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영구자석 동기전동기의 강인한 비선형 속도제어

백 인 철, 김 경 화, 문 건 우, 정 세 교, 윤 명 중
한국과학기술원 전기 및 전자공학과

Robust Nonlinear Speed Control For Permanent Magnet Synchronous Motor

In-Cheol Baik, Kyung-Hwa Kim, Gun-Woo Moon, Se-kyo Chung, and Myung-Joong Youn
Department of Electrical Engineering
Korea Advanced Institute of Science & Technology

Abstract: A robust nonlinear speed control of a permanent magnet synchronous motor(PMSM) is presented. A perturbed dynamic model including the influence of parameter variations and speed measurement error on the nonlinear speed control of a PMSM is derived. Based on this model, a boundary layer integral sliding mode controller to improve the robustness and performance of the nonlinear speed control of a PMSM is proposed and compared with the conventional controller.

1. Introduction

Usually, the speed controllers of a PMSM are based on linear models. Since the dynamics of the mechanical speed and the currents are quite different, they can be decoupled and treated separately in successive regulation loops. However, studies show that such an approximation leads to the lack of torque during the speed transient and reduce the efficiency of control [1]. A solution to this problem is to consider the motor speed as a state variable in the electrical equations, which results in a nonlinear model. Then the nonlinear control method is applied to obtain a linearised and decoupled behaviour [2]. However, the nonlinear controller is very sensitive to not only the speed measurement error but also parameter variations such as stator resistance, flux, and inertia due to the temperature rise or product tolerance of magnets and load variations. By including the integrators in the control loops, the steady state error may go to zero [2]. However, the transient and even steady state performance can be still significantly degraded and no robustness is guaranteed [3]. In this paper, a perturbed dynamic model including the influence of parameter variations and speed measurement error on the nonlinear speed control of a PMSM is firstly derived and then the robust controller employing the boundary layer integral sliding mode is designed to obtain the robust control performance for both the transient and steady state.

2. Perturbed dynamic model

The machine considered is a surface mounted PMSM and the nonlinear state equation in the synchronous dq reference frame can be represented as follows :

$$\begin{pmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \\ \frac{d\Omega}{dt} \end{pmatrix} = \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} + \begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \end{pmatrix} \begin{pmatrix} v_d \\ v_q \end{pmatrix} \tag{1}$$

where, $f_1 = -(R/L_d)i_d + p(L_q/L_d)i_q\Omega$, $f_2 = -p(L_d/L_q)i_d\Omega - (R/L_q)i_q - p(\Phi_f/L_q)\Omega$, $f_3 = (3/2)p(\Phi_f/J)i_q - (F_r/J)\Omega - (T_l/J)$. In order to avoid any zero dynamics and to get a total input-output linearisation, the direct axis current(i_d) and the mechanical speed(Ω) are chosen as outputs. From eqn. 1 and the assumption that $dT_l/dt = 0$, the relationship between the outputs(i_d,Ω) and inputs of the model (v_d,v_q) can be obtained as follows [2] :

$$\begin{pmatrix} \frac{di_d}{dt} \\ \frac{d^2\Omega}{dt^2} \end{pmatrix} = \begin{pmatrix} f_1 \\ \frac{3}{2}\frac{1}{J}\left\{p\Phi_f f_2 - \frac{2}{3}F_r f_3\right\} \end{pmatrix} + \begin{pmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{3}{2}\frac{p\Phi_f}{L_q J} \end{pmatrix} \begin{pmatrix} v_d \\ v_q \end{pmatrix}$$

$$= B + A\begin{pmatrix} v_d \\ v_q \end{pmatrix}. \tag{2}$$

The nonlinear control law which permits a linearised and decoupled behaviour can be deduced. And, the poles for the desired error dynamics of the outputs are easily chosen by means of selecting the design parameters using the integral time-absolute error(ITAE) criterion, etc . However, the actual nonlinear control law employs the nominal parameter values(R_o, J_o, Φ_{fo}) and mechanical speed measured by a speed sensor(Ω_o) as follows :

$$\begin{pmatrix} v_d \\ v_q \end{pmatrix} = A_o^{-1}\left(-B_o + \begin{pmatrix} \mathrm{v}_1 \\ \mathrm{v}_2 \end{pmatrix}\right) \tag{3}$$

