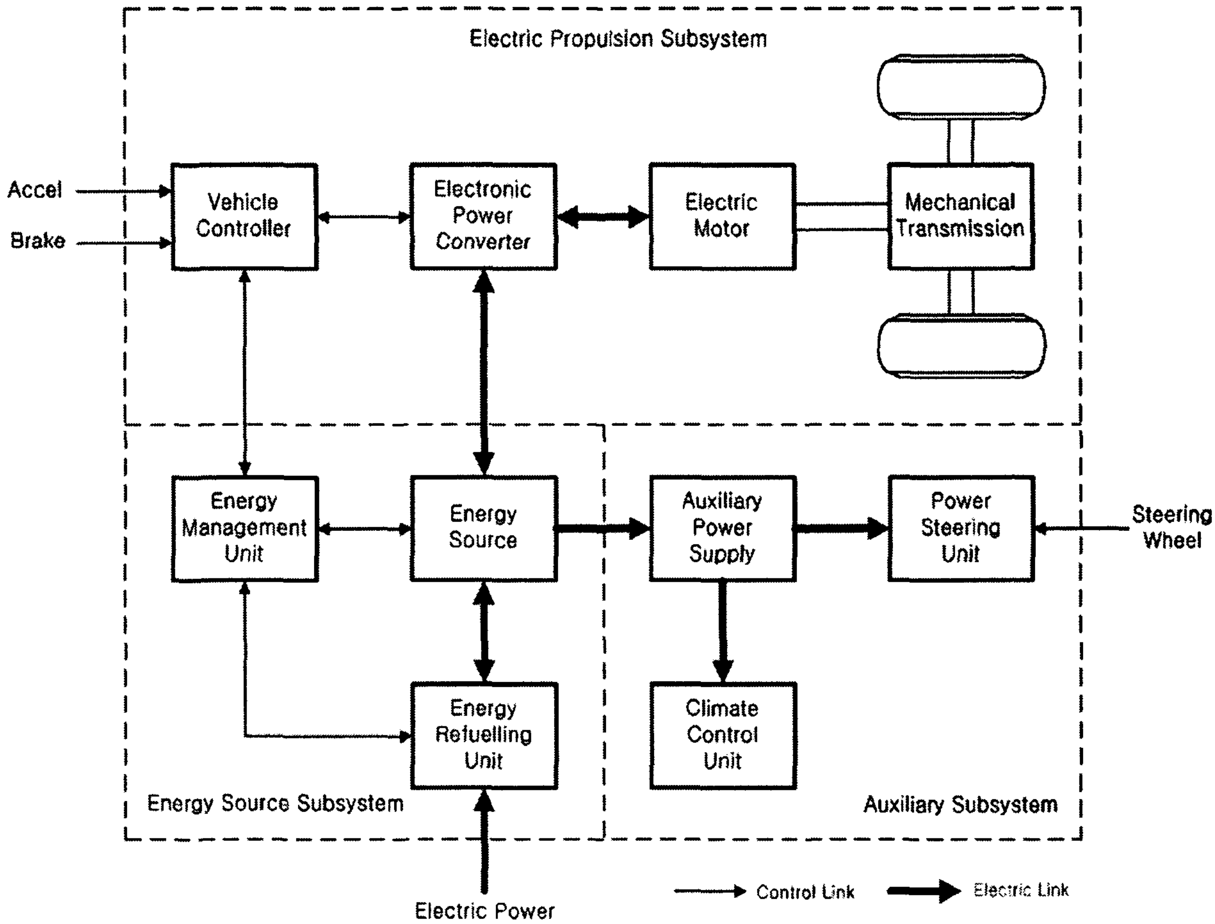


Fig. 1 Conceptual illustration of general PEV configuration

R_f) may not be exactly known or may vary and the system performance may deteriorate due to these uncertainties in the system. Thus we must design a robust controller to deal with the uncertain parameters. Generally, the load torque in PEV is modeled by considering the aerodynamic, rolling resistance and grading resistance as Fig. 2 and represented by Equation 2.

