

电静液传动系统中 BLDCM 的仿人智能 PID 复合控制^{1, 2}

李 军, 付永领, 王占林

(北京航空航天大学 自动化科学与电气工程学院, 北京 100083)

Email: journeyer@yahoo.com

摘 要: 考虑电静液压传动系统的无刷直流电动机(Brushless DC Motor, BLDCM)的非线性因素, 根据仿人智能控制原理, 结合 PID 控制, 提出了一种带负载补偿和死区补偿控制的、基于非线性模型的改进积分分离、改进不完全微分算法的仿人智能 PID 复合控制策略, 有效地实现了无刷直流电动机转速控制的快速、小超调、高精度、鲁棒控制, 成功应用到了机载电静液压作动系统的控制中。

关键词: 电静液传动, 无刷直流电动机, 非线性系统, 仿人智能, 补偿控制, PID 控制

Hybrid PID Control Based on Human Simulating Intelligent for a Brushless DC Motor of Electric Hydrostatic Transmission system

Li Jun, Fu Yongling, Wang Zhanlin

(Beijing University of Aeronautics and Astronautics, School of Automation Science and Electric Engineering, Beijing 100083, China)

Abstract: Analyzing the nonlinear factors, saturation and deadzone, of a Brushless DC Motor of Electric Hydrostatic Transmission system. Based on human simulating intelligent, load compensating and deadzone compensating, designed an innovation hybrid PID controller for the BLDCM. The simulations proved it can obtain the fast response, high accuracy, small overshoot and robustness targets synchronously. The method has been applied to control the BLDCM of an airborne electric hydrostatic actuator prototype successfully.

Key words: hydrostatic transmission, Brushless DC Motor, nonlinear system, human simulating intelligent, compensating control, PID control

1 引言

电静液传动系统的特点是系统集成度高、性能好、效率高、无需外部液压管路、使用维护方便。随着电静液作动器在飞行器^[1,2]和机器人^[3]等移动设备等领域中的成功应用, 近年来, 这项技术已经越来越受到各国学者重视^[4~9]。

作者近年来设计开发了新型机载电静液作动器(Electric Hydrostatic Actuator, EHA)原型^[10], 系统原理如图 1 所示, 该作动器是一个定量泵—变转速调节的闭式电液伺服作动系统。由 DSP 控制器(1)、270VDC 双向高速无刷直流电动机(Brushless DC Motor, BLDCM, 2)、高速(12 000r/min)双向定量柱塞泵(3)、蓄压器(4)、信号检测装置(电流、角速度、压力、转角等)、单向阀(5)、安全阀(7)和

双作用对称缸(8)等组成。该案无需伺服阀, 而是通过对电机调速实现对作动油缸输出位移的精确伺服控制, 从而带动舵面转动到一定转角。

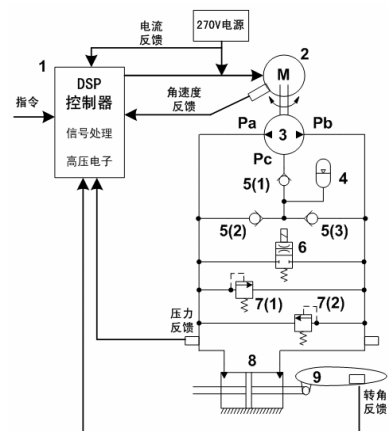


图 1 机载电静液作动器原理图

1 基金项目：高等学校博士点学科专项科研基金（编号：20020006006）

2 本研究得到国防预研项目计划的支持

在实际 EHA 作动系统中, BLDCM 不仅具有死区特性、饱和特性、系统参数不确定等非线性, 同时由于飞行舵面负载扰动存在大范围的变化, 针对实际系统的非线性特性找到一种行之有效的控制方法已经成为当前电液传动与控制中的难点和关键问题之一。

本文通过对系统进行非线性建模和仿真, 提出了一种基于仿人智能控制原理的新型控制策略, 成功实现了对 BLDCM 的快速响应、高精度控制。

2 BLDCM 的双闭环复合控制

2.1 非线性系统建模

BLDCM 的电枢电流和输入电压为一阶传递函数关系, 而电机产生转矩的与通过绕组的电流成正比, 同时由于电机和泵直接刚性相连, 施加在泵上的转矩负载直接由电机驱动。

根据电机绕组的电势平衡方程、电机-泵轴的转矩平衡方程及绕组的电势和电磁力矩方程, 定义 BLDCM 的电磁时间常数 $T_L=L_c/R_c$, 将负载转矩 T_M 为负载摩擦力矩及负载力矩作为系统外部干扰量来列出, 输入量为 U , 输出量为 ω , 并考虑电压、电流饱和特性、系统死区特性及效率, 可以得到电机-泵的非线性模型, 如图 2 所示。

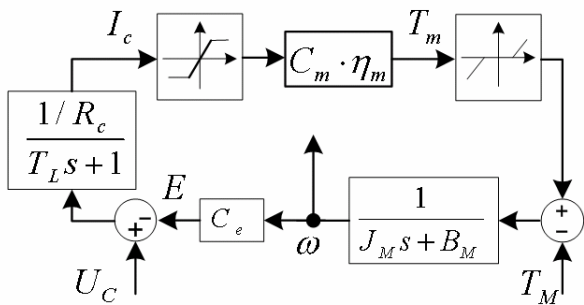


图 2 BLDCM 电机-泵的非线性模型原理方框图

图 2 中, R_c 、 L_c 为电机绕组的电阻和电感, C_m 为电动机磁矩常数, η_m 为电机的效率, C_e 为电机反电势常数, J_M 为电机-泵的转动惯量, B_M 为电机-泵的负载阻尼系数。

2.2 双闭环复合 PID 补偿控制

在 EHA 作动系统中, 为了实现对 BLDCM 的转速进行调节, 选用采用 PWM 技术的 DC-DC 变换器进行驱动和控制; 为了稳定输出转速, 采用角速度负反馈控制、最大控制电压为 10V, 使输出电压跟随给定电压, 达到无静差调节; 为了限制和调节输出电流, 将电流负反馈作为电压负反馈的内环, 从而产生控制电压以调节 PWM 的占空比, 进而控制输出电压(额定 270V)和电流(额定电流 34A, 最大瞬时允许过载 3 倍), 形成了双闭环控制。

