2006년도 대한전기학회 전문대학교육위원회 학술대회 논문집 2006.10.20-10.21

순 전기 자동차용 타여자 직류기의 속도제어기 설계

현근호
신성대학 디지털전기계열

Design of a Speed Controller for the Separately Excited DC Motor in Pure Electric Vehicle Applications

Keun-Ho Hyun
Department of Digital Electrical Engineering, Shinsung College

Abstract - In this study, an robust adaptive backstepping controller is proposed for the speed control of separately excited DC motor with uncertainties and disturbances. 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 and experiment results are provided to demonstrate the effectiveness of the proposed controller in the future.

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]

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.[2]

Recent advances in nonlinear control system resulted in the development of more sophisticated controller based on the variable structure control, feedback linearization, backstepping techniques.[3] 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.

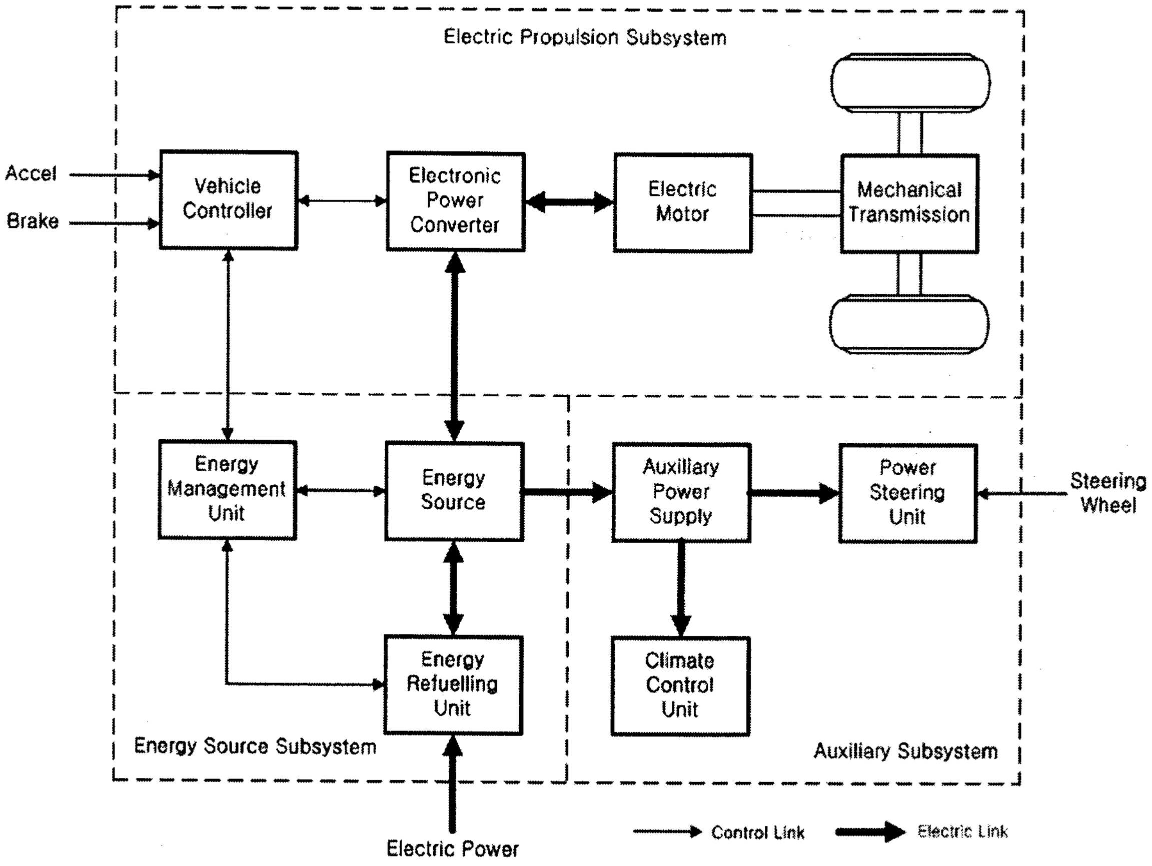
In this paper, robust speed controller based on backstepping technique will be designed to restrain the effect of parameter variations and load torque disturbances in PEV. Simulation results will be show that the proposed controller is feasible for the wide speed control of SEDCM for PEV.

2. Problem formalization

A general electric drive train of PEV is conceptually illustrated in Figure 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 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



<Figure 1> Conceptual illustration of general PEV configuration

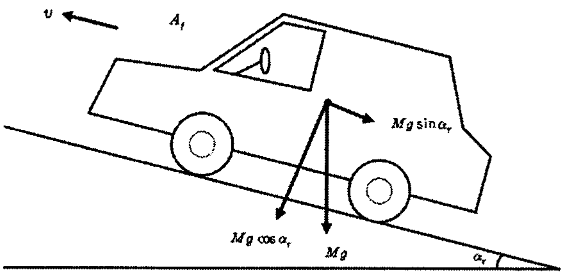
voltage. The significant feature of SEDCM configuration is its ability to produce high starting torque at low operation speed.

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

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

where, $E = K i_f \omega$ is the back electromotive force and $T_e = K i_f i_a$ 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 $K i_f \omega$ (product of field current and rotational speed), $K i_f i_a$ (product of field current and armature current). Practically, the load torque (T_L) and the armature/field resistance (R_a,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 Figure 2 and represented by Equation 2.