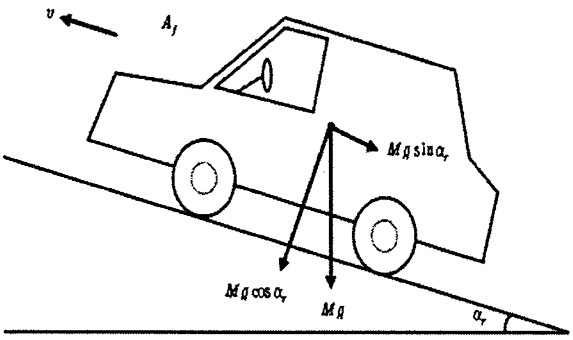


Fig. 2 Components of the load torque in PEV

$$F_a = \frac{1}{2}\rho C_d A_f v^2 \quad : \text{aerodynamic drag} \tag{2}$$
$$F_r = Mg C_r \cos\alpha_r \quad : \text{rolling resistance}$$
$$F_g = Mg\sin\alpha_r \quad : \text{grading resistance}$$
$$\text{total load torque} : T_L = \frac{R_t}{R_f}(F_a + F_r + F_g) + \delta_n$$

where, ρ is the air density, C_d is the aerodynamic drag coefficient, A_f is the frontal surface area, $v = \frac{R_t}{R_f}\omega$ is the linear speed of the vehicle, M is the mass of the vehicle, g is the gravitational constant, C_r is the rolling resistance coefficient, α_r is the grade angle as shown in Figure 2. R_t is the radius of the tires, R_f is the total ratio between the motor shaft and the differential axle of the vehicle, and δ_n represents the irregular disturbance and noise. As shown in Equation 2, the load torque is a function of rotational speed represented as follows

$$T_L = a_n\omega^2 + b_n \tag{3}$$
$$a_n = \frac{1}{2}\rho C_d A_f\left(\frac{R_t}{R_f}\right)^3$$
$$b_n = Mg(C_r\cos\alpha_r + \sin\alpha_r)\frac{R_t}{R_f} + \delta_n$$

3. Robust Speed Controller using Adaptive Backstepping

The control objective in this paper is to design a robust speed controller, which can effectively stabilize and track the desired rotational speed reference ω_{ref} and reject the effect of the parameter variations and disturbances, using the adaptive backstepping technique. Both the armature and field voltages (u_a, u_f) are taken as the control inputs.

Backstepping control is a newly developed technique for the control of uncertain nonlinear systems, particularly those systems that do not satisfy matching conditions. The most appealing point of it is to use the virtual control variable to make the original high-order system simple, thus the final control outputs can be derived step by step through suitable Lyapunov functions. The compact form of the SEDCM in Equation 1 with uncertainties can be written as follows

$$\frac{d}{dt}x = \bar{f}(x) + \Delta f(x) + g_1(x)u_a + g_2(x)u_f \tag{4}$$

$$x = [i_a \;\; i_f \;\; \omega]^T,\quad g_1 = [\frac{1}{L_a} \;\; 0 \;\; 0]^T,\quad g_2 = [0 \;\; \frac{1}{L_f} \;\; 0]^T$$

$$\bar{f}(x) = \begin{bmatrix} -\frac{K}{L_a}i_f\omega - \frac{R_{anom}}{L_a}i_a \\ -\frac{R_{fnom}}{L_f}i_f \\ \frac{K}{J}i_f i_a - \frac{B_{nom}}{J}\omega - \frac{a_{nom}}{J}\omega^2 - \frac{b_{nom}}{J} \end{bmatrix}$$

$$\Delta f(x) = \begin{bmatrix} -\frac{\Delta R_a}{L_a}i_a \\ -\frac{\Delta R_f}{L_f}i_f \\ -\frac{\Delta B}{J}\omega - \frac{\Delta a_n}{J}\omega^2 - \frac{\Delta b_n}{J} \end{bmatrix}$$

where, R_{anom}, R_{fnom}, B_{nom}, a_{nom} and b_{nom} are the nominal values of R_a, R_f, B, a_n and b_n, respectively. Define the uncertainties as $\Delta R_a = R_a - R_{anom}$, $\Delta R_f = R_f - R_{fnom}$, $\Delta B = B - B_{nom}$, $\Delta a_n = a_n - a_{nom}$ and $\Delta b_n = b_n - b_{nom}$.