对于无刷直流电机的双闭环控制, 通常采用的是经典 PID 控制, 并可按调速系统的工程设计方法设计电流环和电压环的控制参数^[11]。对于 EHA 作动系统中 BLDCM 电机控制的核心问题是“快、准、稳”, 从经典 PID 控制来看, 这类系统的三个指标是无法同时满足, 因此, 必须借助先进控制方法, 其中采用模糊控制是一种比较成熟的改进方案^[12], 但是这种方法的缺点是模糊规则需要专家知识, 而且控制的稳态精度不高。

我们提出在经典 PID 基础上, 借助仿人智能控制方法, 对比例、积分、微分三个控制项仿人智能进行有效、自动的调节, 从而实现上述控制性能的要求。系统的控制原理方框图如图 3 所示, 其中电流调节器采用经典的 PI 控制, 而转速调节器采用我们设计的新型仿人智能复合 PID 控制器, 为提高 BLDCM 负载情况下的性能, 还根据结构不变性原理设计了负载补偿控制器, 为克服摩擦产生的死区, 设计了一个前馈死区补偿器。

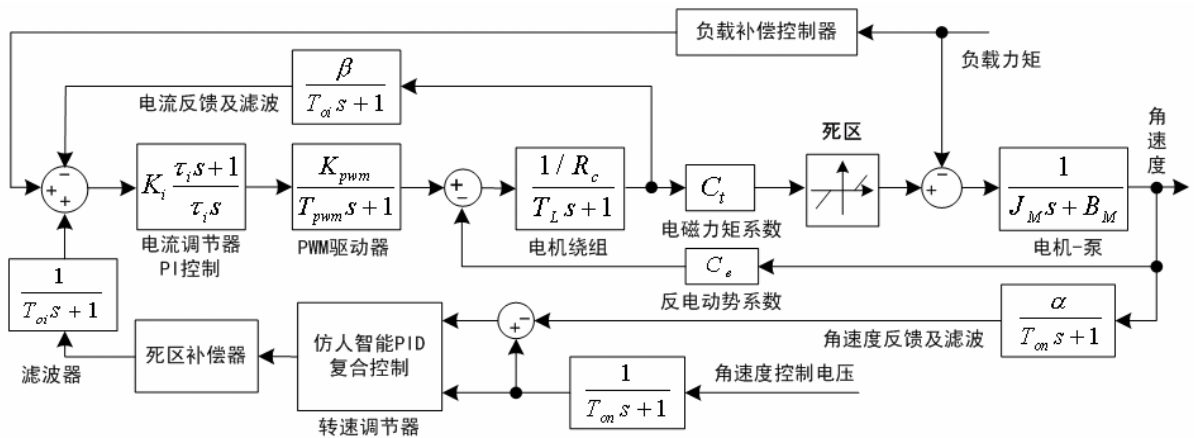


图 3 BLDCM 的复合控制原理方框图

3 BLDCM 的仿人智能 PID 复合控制

3.1 控制器结构

该仿人智能 PID 复合控制策略综合应用 PID 控制研究的已有成果,包括积分分离 PID、不完全微分 PID、死区补偿 PID 等新型算法。结合 EHA 作动系统中 BLDCM 非线性系统控制的专家经验,经过大量的仿真和分析,引入了控制电压输入信号与误差信号,实现了对转速的快速高精度调节,控制器内部结构 Simulink 仿真图如图 4 所示。

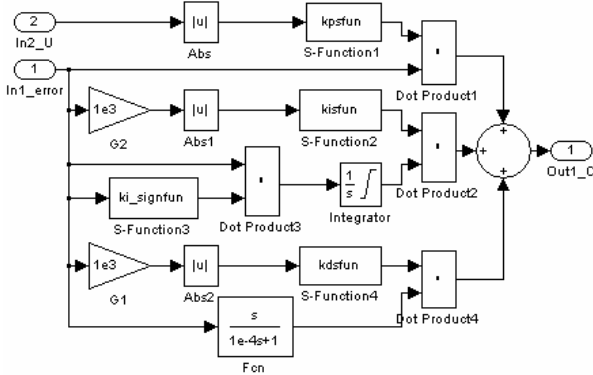


图 4 仿人智能 PID 复合控制器

3.2 控制器设计

该方法设计过程和参数设计如下:

1) 建立 BLDCM 的线性模型,按照传统双闭环调节方法,设计电流环的 PI 控制,该控制器主要用于进行电流调节和限幅。

2) 加入系统的非线性特征,包括摩擦死区、静态负载力矩、系统效率和电流电压饱和和特性等,按照前馈补偿原理,设计一个死区算法,可用式(1)表示。

$$u = \begin{cases} u - u_0 & \text{当 } u < -u_{\min} \\ 0 & \text{当 } -u_{\min} < u < u_{\min} \\ u + u_0 & \text{当 } u > u_{\min} \end{cases} \quad (1)$$

式(1)中, u_{\min} 、 u_0 为摩擦补偿电压值,其大小根据系统的摩擦特性求得;

3) 比例控制的系数 K_p 按式(2)方法求得:

$$K_p = \begin{cases} \frac{K_{p0}}{c_1} & \text{当 } |u| \leq u_1 \\ \frac{K_{p0}}{c_2} & \text{当 } u_1 < |u| < u_2 \\ \frac{K_{p0}}{u} & \text{当 } u_2 \leq |u| \leq u_{\max} \end{cases} \quad (2)$$

式(2)中 K_{p0} 、 c_1 、 c_2 、 u_1 、 u_2 、 u_{\max} 均由系统参数和多次仿真确定。

4) 采用改进的积分分离控制算法,其中积分控制的系数 k_i 按式(3)求得:

$$k_i = \begin{cases} k_{i\max} & \text{当 } u_{\text{error}} \geq u_{\text{err_max}} \\ k_{i0} & \text{当 } u_{\text{err_mid}} \leq u_{\text{error}} < u_{\text{err_max}} \\ k_{i\min} & \text{当 } u_{\text{err_min}} \leq u_{\text{error}} < u_{\text{err_mid}} \\ 0 & \text{当 } u_{\text{error}} < u_{\text{err_min}} \end{cases} \quad (3)$$

