ARTICLE IN PRESS

ISA Transactions ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at SciVerse ScienceDirect

ISA Transactions

journal homepage: www.elsevier.com/locate/isatrans

Research Article

Enhanced robust fractional order proportional-plus-integral controller based on neural network for velocity control of permanent magnet synchronous motor

BiTao Zhang *, YouGuo Pi

Ministry of Education Key Laboratory of Autonomous System and Network Control (South China University of Technology), Guangzhou 510640, PR China

A R T I C L E I N F O

Article history:
Received 10 June 2012
Received in revised form
12 November 2012
Accepted 12 February 2013
This paper was recommended for publication by Prof. Y. Chen.

Keywords:
Fractional order PI controller
Robustness
Parameters tuning
Neural network

A B S T R A C T

The traditional integer order proportional-integral-differential (IO-PID) controller is sensitive to the parameter variation or/and external load disturbance of permanent magnet synchronous motor (PMSM). And the fractional order proportional-integral-differential (FO-PID) control scheme based on robustness tuning method is proposed to enhance the robustness. But the robustness focuses on the open-loop gain variation of controlled plant. In this paper, an enhanced robust fractional order proportional-plus-integral (ERFOPI) controller based on neural network is proposed. The control law of the ERFOPI controller is acted on a fractional order implement function (FOIF) of tracking error but not tracking error directly, which, according to theory analysis, can enhance the robust performance of system. Tuning rules and approaches, based on phase margin, crossover frequency specification and robustness rejecting gain variation, are introduced to obtain the parameters of ERFOPI controller. And the neural network algorithm is used to adjust the parameter of FOIF. Simulation and experimental results show that the method proposed in this paper not only achieve favorable tracking performance, but also is robust with regard to external load disturbance and parameter variation.

1. Introduction

Permanent magnet synchronous motor (PMSM) drives play a vitally important role in high performance motion control applications. The field-oriented control, or vector control, is used in the design of PMSM servo drives to achieve smooth starting and acceleration. Unfortunately, several electromechanical parameters variations (due to temperature variation, saturation and skin effects) and external load disturbances in practical applications lead to degradation of the drive performance [1]. In order to address these drawbacks, several advanced control techniques have been developed in recent years. Neural network and fuzzy control algorithm are used in [2], whereas some experience in designing the fuzzy controller are required. An adaptive approach can also be used to enhance the robustness of the control scheme [3]. However, the converging time of this control approach is rather long. It is difficult to apply in real-time system. A disturbance observer is developed in [4] to improve the robustness of PMSM. But the compensation is confined to voltage disturbance and dead time.

Due to the simplicity and effectiveness, the PID controller is widely used in the control of PMSM [5–7]. However, it is sensitive to the parameters variations and external disturbances. Using the differentiation and integration of fractional order or non-integer order PID in systems control is gaining more and more interests from the systems control community. The $PI^{r}D^{u}$ controller was proposed in [8], where a better control performance was demonstrated in comparison with the classical IO-PID controller because of extra real parameters r and u involved. Several fractional-order controllers based on tuning approaches are actively developed in the last two years [9–12]. Research activities are focused on developing new analysis and parameters tuning methods for fractional order controllers as an extension of classical control theory. However, these design schemes are restricted to the robustness with to open-loop gain variation of system. And the disadvantage of the FO-PID controller is its poor capacity in dealing with system uncertainties (such as external disturbances).

The parameters tuning of IO-PID and FO-PID controller are rather difficult. Herein many tuning approaches are developed to improve the control performance. A revised Ziegler–Nichols Tuning Rule is proposed in [13], however, it does not take disturbances into account. Some tuning rules based phase margin and crossover are developed in [9,14,15], but this tuning method is difficult to find the suitable performance index for given phase margin and crossover. An advanced tuning method based Genetic

---

* Corresponding author.
E-mail address: z.bitao@mail.scut.edu.cn (B. Zhang).

0019-0578/$ - see front matter Crown Copyright © 2013 Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.isatra.2013.02.003

Please cite this article as: Zhang B, Pi Y. Enhanced robust fractional order proportional-plus-integral controller based on neural network for velocity control of permanent.... ISA Transactions (2013), http://dx.doi.org/10.1016/j.isatra.2013.02.003

Algorithm (GA) is proposed in [16], however, the iterating time is rather long. Ali Fadaei and Karim Salahshoor proposed a fuzzy adaptive auto-tuning scheme [17], but the building of fuzzy inference system requires some experience and knowledge.

It is the motivation of this study to achieve the favorable performance by proposed an enhanced robust fractional order PI (ERFOPI) control approach for PMSM drive system, even when stringent dynamic specifications(such as parameters variations and external load disturbances) are met. In this paper, the ERFOPI controller is designed based on the vector control for the velocity-loop of PMSM. And the control law acts on an FOIF of system state, but not tracking error directly. Then, a simple tuning method based on phase margin and crossover frequency is provided to obtain the parameters of the controller. And the neural network identification algorithm is used to adjust the gain of FOIF. The contributions of this paper are that an FOIF is designed for the ERFOPI control law, which is robustness rejecting parameters variations and external load disturbances, and successfully apply the control scheme in velocity-loop control of PMSM.

The remainder of this paper is organized as follow. In Section 2, the dynamics of field-oriented PMSM servo drive is presented. In Section 3, an ERFOPI controller including control law and FOIF is designed. In Section 4, the parameters tuning methods for obtaining the parameters of ERFOPI controller and adjusting the gain of FOIF are given. In Section 5, the robust performance with regard to parameters variations and external disturbances and converging characteristic are analyzed. Simulations and experiments are carried out to validate the effectiveness of the proposed method in Section 6. Concluding remarks are made in Section 7.