STEP 1 : Define the new variables as follow

$$z_1 = h_1(x) = \omega,\quad z_2 = L_{\bar{f}}h_1(x),\quad z_3 = h_2(x) = i_f \tag{5}$$

In the new coordinates, the system can be written as follows

$$\frac{d}{dt}\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} z_2 \\ L_{\bar{f}}^2 h_1 \\ L_{\bar{f}} h_2 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}\begin{bmatrix} \bar{u}_a \\ \bar{u}_f \end{bmatrix} + \begin{bmatrix} \theta_1\phi_1 \\ \theta_2\phi_2 \\ \theta_3\phi_3 \end{bmatrix} \tag{6}$$

$$\theta_1\phi_1 = [\theta_{11} \;\; \theta_{12} \;\; \theta_{13}][\phi_{11} \;\; \phi_{12} \;\; \phi_{13}]^T = \left[\frac{\Delta a_n}{J} \;\; \frac{\Delta B}{J} \;\; \frac{\Delta b_n}{J}\right][-\omega^2 \;\; -\omega \;\; -1]^T$$

$$\theta_2\phi_2 = [\theta_{21}\ \ \theta_{22}\ \ \theta_{23}\ \ \theta_{24}\ \ \theta_{25}][\phi_{21}\ \ \phi_{22}\ \ \phi_{23}\ \ \phi_{24}\ \ \phi_{25}]^T$$
$$= \begin{bmatrix} \frac{K}{J}(\frac{\Delta R_a}{L_a}+\frac{\Delta R_f}{L_f}) \\ \frac{2a_{nom}\Delta a_n}{J^2} \\ \frac{B_{nom}\Delta a_n + 2a_{nom}\Delta B}{J^2} \\ \frac{B_{nom}\Delta B + 2a_{nom}\Delta b_n}{J^2} \\ \frac{B_{nom}\Delta b_n}{J^2} \end{bmatrix}^T \begin{bmatrix} -i_f i_a \\ \omega^3 \\ \omega^2 \\ \omega \\ 1 \end{bmatrix}$$

$$\theta_3\phi_3 = [\frac{\Delta R_f}{L_f}][-i_f]$$

The uncertainties of the system now are reflected by the three unknown constant parameters as θ_1, θ_2 and θ_3, where, θ_1, θ_2 are vectors and θ_3 is scalar. The Lie derivatives in Equation 6 are as follows

$$L_f^2 h_1 = -\frac{Ki_f}{JL_a}(Ki_f\omega + R_{anom}i_a) - \frac{Ki_a}{JL_f}R_{fnom}i_f - \frac{B_{nom}+2\omega a_{nom}}{J^2}(Ki_f i_a - a_{nom}\omega^2 - B_{nom}\omega - b_{nom}) \quad (7)$$
$$L_f h_2 = \frac{1}{L_f}(-R_{fnom}i_f)$$

and the new control inputs are related the original control inputs as follows

$$\begin{bmatrix} \bar{u}_a \\ \bar{u}_f \end{bmatrix} = \begin{bmatrix} L_{g1}L_f h_1 & L_{g2}L_f h_1 \\ 0 & L_{g2}h_2 \end{bmatrix} \begin{bmatrix} u_a \\ u_f \end{bmatrix} \quad (8)$$

$$L_{g1}L_f h_1 = \frac{Ki_f}{JL_a}, \quad L_{g2}L_f h_1 = \frac{Ki_a}{JL_f}, \quad L_{g2}h_2 = \frac{1}{L_f}$$

Now, a reference model is used to assign the desired output dynamic behaviour in the following

$$\frac{d}{dt}\begin{bmatrix} z_{m1} \\ z_{m2} \\ z_{m3} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 \\ -k_{m1} & -k_{m2} & 0 \\ 0 & 0 & -k_{m3} \end{bmatrix}\begin{bmatrix} z_{m1} \\ z_{m2} \\ z_{m3} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ k_{m1} & 0 \\ 0 & k_{m3} \end{bmatrix}\begin{bmatrix} \omega_{ref} \\ i_{fref} \end{bmatrix} \quad (9)$$

where, the model parameters k_{m1}, k_{m2} and k_{m3} are chosen by the designer for obtaining the response characteristics. The inputs of reference model are the rotational speed command ω_{ref} and the field current command i_{fref} and <u>in this paper we will use the method that the control inputs are only burdened by the armature current i_a while the filed current i_f is kept to constant.</u> Using the reference model, the performance of the system can be evaluated, as the tracking problem could be changed to a regulation problem. Define the error variables as