式(3)中, $u_{\text{err_max}}$ 、 $u_{\text{err_mid}}$ 、 $u_{\text{err_min}}$ 为反映系统负载扰动变化和转速误差的控制量, u_{error} 为当前系统负载扰动变化和转速误差的输入量, $k_{i\min}$ 、 $k_{i\max}$ 为最小、最大积分控制项的系数。

当系统误差较大或负载扰动变化较大时,该方法可使积分系数迅速增大,当误差或负载变化较小时,相应地调整积分系数,而当误差或负载变化小于一定值时,使积分项为零,从而实现改进的积分分离控制。

5) 采用改进的不完全微分控制算法,形式为

$$\frac{c_{kd} \cdot s}{t_f s + 1}$$

其中 $t_f = 1.0 \times 10^{-4}$ 不完全微分所加的惯性环节时间常数, c_{kd} 为微分项调节系数,可按式(4)求得:

环节时间常数, c_{kd} 为微分项调节系数,可按式(4)求得:

$$c_{kd} = \begin{cases} c_1 & \text{当 } |u| < u_0 \\ c_2 & \text{当 } u_0 \leq |u| < u_1 \\ c_3 & \text{当 } u_1 \leq |u| < u_2 \\ c_4 & \text{当 } u_2 \leq |u| < u_{\max} \end{cases} \quad (4)$$

式(4)中 u_0 、 u_1 、 u_2 、 u_{\max} 为输入电压(分段设置), c_1 、 c_2 、 c_3 、 c_4 为不完全微分项系数。

6) 负载补偿控制器的设计可采用结构对消法(不变性原理)^[13],并忽略次要项。由于 BLDCM 的负载力矩可用系统压力乘以泵排量进行表示,因此,可引入系统压力信号进行正反馈补偿,最后给出的补偿控制器为“比例+微分”形式,关于其详细设计方法将另文介绍。

3.3 仿真原理图

根据前面的分析,可建立完整的 BLDCM 控制图,在 MATLAB/Simulink 中的仿真方块图如图 5 所示。图 5 中,对电流、角速度反馈加入了滤波器, PWM 驱动器用一阶惯性环节进行表示,死区补偿通过 S-函数加入到系统中。

4 结论

基于仿人智能原理,采用基于非线性模型快速分离积分、不完全微分 PID 复合控制方法,可以针对实际系统的饱和特性和系统参数模型,设计出比例、积分、微分系数,并动态调整 PID 参数,从而使电机的运行以最大角加速度启动,并保持该加速度,达到最大转速,并具有很好的速度跟踪能力,精度好,基本无超调,加入负载补偿控制器,使 BLDCM 同时具有很好的负载干扰能力,可用于机载 EHA 作动系统的电机伺服和调速控制。该方法设计实现简单,便于工程实现,也可以用于其他伺服系统的高响应、高精度和非线性控制中,具有较好的应用前景。

参考文献

- [1] Steven Croke, Jack Herrenschmidt, More Electric Initiative Power-By-Wire Actuation Alternatives[A], Aerospace and Electronics Conference, 1994 (NAECON 94), in: Proceedings of the IEEE 1994 National Aerospace & Electronics Conference[C], New York, NY, USA: IEEE, 1994,1338-1346
- [2] Robert Navarro, Performance of an Electro-Hydrostatic Actuator on the F-18 Systems Research Aircraft[R], NASA, TM-97-206224, 1997
- [3] Saeid Habibi, Andrew Goldenberg, Design of a New High Performance ElectroHydraulic Actuator[A], In: 1999 IEEE/ASME International Conference on Advanced Intelligent Mechatronics Proceedings [C], October 1, 1999, New York, NY, USA: IEEE, 227 ~ 232
- [4] Lee, C.B.; Wu, H.W. Self-tuning adaptive speed control for hydrostatic transmission systems[J], International Journal of Computer Applications in Technology, v 9, n 1, 1996, p 18-33
- [5] Fulkerson, Tom. Integrated hydrostatic transmission control[J], SAE Special Publications, v 1192, Aug, 1996, New Fluid Power Applications, Components, and Testing, p 15-19
- [6] Njabeleke, Ignatius A.; Pannett, Richard F.; Chawdhry, Pravir K.;et al. Modelling and control of a high speed hydrostatic transmission[J], American Society of Mechanical Engineers, The Fluid Power and Systems Technology Division (Publication) FPST, v 5, Fluid Power Systems and Technology, 1998, p 1-10
- [7] 祁晓野, 付永领, 王占林. 功率电传机载作动系统方案分析[J], 北京航空航天大学学报, 1999 年 04 期, Vol. 25(4): 426 ~ 430
- [8] Kwasniewski, Janusz; Piotrowska, Agata; Raczka, Waldemar, et al. The mathematical model of a hydrostatic transmission for controller design[C], Proceedings of the IASTED International Conference on Modelling and Simulation, 2003, p 275-280
- [9] Messenger, Ben, Hydrostatic Transmission Designed for Compact Mobile Applications[J], Diesel Progress North American Edition, v 69, n 9, September, 2003, p 76-77
- [10] 李军, 付永领, 王占林等, 一种新型机载一体化电液作动器的设计与分析[J], 北京航空航天大学学报, 2003.12, Vol.29(12): 1101 ~ 1104
- [11] 柴肇基, 电力传动与调速系统[M], 北京航空航天大学出版社, 1992.9
- [12] Njabeleke, I.A.; Pannett, R.F.; Chawdhry, P.K.;et al. Self-organising fuzzy logic control of a hydrostatic transmission, IEE Conference Publication, n 455, 1, 1998, p 66-72
- [13] 王占林, 近代液压控制[M], 北京: 机械工业出版社, 1997.8

Comparison of Current Controllers for High Performance Induction Machine Drives*

Jin-Lu Cheng, Cheng-Jin Zhang

(School of Control Science and Engineering, Shandong University, Jinan, 250061)

E-mail: chengjinlu@hotmail.com

Abstract: This paper is aim to present a brief review of current controllers applied in high performance vector controlled induction machine drives. Various conventional strategies together with intelligent methods such as neural network controller and fuzzy logic based regulator are investigated. Basic principles of each method are simply described, accompanied by selected block diagrams; their advantages and limitations are explored and their performances are compared. In the end, some future research interests are also observed.