2. Dynamics of field-oriented PMSM servo drive

The mathematics model of a PMSM can be described in the rotor rotating reference frame as follows [4]:

$$\left.\begin{aligned} u_q^* &= R_s i_q^* + \dot{\lambda}_q + \omega_f \lambda_d \\ u_d^* &= R_s i_d^* + \dot{\lambda}_d - \omega_f \lambda_q \\ \lambda_q &= L_q i_q^* \\ \lambda_d &= L_d i_d^* + L_{md} I_{df} \\ \omega_f &= n_p \omega_r^* \end{aligned}\right\} \tag{1}$$

where u_d^*, u_q^* are the d, q-axis stator voltages; i_d^*,i_q^* are the d, q-axis stator currents; λ_d,λ_q are the d, q-axis stator flux linkages; L_d,L_q are the d, q-axis stator inductances. While ω_f and ω_r^* are the inverter frequency and rotor speed respectively; L_{md} is the d-axis mutual inductance; I_{df} is the equivalent d-axis magnetizing current; n_p is the number of pole pairs; R_s is the stator resistance.

The electric torque is stated as

$$T_e = 3n_P[L_{md} I_{df} i_q^* + (L_d - L_q) i_q^* i_d^*]/2 \tag{2}$$

Motor dynamics is presented as

$$T_e = J\dot{\omega}_r + B_m \omega_r + T_l \tag{3}$$

where T_l is the load torque, B_m is the viscous friction coefficient, and J is the moment of inertia.

By using the field-oriented mechanism with $i^*{}_d = 0$, the electric torque can be simplify as

$$\left.\begin{aligned} T_e &= k_p i_q^* \\ k_p &= 3n_p L_{md} I_{df}/2 \end{aligned}\right\} \tag{4}$$

where i_q^* denotes as the ERFOPI controller output (i_q).

Substituting (3) into (4), one can obtain state equation of servo drive:

$$\left.\begin{aligned} &\dot{\omega}_r = -a\omega_r + bi_q - c \\ &a = \tfrac{B_m}{J},\ b = \tfrac{k_p}{J},\ c = \tfrac{T_l}{J} \end{aligned}\right\} \tag{5}$$

Considering the uncertainties and time-varying parameters, Eq. (5) can be rearranged:

$$\dot{\omega}_r = -(a + \Delta a)\omega_r + (b + \Delta b)i_q - (c + \Delta c) \tag{6}$$

where Δa, Δb, Δc are the time-varying value of the system parameters.

The control problem is to find a suitable control input $i_q^*(t)$ such that the output tracks a desired command asymptotically in the presence of model uncertainties. The tracking error $e(t)$,$e(t) \in R$, in terms of the command input signal$\omega_r^*(t)$,$\omega_r^*(t) \in R$, and the measured actual output signal$\omega_r(t)$,$\omega_r(t) \in R$ is defined as

$$e(t) = \omega_r^*(t) - \omega_r(t) \tag{7}$$

The time derivative of $e(t)$ is

$$\left.\begin{aligned} \dot{e}(t) &= -ae(t) - bi_q(t) + \phi(t) + \delta(t) \\ \phi(t) &= a\omega_r^*(t) + c(t) + ?\dot{\omega}^*{}_r(t) \\ \delta(t) &= \Delta a\omega_r(t) - \Delta bi_q(t) + \Delta c(t) \end{aligned}\right\} \tag{8}$$

where $\delta(t)$is lumped uncertainty and assume $|\delta(t)| \le \Omega$, $\Omega \in R^+$.

3. Design of ERFOPI controller

The control objective is to get the speed $\omega_r(t)$ to track the specific speed $\omega_r^*(\mathrm{t})$. It means that the control objective is required to drive the tracking error ($e(t)$) asymptotically to zero for any arbitrary initial conditions and uncertainties.

In traditional integer or fractional order PI controller, the control effort is acted on the tracking error ($e(t)$). In this study, the control input is expanded to an FOIF(s) with regard to the tracking error, defined as

$$s(e(t)) = k_{si} e(t) + {}_0D_t^{1\text{-}r} e(\tau) \tag{9}$$

Where $k_{is} \in \mathrm{R}^+$ and ${}_0D_t^r(.)$ is fractional derivative, defined as

$${}_0D_t^r f(t) = \begin{cases} \frac{1}{\Gamma(n-r)} \int_0^t \frac{f^{(n)}(\tau)}{(t-\tau)^{r+1-n}} d\tau,\ n-1 < r < n \\ \frac{d^n}{dt^n} f(t),\ r = n \end{cases} \tag{10}$$

where $\Gamma(z)$ is the Gamma function with the definition as $\Gamma(z) = \int_0^\infty t^{z-1} e^{-t}\, dt$.

Here, the following fractional order proportional-plus-integral control(FOPI) law is adopted:

$$i_q(t) = k_p(s(e(t)) + k_{i\,0}D_t^{\text{-}r} s(e(t))) \tag{11}$$

where k_p,$k_i \in R^+$,${}_0D_t^{\text{-}r} s(e(t))$ is a rth order integral operator. It is focused on $0 < r < 1$ in this paper.

4. Parameters tuning

4.1. Tuning rules for FOPI control law

Consider the ideal condition ($\delta(t) = 0$, $T_l = 0$), one can deduce the transfer function of simplified motor model for velocity-loop from Eq. (8) as follows:

$$\begin{aligned} &P(s) = \frac{b}{s+a} = \frac{K}{Ts+1} \\ &K = b/a, T = 1/a \end{aligned} \tag{12}$$

Please cite this article as: Zhang B, Pi Y. Enhanced robust fractional order proportional-plus-integral controller based on neural network for velocity control of permanent.... ISA Transactions (2013), http://dx.doi.org/10.1016/j.isatra.2013.02.003