$$e = [e_1\ \ e_2\ \ e_3]^T = [z_1 - z_{m1}\ \ \ z_2 - z_{m2}\ \ \ z_3 - z_{m3}]^T \quad (10)$$

and use the following transformation

$$\tilde{U} = \begin{bmatrix} \tilde{u}_a \\ \tilde{u}_f \end{bmatrix} = \begin{bmatrix} \bar{u}_a + k_{m1}z_{m1} + k_{m2}z_{m2} - k_{m1}\omega_{ref} \\ \bar{u}_f + k_{m3}z_{m3} - k_{m3}i_{fref} \end{bmatrix} \quad (11)$$

Then the differential equations of the errors can be derived as follows

$$\frac{d}{dt}e = \bar{A}(x) + \Delta A(x) + B(x)\tilde{U} \quad (12)$$

$$\bar{A}(x) = \begin{bmatrix} e_2 \\ L_f^2 h_1 \\ L_f h_2 \end{bmatrix}, \quad \Delta A(x) = \begin{bmatrix} \theta_1\phi_1 \\ \theta_2\phi_2 \\ \theta_3\phi_3 \end{bmatrix}, \quad B(x) = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

The uncertain parameter errors are defined as

$$\tilde{\theta}_1 = \theta_1 - \hat{\theta}_1, \quad \tilde{\theta}_2 = \theta_2 - \hat{\theta}_2, \quad \tilde{\theta}_3 = \theta_3 - \hat{\theta}_3 \quad (13)$$

where, $\hat{\theta}_1$, $\hat{\theta}_2$, $\hat{\theta}_3$ are the estimations of θ_1, θ_2, θ_3 and $\tilde{\theta}_1$, $\tilde{\theta}_2$, $\tilde{\theta}_3$ the estimation errors, respectively.

<u>**STEP 2**</u> : For the Equation 12, e_2 is taken as the new control input according to backstepping control technique. It can be easily obtained that, if the uncertain parameter θ_1 is known, the Equation 12 is obviously stable by a Lyapunov function $V_1 = \frac{1}{2}e_1^2$ and a virtual controller will be $\alpha' = -k_1 e_1 - \theta_1\phi_1$. However, θ_1 is actually unknown and e_2 can not the real control. Hence an estimation $\hat{\theta}_1$ is used to replace θ_1 and define the new virtual control α for e_2 as follows

$$\alpha = -k_1 e_1 - \hat{\theta}_1\phi_1 \quad (14)$$

where, k_1 is a control gain. Then define new error variables as

$$\bar{e}_1 = e_1, \quad \bar{e}_2 = e_2 - \alpha, \quad \bar{e}_3 = e_3 \quad (15)$$

The derivatives of the new error variables can be conducted as follows

$$\frac{d}{dt}\bar{e}_1 = \bar{e}_2 + \alpha + \theta_1\phi_1 = -k_1\bar{e}_1 + \bar{e}_2 + \tilde{\theta}_1\phi_1 \quad (16)$$
$$\frac{d}{dt}\bar{e}_2 = \frac{d}{dt}e_2 - \frac{d}{dt}\alpha$$
$$= L_f^2 h_1 + \theta_2\phi_2 + \tilde{u}_a + k_1\frac{d}{dt}\bar{e}_1 + \phi_1^T\frac{d}{dt}\hat{\theta}_1^T + \hat{\theta}_1\frac{d}{dt}\phi_1$$
$$\frac{d}{dt}\bar{e}_3 = L_f h_2 + \theta_3\phi_3 + \tilde{u}_f$$

Now, the nonlinear adaptive controller and the adaptation laws can be easily designed by a suitable Lyapunov function in the next step.