Key words: induction machine; vector control; current control; voltage source inverter

1 Introduction

Of all the drive types, induction machine (IM) motor is the most widely used and is often viewed as the workhorse of modern industry, undertaking an estimated 70-80% of electro-mechanical energy conversion. It is characterized mainly by simple mechanical construction, low maintenance costs and high reliability. However, the induction machine is employed mostly in constant speed low performance applications, for it is hard to acquire satisfactory torque performance due to the coupled flux and torque. With the development of semiconductor technology and microprocessor control technique, the introduction of vector control (VC) has brought induction machine drives to a new development stage in which it is possible to achieve high control performance, giving fast, near step changes in machine torque.

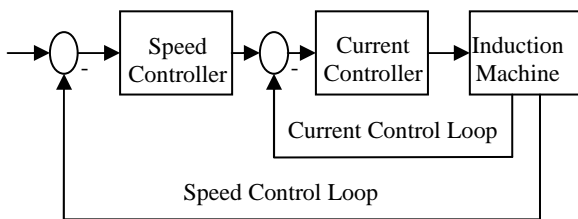


Fig. 1 Basic structure of vector control

In vector control [Fig. 1], the structure consists of a current control loop and a velocity control loop. The current control is fulfilled by an internal current feedback loop. The decoupled direct and quadrature axis currents are controlled via the direct and quadrature axis voltages,

associated with a pulse width modulated (PWM) voltage source inverter (VSI). As a result, the drive performance largely depends on the current control techniques. Therefore, current regulation is one of the most important subjects in high performance induction machine control.

With the development of current control techniques, a great deal of work has been undertaken to develop the current controllers [1]. It is a necessity to summarize and compare the characteristics of the available solutions. In this paper, brief control strategies of each method are described. Their advantages and limitations are evaluated as well.

2 Vector Control

In vector control, the three phase induction machine model is transformed to a two phase model in the synchronous rotating coordinates with the voltage equations

$$v_{dse} = R_s i_{dse} + p\psi_{dse} - \omega_e \psi_{qse} \tag{1a}$$

$$v_{qse} = R_s i_{qse} + p\psi_{qse} + \omega_e \psi_{dse} \tag{1b}$$

$$0 = R_r i_{dre} + p\psi_{dre} \tag{1c}$$

$$0 = R_r i_{qre} + \omega_{sl} \psi_{dre} \tag{1d}$$

and the flux equations

$$\psi_{dse} = i_{dse} L_s + i_{dre} L_m \tag{2a}$$

$$\psi_{qse} = i_{qse} L_s + i_{qre} L_m \tag{2b}$$

$$\psi_{dre} = i_{dre} L_r + i_{dse} L_m \tag{2c}$$

$$\psi_{qre} = i_{qre} L_r + i_{qse} L_m \tag{2d}$$

where i_{dse} is the stator d axis flux current and i_{qse} is the stator q axis torque current;

* This work is partly supported by the Department of Science & Technology of Shandong Province (Grant No.03BS089).

i_{dre} and i_{qre} are the rotor d and q axis currents respectively; v_{dse} and v_{qse} are the stator d and q axis voltages respectively; ψ_{dse} , ψ_{qse} , ψ_{dre} and ψ_{qre} are the stator and rotor flux; R_s and R_r are the stator and rotor resistances respectively; L_s , L_r and L_m are the stator, rotor and magnetizing inductances; ω_e , ω_r and ω_{sl} are the synchronous, rotor and slip frequency; p is the differential operator. Thus, it is possible for the stator d and q axis currents to control the flux and torque independently, which is similar to that of a separately excited D.C. machine.

3 Current Control

Among the various current controllers, hysteresis controller, proportional plus integral (PI) regulator and deadbeat controller are all effective solutions. In recent years, neural network (NN) and fuzzy logic (FL) based controllers are applied as well, which offer a new interesting perspective for this vast subject.

3.1 Hysteresis Controller

Hysteresis current controller is the simplest one of all the approaches, since it controls the switching of power devices directly. It shares many advantages such as fast transient response and outstanding robustness. The VSI output voltage can be represented as space vectors [Fig.2], where U_7 is a zero vector. In the control structure, the current error is compared with the hysteresis band; the switching signal is produced once the current error crosses the boundary, so that the suitable voltage vector is selected and hence the error is confined between the negative and positive band limits. However, the switching frequency largely depends on the load conditions due to the interaction among the three independent controllers; furthermore, the instantaneous error can reach double the value of the hysteresis band for systems without neutral leaders.

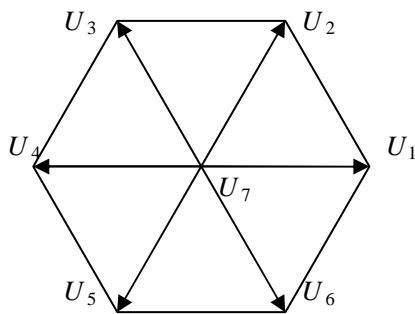


Fig. 2 Diagram of voltage vector

In recent years, many schemes have been

proposed to acquire constant switching frequency. One of the approaches is to constrain the switching frequency to a constant value by modifying the error with a phase locked loop (PLL) [2, 3]. The alternative strategy is to program the hysteresis band as a function of load parameters to develop an adaptive hysteresis band controller [4]. It is a novel scheme to use fuzzy logic rules adapting hysteresis bandwidth and other controller parameters to obtain reduced frequency fluctuations and optimum switching patterns [5].

The space vector based controllers treat three current errors as space vectors, thus, the interaction can be compensated [6]. While this strategy requires the back EMF vector, it is able to force the output current vector to track the command vector with almost negligible response time. If the zero vectors are also considered, the decreased switching frequency will be obtained. The digital implementation of the hysteresis regulator is strongly recommendable [7], since the digital methods share a variety of advantages over the analog ones and obviously they are today's technique trends.

3.2 PI Regulator

PI regulator is one of the commonly applied approaches to high performance current control. This scheme gives zero steady state current error and a well defined current spectrum due to the use of PWM modulators. The controllers can be divided into two groups: when the current command is transformed to a stationary frame, the d and q axis currents are sinusoidal components; when the current command is transformed to a synchronous rotating frame, the d and q axis currents are D.C. components and regulation is then performed in synchronous rotating coordinates [8].