where v_1, v_2 are the new control inputs and A_o, B_o are obtained from A, B using the nominal parameter values and measured speed. As a result, the perturbed dynamic model instead of a linearised and decoupled model, can be obtained as follows :

$$\frac{di_d}{dt}=\frac{R_o-R}{L_d}i_d-p\frac{L_q}{L_d}i_q(\Omega_o-\Omega)+\nu_1=f_{n1}(\cdot)+\nu_1 \tag{4}$$

$$\frac{d^2\Omega}{dt^2}=-\frac{F_r}{J}\left(f_3-f_{3o}\frac{\Phi_f}{\Phi_{fo}}\right)+\frac{3}{2}p\frac{\Phi_f}{J}\left(\frac{R_o-R}{L_q}i_q+\frac{p}{L_q}(\Phi_{fo}\Omega_o-\Phi_f\Omega)+p\frac{L_d}{L_q}i_d(\Omega_o-\Omega)\right)$$
$$+\frac{\Phi_f}{\Phi_{fo}}\frac{J_o}{J}\nu_2=f_{n2}(\cdot)+b\nu_2 \tag{5}$$

where the terms f_{n1}, f_{n2} and the control input gain b are unknown but bounds of them can be deduced. Now, we consider the feedback linearisation technique as a model-simplifying device for the robust control [3].

3. *Control strategy*

Assume the bounds of parameter variations and speed measurement error as follows :

$$R=\alpha R_o,\quad \alpha_{min}(=1.)\le\alpha\le\alpha_{max}(=1.5)$$
$$J=\beta J_o,\quad \beta_{min}(=1.)\le\beta\le\beta_{max}(=4.)$$
$$\Phi_f=\gamma\Phi_{fo},\quad \gamma_{min}(=0.9)\le\gamma\le\gamma_{max}(=1.1)$$
$$\Omega=\delta\Omega_o,\quad \delta_{min}(=1/1.05)\le\delta\le\delta_{max}(=1/0.95). \tag{6}$$

And the parameters of a PMSM are $R_o=1.07\Omega$, $L_d=L_q=2.1mH$, $\Phi_{fo}=0.17Wb$, $J_o=1.313\cdot10^{-4}Kgm^2$, $F_r=8.75\cdot10^{-4}Nmsec$,
$p=2$, *rated speed* $=314rad/\sec$, *rated power* $=120W$.

Using eqn. 6 and the above parameters, the estimates $\hat{f}_{n1},\hat{f}_{n2}$ and error bounds F_{n1},F_{n2} of f_{n1},f_{n2} for the perturbed dynamic model can be obtained as follows :

$$\hat{f}_{n1}=-254.762i_d-0.00501\Omega_o i_q$$
$$F_{n1}=|-254.762i_d-0.10025\Omega_o i_q|$$
$$\hat{f}_{n2}=-533577.672i_q-5212.539\Omega_o-19033.115T_r-21.417\Omega_o i_d$$
$$F_{n2}=|554932.827i_q+104042.701\Omega_o+24108.612T_r(\mp)428.337\Omega_o i_d|.$$

Bound on control input gain $b=\Phi_f J_o/(\Phi_{fo}J)$ is

$$b_{min}\left(=\frac{\gamma_{min}}{\beta_{max}}=0.225\right)\le b\le b_{max}\left(=\frac{\gamma_{max}}{\beta_{min}}=1.1\right). \tag{8}$$

Let $e_1=i_{dr}-i_d, e_2=\Omega_{tr}-\Omega$ for the boundary layer integral sliding mode controller where i_{dr} and Ω_{tr} are the tracking commands of the direct axis current and mechanical speed of a PMSM. From the bound on control input gain b of eqn. 8, the geometric mean $\hat{b}$ can be defined as

$$\hat{b}=(b_{min}b_{max})^{1/2}=\left(\frac{\gamma_{min}\gamma_{max}}{\beta_{max}\beta_{min}}\right)^{1/2} \tag{9}$$

The sliding surfaces s_1, s_2 are chosen as

$$s_1=\left(\frac{d}{dt}+\lambda_1\right)\int^t e_1\,dt=e_1+\lambda_1\int_0^t e_1\,dt-e_1(0) \tag{10}$$

$$s_2=\left(\frac{d}{dt}+\lambda_2\right)^2\int^t e_2\,dt=\frac{de_2}{dt}+2\lambda_2e_2+\lambda_2^2\int_0^t e_2\,dt$$
$$-\frac{de_2}{dt}|_{t=0}-2\lambda_2e_2(0). \tag{11}$$