STEP 3 : Define the final Lyapunov function as follows

$$V=\frac{1}{2}\bar{e}_1^2+\frac{1}{2}\bar{e}_2^2+\frac{1}{2}\bar{e}_3^2+\frac{1}{2\gamma_1}\tilde{\theta}_1\tilde{\theta}_1^T+\frac{1}{2\gamma_2}\tilde{\theta}_2\tilde{\theta}_2^T+\frac{1}{2\gamma_3}\tilde{\theta}_3^2 \tag{17}$$

where, γ_1, γ_2 and γ_3 are the adaptation gains. The derivative of the Lyapunov function becomes as follows

$$\begin{aligned}\frac{d}{dt}V &= \bar{e}_1\frac{d}{dt}\bar{e}_1+\bar{e}_2\frac{d}{dt}\bar{e}_2+\bar{e}_3\frac{d}{dt}\bar{e}_3 \\ &\quad +\frac{1}{\gamma_1}\tilde{\theta}_1\frac{d}{dt}\tilde{\theta}_1^T+\frac{1}{\gamma_2}\tilde{\theta}_2\frac{d}{dt}\tilde{\theta}_2^T+\frac{1}{\gamma_3}\tilde{\theta}_3\frac{d}{dt}\tilde{\theta}_3 \\ &= -k_1\bar{e}_1^2+\tilde{\theta}_1[\bar{e}_1\phi_1+k_1\bar{e}_2\phi_1+\frac{1}{\gamma_1}\frac{d}{dt}\tilde{\theta}_1^T] \\ &\quad +\tilde{\theta}_2[\bar{e}_2\phi_2+\frac{1}{\gamma_2}\frac{d}{dt}\tilde{\theta}_2^T]+\tilde{\theta}_3[\bar{e}_3\phi_3+\frac{1}{\gamma_3}\frac{d}{dt}\tilde{\theta}_3] \\ &\quad +\bar{e}_2[\bar{e}_1+L_f^2h_1+\hat{\theta}_2\phi_2+\tilde{u}_a-k_1^2\bar{e}_1+k_1\bar{e}_2 \\ &\quad +\phi_1^T\frac{d}{dt}\hat{\theta}_1^T+\hat{\theta}_1\frac{d}{dt}\phi_1]+\bar{e}_3[L_fh_2+\hat{\theta}_3\phi_3+\tilde{u}_f]\end{aligned} \tag{18}$$

The simplest way to make $\frac{d}{dt}V\le 0$ (negative definite) will be to make the items in the square brackets in the second, third and fourth items equal to zero to cancel the uncertainties and make the fifth term equal to $-k_2\bar{e}_2^2$, the sixth term equal to $-k_3\bar{e}_3^2$, where, k_2 and k_3 are also control gains as k_1. Then the following results(control and adaptive laws) can be obtained.

$$\begin{aligned}\tilde{u}_a &= -k_2\bar{e}_2-\bar{e}_1-L_f^2h_1-\hat{\theta}_2\phi_2+k_1^2\bar{e}_1 \\ &\quad -k_1\bar{e}_2-\phi_1^T\frac{d}{dt}\hat{\theta}_1^T-\hat{\theta}_1\frac{d}{dt}\phi_1 \\ \tilde{u}_f &= -k_3\bar{e}_3-L_fh_2-\hat{\theta}_3\phi_3\end{aligned} \tag{19}$$

$$\begin{aligned}\frac{d}{dt}\hat{\theta}_1 &= \gamma_1(\bar{e}_1+k_1\bar{e}_2)\phi_1^T \\ \frac{d}{dt}\hat{\theta}_2 &= \gamma_2\bar{e}_2\phi_2^T \\ \frac{d}{dt}\hat{\theta}_3 &= \gamma_3\bar{e}_3\phi_3\end{aligned} \tag{20}$$

Thus, the derivative of the Lyapunov function is negative definite as follows

$$\frac{d}{dt}V=-k_1\bar{e}_1^2-k_2\bar{e}_2^2-k_3\bar{e}_3^2\le 0 \tag{21}$$

Through Barbalat's lemma [9], it can be shown that $\bar{e}_1$, $\bar{e}_2$ and $\bar{e}_3$ will be converge to zero as $t\to\infty$. Therefore it can be concluded that the tracking objectives of the rotational speed ω and the field current i_f have been