In the rotor flux oriented synchronous rotating frame, it follows

$$\psi_{qre} = 0 \quad (3)$$

In the steady state

$$\psi_{dre} = L_m i_{dse} \quad (4)$$

Hence, the induction machine voltage equations can be expressed as

$$v_{dse} = R_s i_{dse} + \sigma L_s p i_{des} - \omega_e \sigma L_s i_{qse} \quad (5a)$$

$$v_{qse} = R_s i_{qse} + \sigma L_s p i_{qse} + \omega_e \sigma L_s i_{dse} \quad (5b)$$

where

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (6)$$

It can be seen that d and q axis voltage equations are coupled by terms $-\omega_e \sigma L_s i_{qse}$ and $\omega_e \sigma L_s i_{dse}$. If the decoupling is implemented, the voltage equations become

$$v_{dse} = R_s i_{dse} + \sigma L_s p i_{des} \tag{7a}$$

$$v_{qse} = R_s i_{qse} + \sigma L_s p i_{qse} \tag{7b}$$

The dynamics of the decoupled d and q axis currents are expressed by two simple linear first order differential equations [9], thus two PI regulators can be employed. However, the transient response of the PI controller is somewhat slow, since only the current error is used for generating the voltages.

If two PI controllers are replaced by a state feedback controller, multivariable state feedback control theory can then be applied. The regulator works in a synchronous frame. The pole placement technique is utilized to derive the feedback gain matrix $K = [K_1, K_2]$. The steady state error is reduced to zero by the integral part $K_2 \int dt$. Fast transient response is acquired by introducing the feedforward control for input reference and disturbance where the back EMF is modeled as a disturbance as well. The performance of the state feedback controller is superior to conventional PI controllers due to the introduction of the compensation for the back EMF voltage [10].

3.3 Deadbeat Controller

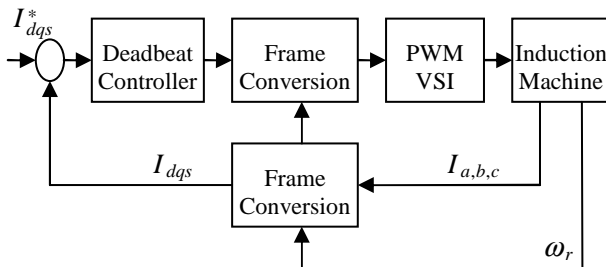


Fig. 3 Deadbeat controller in the stationary frame

Deadbeat controllers [Fig. 3] exhibit, in general, both satisfactory dynamic response and steady state performance with low current and torque ripple. In this strategy, the voltage equation is often described as

$$I_{dqs}(k+1) = AI_{dqs}(k) + BV_{dqs}(k) - BE_{dqo}(k) \tag{8}$$

where $I_{dqs}(k)$, $V_{dqs}(k)$ and $E_{dqo}(k)$ are current vector, voltage vector and back EMF vector respectively. Thus, the algorithm applies the command current vector from the velocity controller, substituting $I_{dqs}^*(k+1)$ into $I_{dqs}(k+1)$ in equation (8) and calculates the control

voltage $V_{dqs}(k)$ according to

$$V_{dqs}(k) = \frac{1}{B} [I_{dqs}^*(k+1) - AI_{dqs}(k) + BE_{dqo}(k)] \tag{9}$$

where the current vector $I_{dqs}(k)$ is available at the k th sampling instant. It is worth noting that $E_{dqo}(k)$ is unknown.

A number of proposals have been put forward to obtain the back EMF vector $E_{dqo}(k)$. By rotating the back EMF vector, a recursive algorithm of $E_{dqo}(k)$ can be obtained, hence, it follows the control voltage [11]. According to equation (8), the voltage equation at the $k-1$ th sample instant is

$$I_{dqs}(k) = AI_{dqs}(k-1) + BV_{dqs}(k-1) - BE_{dqo}(k-1) \tag{10}$$

It is reasonable to assume that the rotor flux and motor speed are constant within one control period because current control is performed a few thousand times per second, its execution rate is much faster than the mechanical and rotor flux dynamic responses, thus, combining equations (8) and (10) yields the control voltage which eliminates the back EMF [12]. A novel deadbeat fuzzy current regulator which consists of a deadbeat loop and a fuzzy logic based compensation loop is proposed [13]. The fuzzy control loop is utilized to generate additional part of the command voltage to compensate the back EMF. This strategy is very robust and needs little information about the load and system parameters.

Because parameters are needed when control voltage is calculated, deadbeat control calls for the precise knowledge of plant information [14]; therefore it is difficult for the controller without self-tuning structure to maintain desired performance in the challenging operating conditions.

3.4 Neural Network Controller

Neural network has such advantages as parallel processing, self learning ability, and generalization. Recently, neural network is applied in current regulation for induction machine drives which shows promising to certain extent, since it is difficult for conventional strategies to deal with such a problem due to nonlinearities and uncertainties existing [8]. The performance of the off-line trained system depends on the amount and quality of training data used, which in turn depends on system complexity and the range of operating conditions involved and is also sensitive to parameter variations, since no further training is

possible after the drive is commissioned. Controllers with on-line training guarantee more advantages. One of the most attractive features of the on-line trained system is that it remains adaptive throughout operation [15], which gives it the ability to deal with parameter variations under all conditions. This technique suffers from a large computational overhead.

3.5 Fuzzy Logic Based Controller

Fuzzy logic based controller is an attractive solution to improve the current loop performance [16]. When this method is applied, it is not necessary an exact modeling and analyzing the system mathematically. Furthermore, optimal control within the expert's knowledge can be implemented, since this method makes effective use of heuristic information. The fuzzy logic controller without explicit modulation part works also as a modulator which defines the sequence and duration of inverter output voltage vectors. In basic applications, the fuzzy logic controller is utilized as a substitute for the conventional regulator. A fuzzy logic based control loop can be used to compensate a deadbeat controller [13]. Unfortunately, these schemes suffer from the sensitivity to the change of fuzzy sets shapes and overlapping. Moreover, the expertise and experience of the designer have direct influence on the resulting performance.