And the control laws ν_1,ν_2 are

$$\nu_1=\hat{\nu}_1-k_1\,sat\left(\frac{s_1}{\phi_1}\right) \tag{12}$$

$$\nu_2=\hat{b}^{-1}\left(\hat{\nu}_2-k_2\,sat\left(\frac{s_2}{\phi_2}\right)\right) \tag{13}$$

where, $\hat{\nu}_1=-\hat{f}_{n1}-\lambda_1e_1, k_1=F_{n1}+\eta, \hat{\nu}_2=-\hat{f}_{n2}-2\lambda_2de_2/dt-\lambda_2^2e_2$, $k_2=\Psi(F_{n2}+\eta)+(\Psi-1)|\hat{\nu}_2|$, $sat(\cdot)$ is the saturation function, ϕ_1, ϕ_2 are the boundary layer thicknesses, and $\Psi=(b_{max}/b_{min})^{1/2}=\{(\gamma_{max}\beta_{max})/(\gamma_{min}\beta_{min})\}^{1/2}$. Also, λ_1,λ_2, and η are the strictly positive constants.

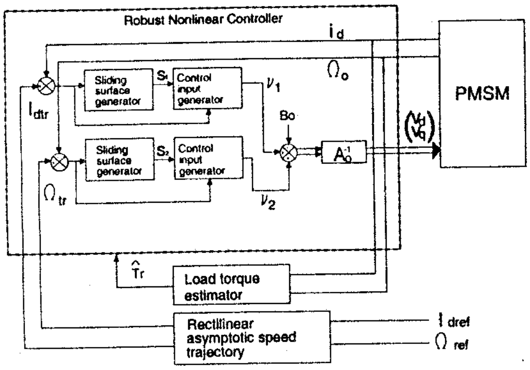

Fig. 1 Overall block diagram of the proposed robust nonlinear speed controller

4. *Simulations and concluding remarks*

For the scheme of the proposed robust nonlinear speed controller described in Fig. 1 and conventional nonlinear controller, Fig. 2 and 3 show the speed response, i_d, and i_q without or with parameter variations and speed measurement error, respectively. The design parameters used for the conventional nonlinear control scheme are selected to show nearly same settling time with proposed controller. As shown in Fig. 3, there are significant degradations in the transient response such as the enhanced overshoot, sustained settling time, and even steady state oscillating error for the conventional nonlinear control scheme [2]. However, the proposed robust nonlinear control scheme shows the transient and steady state responses robust to parameter variations and speed measurement error. Bounds

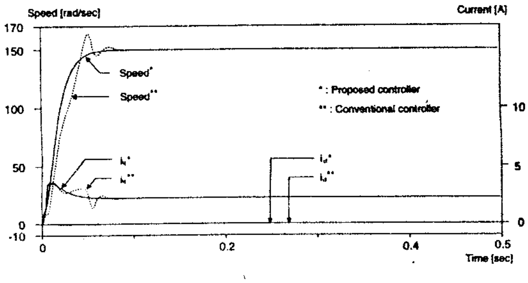

Fig. 2 Simulated speed response, i_q, and i_d without parameter variations and speed measurement error

of uncertainties needed for the robust nonlinear control are obtained by deriving a perturbed dynamic model and the robustness is obtained by using these bounds to generate the

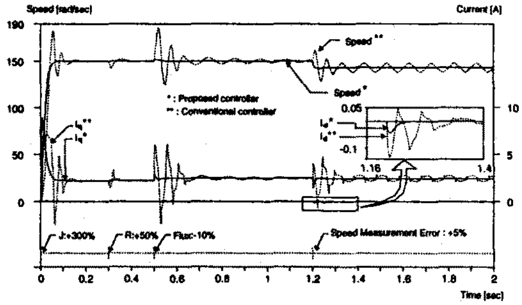

Fig. 3 Simulated speed response, i_q, and i_d with parameter variations and speed measurement error

control inputs which compensate the parameter uncertainties and speed measurement error. Chattering and reaching phase problems are avoided by using the boundary layer and integral sliding mode [3-5]. Consequently, with the proposed robust nonlinear speed control scheme, the solution to the nonlinear speed control problem of a PMSM to avoid the lack of torque during the transient is obtained, which is little affected by the parameter variations and speed measurement error.

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