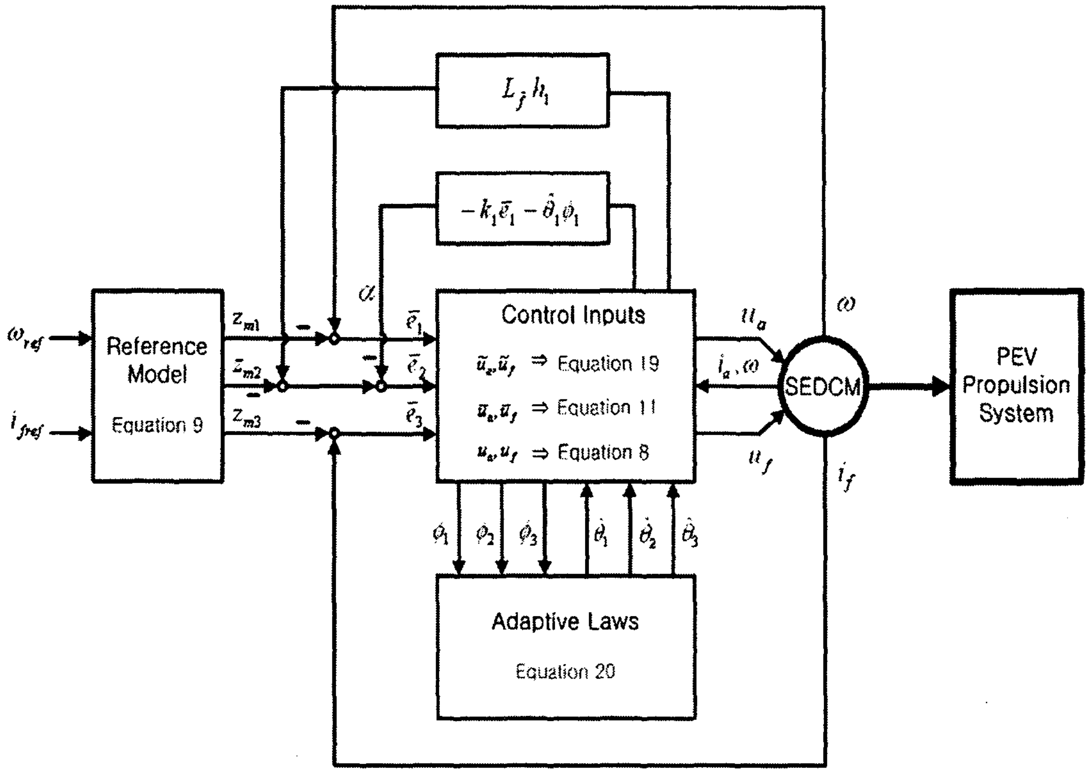


Fig. 3 Block diagram of the proposed control system

achieved under parameter uncertainties and load torque disturbance. The block diagram of the nonlinear controller and adaptation laws for a speed tracking of SEDCM in PEV is given in Fig. 3.

4. Simulation Results

Computer simulations will be provided to demonstrate the effectiveness of the proposed controller by using Turbo-C language. System parameters for the motor(SEDCM) and the vehicle(PEV) are setting as shown in Table 1 and 2, respectively. Design parameters for the proposed controller is setting as shown in Table 3.

Table 1. Motor parameter values of the SEDCM

Nomenclature (Symbol)	Setting Value [Unit]
Rated Power (P)	4[kW]
Rated Speed (ω)	200[rad/sec]
Rated Torque (T)	20[N · m]
Armature Inductance (L_a)	0.013[H]
Armature Resistance (R_a)	1.2[Ω]
Field Inductance (L_f)	60[H]
Field Resistance (R_f)	60[Ω]
Motor Constant (K)	0.3[N · m/A^2]
Rotor Inertia (J)	0.208[kg · m^2]
Damping Coefficient (B)	0.011[kg · m^2/sec]

Table 2. Vehicle parameter values of the model PEV

Nomenclature (Symbol)	Setting Value [Unit]
Radius of Tire (R_t)	0.2[m]
Axle Ratio (R_f)	4.0
Air Density (ρ)	1.2
Drag Coefficient (C_d)	0.4
Frontal Surface (A_f)	1.0[m^2]
Vehicle Mass (M)	30[kg]
Rolling Coefficient (C_r)	0.015
Grade Angle (α_r)	5[deg]

Table 3. Design parameter values of the closed loop

Parameter	Setting Value
Reference Model	$k_{m1} = 160,\ k_{m2} = 23,\ k_{m3} = 50$
Adaptation Gain	$\gamma_1 = 0.00001,\ \gamma_2 = 0.001,\ \gamma_3 = 0.01$
Control Gain	$k_1 = 100,\ k_2 = 200,\ k_3 = 200$

The reference motor speed is depicted in Fig. 4. It represents typical acceleration, constant speed and deceleration behaviors in a electric vehicle. The variations of load torque are appropriately given as a several sine functions and white noises. Fig. 5 show the simulation results. It is clearly known that the motor speed is tracking to the reference very well and speed tracking error($e_1 = z_1 - z_{m1} = \omega - \omega_{ref}$) decrease into ±20[rpm] ranges after 20[sec].