4 Evaluation of Current Controllers

Table 1 Comparison of current controllers

	Advantages	Limitations
Hysteresis Controller	<ul style="list-style-type: none"> * Simplicity * Fast dynamic response * Robustness 	<ul style="list-style-type: none"> * Varying switching frequency * Poor steady state performance
PI Controller	<ul style="list-style-type: none"> * Zero steady state current error * Well defined current spectrum 	<ul style="list-style-type: none"> * Transient response is slow
Deadbeat Controller	<ul style="list-style-type: none"> * Fast transient response * Good steady state current error 	<ul style="list-style-type: none"> * Sensitivity to parameter variations * Lower robustness
Neural Network Controller	<ul style="list-style-type: none"> * Adaptive to operating conditions 	<ul style="list-style-type: none"> * A large computational overhead
Fuzzy Logic Controller	<ul style="list-style-type: none"> * Insensitivity to parameter variations * The use of heuristic information 	<ul style="list-style-type: none"> * Dependent on the expertise of designers

Characteristics of each method are summarized in Table 1. The hysteresis current control technique gives fast response and can be

implemented with a minimum of hardware. However, depending on load conditions, switching frequency may vary widely. Thus, the actual current waveform is not only determined by the hysteresis control; current peaks may appreciably exceed the limits of the hysteresis band. Improved hysteresis controllers with constant switching frequency can acquire limited tracking error together with fast transient response. They are suitable for high performance induction machine control, although the simplicity is somehow lost. According to the technique trend, more and more digital algorithms have been proposed, which are highly flexible and easier to be implemented with the microprocessor.

Utilizing a two phase reference frame rotating at the synchronous speed allows the use of PI regulators without the phase lag associated with stationary frame PI regulators which have to control sinusoidal values. PI controllers can achieve zero steady state error, but the transient response is somewhat slow. Therefore, many schemes with the consideration of back EMF are proposed to improve the dynamic performance. However, the induction machine parameters are time varying with temperature, magnetic saturation and frequency. It is desirable that parameter estimation technique is employed in the controller to ensure on-line tuning at all times.

Deadbeat current controller has proven to be able to achieve very good steady state performance and fast transient response, but the satisfactory results heavily depend on the accuracy of the model and parameters used, which decrease the overall system performance extremely. The introduction of adaptation in the control algorithm guarantees that accurate current regulation is maintained when machine parameters vary. Interests toward robust deadbeat controllers are still increasing.

Intelligent control methods such as neural network controllers and fuzzy logic regulators provide a new perspective for future research. They are considered mostly as an alternative strategy to existing current regulation methods. The off-line trained neural network controllers are still sensitive to parameters variations, since no further training is possible. While intelligent methods do not have any better performance than conventional current regulators [17], it is noted that good results can be acquired by combining the intelligent schemes and conventional strategies.

5 Conclusions

Current control is one of the most important parts of vector control for high performance

induction machine drives. A good many of works have been proposed in this field. Various control strategies have been evaluated in this paper. Associated with the block diagrams, the basic principles of each method have been described. In the end, advantages and drawbacks of different types of current regulators were listed and their overall performances were compared.

References

- [1] Kazmierkowski, M.P. Malesani, L. Current control techniques for three-phase voltage-source PWM converters: a survey [J], *Industrial Electronics, IEEE Transactions on*, 1998, 45(5): 691 -703.
- [2] Risseuw, P.M. Development of a novel hysteresis current controller for three phase induction machines [A], *Industrial Electronics, 1999, ISIE'99 [C], Proceedings of the IEEE International Symposium on*, 1999, 3(12-16): 1496 -1501.
- [3] Malesani, L. Mattavelli, P. Tomasin, P. Improved constant-frequency hysteresis current control of VSI inverters with simple feedforward bandwidth prediction [J], *Industry Applications, IEEE Transactions on*, 1997, 33(5):1194 -1202.
- [4] Ting-Yu Chang, Kuie-Lin Lo, Ching-Tsai Pan, A novel vector control hysteresis current controller for induction motor drives [J], *Energy Conversion, IEEE Transactions on*, 1994, 9(2): 297 -303.
- [5] Cecati, C. Corradi, S. Rotondale, N. Digital adaptive hysteresis current control based on the fuzzy logic [for PWM inverters] [A], *Industrial Electronics, 1997, ISIE'97[C], Proceedings of the IEEE International Symposium on*, 1997, 3(7-11):1232 -1237.
- [6] Wang Jun, Peng Hong, A new hysteresis current controller for induction motor [A], *Electrical Machines and Systems, 2001, ICEMS 2001[C], Proceedings of the Fifth International Conference on*, 2001, 2(18-20):1289 -1292.
- [7] Buso, S. Fasolo, S. Malesani, L. Mattavelli, P. A dead-beat adaptive hysteresis current control [J], *Industry Applications, IEEE Transactions on*, 2000, 36(4):1174 -1180.
- [8] Wang Dazhi, Wang Zhenlei, Gu Shusheng, Identification and control of induction motor using artificial neural networks [A], *Electrical Machines and Systems, 2001, ICEMS 2001[C], Proceedings of the Fifth International Conference on*, 2001, 2(18-20):751 -754.
- [9] Telford, D. Dunnigan, M.W. Williams, B.W. A self-tuning regulator for induction machine vector control [A], *Power Electronics Specialists Conference, 2002, PESC 02[C], 2002 IEEE 33rd Annual, 2002*, 3(23-27):1463 -1468.
- [10] Dong-Choon Lee, Seung-Ki Sul, Min-Ho Park, High performance current regulator for a field-oriented controlled induction motor drive [J], *Industry Applications, IEEE Transactions on*, 1994, 30(5):1247 -1257.
- [11] Telford, D. Dunnigan, M.W. Williams, B.W. Adaptive high bandwidth current control for induction machines [J], *Power Electronics, IEEE Transactions on*, 2003, 18(2):527 -538.
- [12] Sheng-Ming Yang, Chen-Haur Lee, A deadbeat current controller for field oriented induction motor drives [J], *Power Electronics, IEEE Transactions on*, 2002, 17(5):772 -778.
- [13] Jianrong Bu, Longya Xu, A new deadbeat fuzzy algorithm for current regulated PWM without rotating reference frame transformation [A], *Industrial Electronics Society, 1998, IECON '98[C], Proceedings of the 24th Annual Conference of the IEEE*, 1998, 1:513 -518.
- [14] Malesani, L. Mattavelli, P. Buso, S. Robust dead-beat current control for PWM rectifiers and active filters [J], *Industry Applications, IEEE Transactions on*, 1999, 35(3):613 -620.
- [15] Burton, B. Harley, R.G. Diana, G. Rodgerson, J.L. Implementation of a neural network to adaptively identify and control VSI-Fed induction motor stator currents [J], *Industry Applications, IEEE Transactions on*, 1998, 34(3): 580 -588.
- [16] Jianrong Bu, Longya Xu, A high performance full fuzzy controller for induction machine drives [A], *Applied Power Electronics Conference and Exposition, 1998, APEC '98[C], Conference Proceedings 1998, Thirteenth Annual, 1998*, 2(15-19):592 -596.
- [17] Cheng-Jin Zhang, Dunnigan, M.W. Robust adaptive stator current control for an induction machine [A], *Control Applications, 2003, CCA 2003[C], Proceedings of 2003 IEEE Conference on*, 2003, 1(23-25):779 -784