<Figure 2> Components of the load torque in PEV

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

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

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

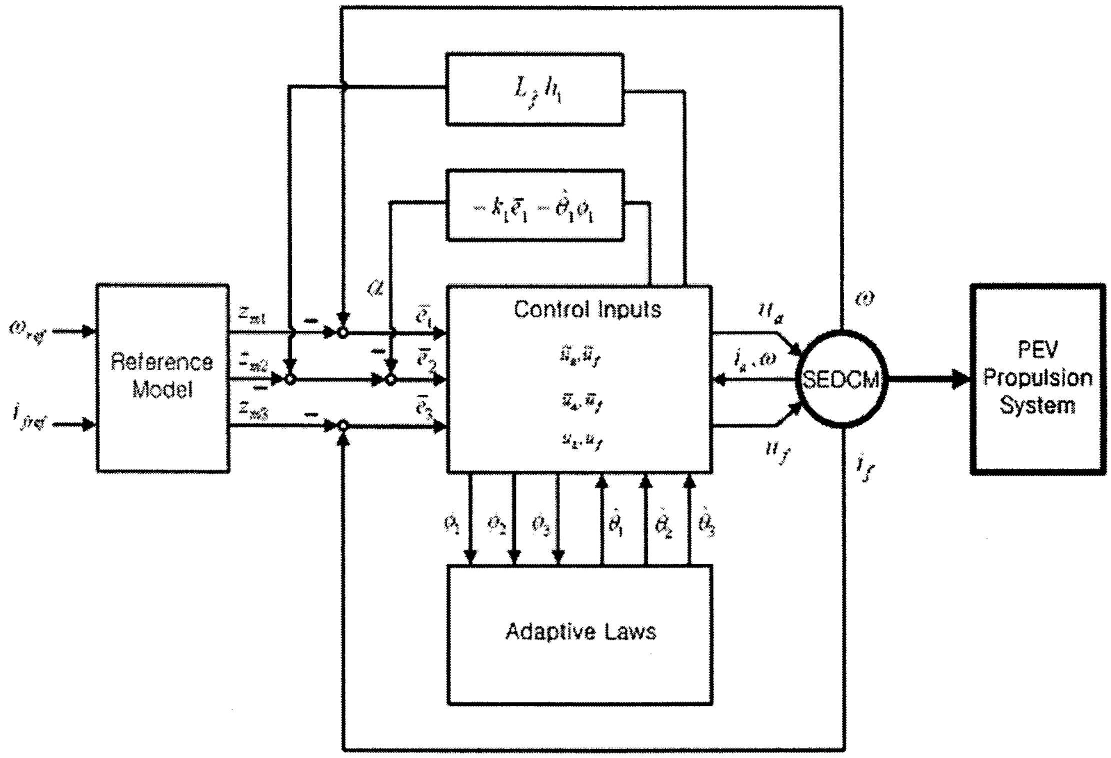
$$\frac{d}{dt}x = \bar{f}(x) + \Delta f(x) + g_1(x)u_a + g_2(x)u_f \tag{4}$$

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

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

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

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.



<Figure 3> Block diagram of the proposed control system

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 $\Delta b_n = b_n - b_{nom}$.

The inputs of reference model are the rotational speed command ω_{ref} and the field current command i_{fref} and **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.** Hence, we can design a robust speed controller using adaptive backstepping as [4] and obtain the results as Figure 3.

4. Preparation for simulations

Simulation and experiment results are provided to demonstrate the effectiveness of the proposed controller in the future. It is shown that the motor, vehicle and design parameters are suggested in Table 1, 2, 3 and the sample of the reference speed in Figure 4.

<Table 1> Motor parameter of the SEDCM

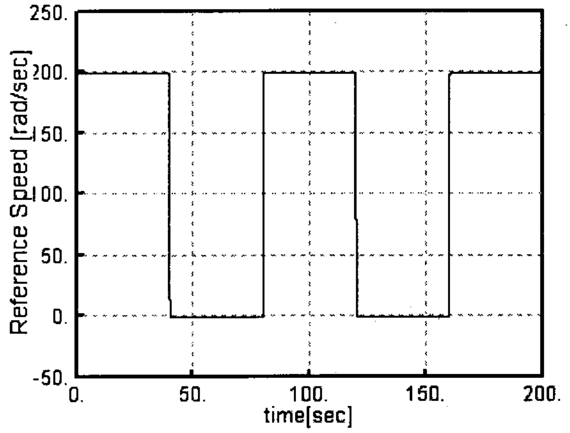
Nomenclature (Symbol)	Setting Value [Unit]
Rated Power (P)	4[kW]
Rated Speed (ω)	200[rad/sec]
Rated Torque (T)	20[N·m]
Armature Inductance (L_a)	0.013[H]
Armature Resistance (R_a)	1.2[Ω]
Field Inductance (L_f)	60[H]
Field Resistance (R_f)	60[Ω]
Motor Constant (K)	0.3[N·m/A^2]
Rotor Inertia (J)	0.208[kg·m^2]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

<Table 2> Vehicle parameter 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

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



<Figure 4> Sample of the reference speed

5. Conclusions

An robust adaptive backstepping controller is proposed for the speed control of separately excited DC motor with uncertainties and disturbances which used in pure electrical vehicle(PEV). 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 and experiment results are provided to demonstrate the effectiveness of the proposed controller in the future.

[Reference]

[1] M.Ehsani, Y.Gao, S.Gay and A.Emadi, "*Modern electric, hybrid electric and fuel cell vehicles*", CRC Press, 2004

[2] Z.Z.Liu, F.L.Luo and M.H.Rashid, "Speed nonlinear control of DC motor drive with field weakening", IEEE Transactions on Industry Applications, pp.417-423, Vol.39, No.2, 2003

[3] M.Krstic, I.Kanellakopoulos and P.Kokotovic, "*Nonlinear and adaptive control design*", John Wiley & Sons, 1995

[4] K.H.Hyun and I.H.Son, "Design of robust adaptive backstepping controller for speed control of separately excited DC motor", Trans. KIEE. pp.80-87, Vol.54P, No.2, JUN, 2005