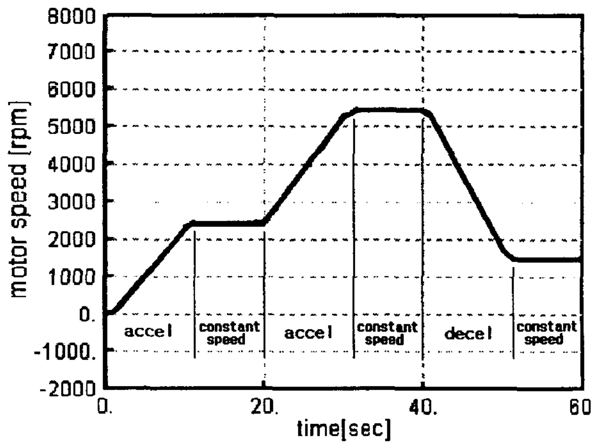
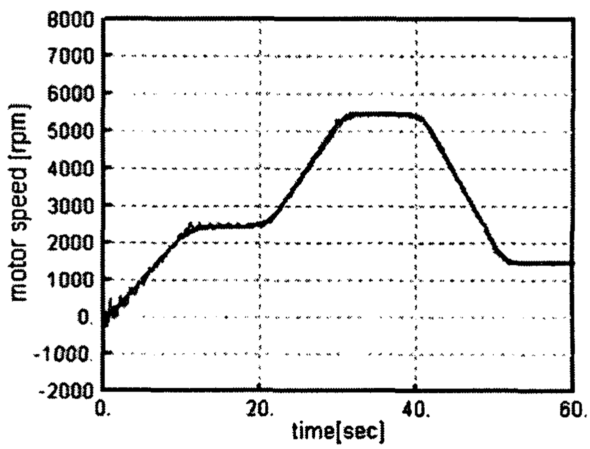
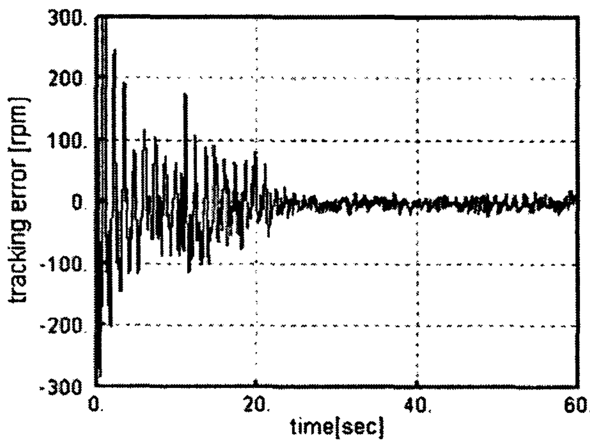


Fig. 4 Curve for reference motor speed



(a) Motor speed (red) and reference (black)



(b) Tracking error

Fig. 5 Simulation results

5. Conclusions

In this paper, an robust adaptive backstepping controller was proposed for the speed control of separately excited DC motor (SEDCM) in pure electric vehicles (PEV). A general electric drive train of PEV was conceptually rearrange to major subsystems as electric propulsion, energy source, and auxiliary subsystem and the load torque was modeled by considering the aerodynamic, rolling resistance and grading resistance. Armature and field resistance, damping coefficient and load torque were considered as uncertainties and noise generated at applying load torque to motor is also considered. We have used the method that the control inputs are only burdened by the armature current while the filed current is kept to constant. It shown that the backstepping algorithm can be used to solve the problems of nonlinear system very well and robust controller can be designed without the variation of adaptive law. Simulation results were provided to demonstrate the effectiveness of the proposed controller.

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