远程网络运动控制系统的模糊 PI 时滞补偿算法研究

薛 花, 纪志成

(江南大学控制与网络系统研究所, 江苏无锡, 214036)

E-mail: xuehua@sytu.edu.cn

摘 要: 针对远程网络运动控制系统中普遍存在的时滞问题, 将模糊逻辑补偿算法引入传统 PI 控制器的设计, 以消除闭环网络控制系统中由时滞引起的控制性能下降、系统不稳定等不利影响。模糊 PI 时滞补偿算法中, 无需更改传统 PI 控制器的设计, 以模糊补偿器调制 PI 控制器的输出, 采用离线寻优与在线自适应相结合的方式, 实现模糊逻辑条件参数与结论参数的全局自整定。以实时性要求较高的无刷直流电机为应用实例, 仿真结果证明了该控制算法的有效性和可行性, 该方法可使具有时滞特性的远程网络控制系统保持良好的动、静态特性与较强的抗干扰能力。

关键词: 远程网络运动控制系统; 模糊 PI 复合控制; 时滞补偿; 全局自适应

Study on Fuzzy PI Time-delay Compensation Arithmetic of Remote Networked Motion Control System

Xue Hua, Ji Zhicheng

(Institute of Control and Networked System, Southern Yangtze University, Jiangsu Wuxi, 214036)

Abstract: When using a remote networked control system, a network-induced time-delay is generated, which causes advert effects on the closed-loop networked control system such as performance degradation and system destabilization. In this paper, contraposing the time-delay commonly existing in the remote control system, an intelligent fuzzy logic compensator is introduced to design the traditional networked PI control system. One of the advantages of this fuzzy PI time-delay compensation arithmetic is that it is not needed to completely redesign the existing PI controller, but simply modulates the PI controller action with the output of the intelligent fuzzy compensation. In the full adaptive fuzzy parameter adjustment, off-line optimization and on-line adaptation are applied to the design of the controller, and not only the consequent parameters can be tuned adaptively, but also the membership functions in the antecedent part are tuned adaptively. Simulation results of a networked controlled Brushless DC motor is used to illustrate the effectiveness and feasibility of the proposed fuzzy PI control scheme, and the use of the method makes the closed-loop system posses favorable dynamic and static performance and free from load disturbance.

Keywords: remote networked motion control system; fuzzy PI synthesis control; time-delay compensation; full adaptation

1 引言

随着现代控制系统规模的日益扩大, 远程网络控制的应用也日益广泛^[1]。网络运动控制系统将实时网络纳入闭环形成反馈控制系统, 因而具有成本低廉、控制分散、易于扩展与集成、维护与故障诊断简易等优点, 但分时传输的特性使得网络时滞成

为影响控制性能与系统稳定性的主要因素之一^{[2]-[3]}。因此, 如何使具有时滞特性的运动控制网络依然能够保持稳定的高性能的表现, 成为控制算法设计人员迫切需要解决的关键问题, 从而, 对于解决网络时滞问题方法的研究具有十分重要的意义。

现有的控制手段, 如状态增广方法^[4]、基于定值预测或盖然预测的队列方法^{[5]-[6]}、扰动方法^[7]等,

主要采用传统的控制理论，且理想化的限定较多，如假设单包传送、通讯无误等，因此应用于实际控制网络时难以获得理想控制效果。针对网络时滞的随机时变特性，本文将智能模糊逻辑引入控制系统，在不更改传统 PI 控制网络结构的基础上，利用模糊补偿器调制 PI 控制器的作用力，以消除网络时滞对控制系统产生的不利影响。将对实时性要求较高的无刷直流电机作为远程控制对象，仿真结果表明：这种新型的模糊 PI 时滞补偿算法的收敛速度快，动、静态控制性能好，抗负载扰动强，证明了有效性与可行性。

2 模糊 PI 时滞补偿算法的设计

传统的 PI 网络控制系统结构如图 1 所示，PI 控制器的传递函数：

$$G_{PI}(s) = K_p + \frac{K_i}{s} \quad (1)$$

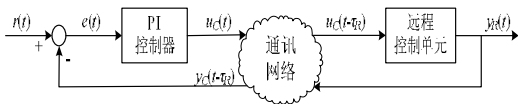


图 1 PI 网络控制系统结构框图

若考虑网络时滞，则有：

$$u(t_k) = u_c(t - \tau) \quad y_c(t) = y(t_R - \tau_C) \quad (2)$$

定义 $e(t) = r(t) - y_R(t - \tau_C)$ ，则 PI 控制器可采用以下表示形式：

$$u(t) = u_c(t) = K e(t) + K_i \int e(t) dt = K (r(t) - y_p(t_R - \tau_C)) + K_i \int (r(t) - y(t_R - \tau_C)) dt \quad (3)$$

网络系统的通讯具有随机性和非线性时变的特点，因此难以建立精确的数学模型。当被控对象的参数和结构不确定或未知时，传统控制方法已较难确保理想的控制性能，而采用模糊逻辑控制正是有效的解决方法。针对具有不确定性时滞的网络控制系统，利用模糊补偿方式，对 PI 控制器的输出进行调制，可有效克服随机时滞的不利影响。

图 2 为带有模糊调制作用的远程网络控制系统框图，此时，中央控制器的输出满足关系式：

$$u_C(t) = \beta u_{PI}(t) \quad (4)$$

其中： β 为模糊调制器输出的调制参数，用于提高网络时滞变化时 PI 控制器的性能表现。模糊调制

的基本原理是：通过对远程被控单元输入量的调制，如减小 PI 控制的增益，使中央控制器的输出符合控制对象所需的控制量，防止进入不稳定的运行状态，同时确保获得理想的动态响应特性。

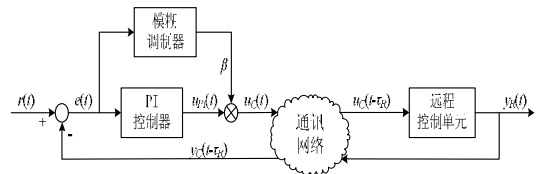


图 2 模糊调制的网络控制系统结构框图

设计模糊逻辑调制器的输入为参考信号 $r(t)$ 与网络反馈信号 $y_C(t - \tau_R)$ 的差值 $e(t)$ ，输出为补偿网络时滞对 PI 控制器影响的调制参数 β 。模糊补偿器的设置仅两条规则语句：

If $e(t)$ is Small, then $\beta = \beta_1$;

If $e(t)$ is Large, then $\beta = \beta_2$;

其中： β_1 、 β_2 为结论参数。模糊调制器的输入输出隶属度函数如图 3 所示，满足：

$$\mu_{small}(e) = \begin{cases} 1 & e/r \leq \gamma_{11} \\ \frac{\gamma_{12} - e/r}{\gamma_{12} - \gamma_{11}} & \gamma_{11} < e/r \leq \gamma_{12} \\ 0 & e/r > \gamma_{12} \end{cases}$$

$$\mu_{large}(e) = \begin{cases} 1 & e/r \leq \gamma_{21} \\ \frac{e/r - \gamma_{22}}{\gamma_{22} - \gamma_{21}} & \gamma_{21} < e/r \leq \gamma_{22} \\ 0 & e/r > \gamma_{22} \end{cases} \quad (5)$$

$$0 < \gamma_{21} < \gamma_{11} < \gamma_{22} < \gamma_{12} < 1, \quad 0 < \beta_1 < \beta_2 < 1$$

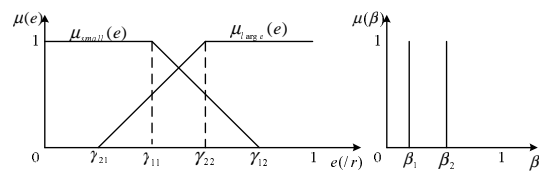


图 3 模糊调制器的输入、输出隶属度函数

模糊调制参数 β 采用中心解模糊方法获得：

$$\beta = \frac{\beta_1 \mu_{small}(e) + \beta_2 \mu_{large}(e)}{\mu_{small}(e) + \mu_{large}(e)} \quad (6)$$

2.1 离线寻优

首先采用离线方式寻找模糊调制器参数的优化设置，选择性能指标函数：

$$J = \lambda J_1 + (1 - \lambda) J_2$$

其中：

$$J_1(p) = \frac{\sum_{k=0}^N e(k)^2}{\|J_1(p)\|_\infty}, \quad J_2(p) = \frac{\sum_{i=0}^M e_b(k)^2}{\|J_2(p)\|_\infty},$$

$$p = [\beta_1, \beta_2, \gamma_{11}, \gamma_{12}, \gamma_{21}, \gamma_{22}],$$

$$\{\Delta e_b(i)\} = \{\Delta e(k) \mid e(k)\Delta e(k) > 0\}.$$

其中： J_1 代表系统的响应速度和收敛特性， J_2 代表系统超调、欠调、振荡的现象， λ 为两者之间的权重系数。给定一个搜索领域，就可在其中搜索出性能指标函数最小时的模糊调制器参数 $(\beta_1, \beta_2, \gamma_{11}, \gamma_{12}, \gamma_{21}, \gamma_{22})$ ，获得不同给定条件下的调制器优化参数。

2.2 在线自适应

运用离线寻优，对于每一对给定的采样周期、时滞参数对 (h, τ) 和给定的 λ ，都可采用查表法来选择优化的模糊调制器参数，但当网络上出现了表中未包含的状态时，就需使模糊调制器具有在线自适应的功能。在线实时控制时，全局自适应调制通过中间件监测系统状态和网络服务品质 $QoS(t)$ ，使之与期望的控制性能作对比，设计自适应控制律，实时更新模糊调制器的条件参数 $(\gamma_{11}, \gamma_{12}, \gamma_{21}, \gamma_{22})$ 和结论参数 (β_1, β_2) ，确保性能指标函数为最小。

应用梯度下降算法设计模糊调制器的全局自适应控制律，瞬时性能指标函数选择为：

$$J(k) = e(k)^2$$

模糊 PI 复合控制器的输出控制力可用差分方程表示为：

$$u(k) = u(k-1) + \beta(K_p + \frac{K_i h}{2})e(k) + \beta(-K_p + \frac{K_i h}{2})e(k-1) \quad (7)$$

其中： h 为采样周期。则由(3)-(7)式推导可得模糊调制器条件参数与结论参数的在线全局自适应律可表示为：

$$\gamma_{mn}(k+1) = \gamma_{mn}(k) - \eta \frac{\partial J(k)}{\partial \gamma_{mn}}$$

$$= \gamma_{mn}(k) + 2\eta \frac{e(k)\mu_{\text{argz}}(e(k))u_p(k)(\beta_1(k) - \beta_2(k))(\gamma_{12}(k) - \frac{e(k)}{r(k)})}{(K_p(k) + \frac{K_i(k)h}{2})(\beta_1(k)\mu_{\text{small}}(e(k)) + \beta_2(k)\mu_{\text{argz}}(e(k)))}$$

$$\frac{\prod(e(k)/r(k), \gamma_{mn}(k), \gamma_{m,n+1}(k))}{(\mu_{\text{small}}(e(k)) + \mu_{\text{argz}}(e(k)))(\gamma_{m,n+1}(k) - \gamma_{mn}(k))^2}$$

其

$$\beta_m(k+1) = \beta_m(k) + 2\eta \frac{e(k)\mu_{\text{mit}}(e(k))u(k)}{(K_p(k) + \frac{K_i(k)h}{2})(\beta_1(k)\mu_{\text{mit}}(e(k)) + \beta_2(k)\mu_{\text{argz}}(e(k)))}$$

中： $m, n = 1, 2$ ， η 为学习率，

$$\prod(x, x_1, x_2) = \begin{cases} 1 & x_1 \leq x \leq x_2 \\ 0 & \text{其他} \end{cases}$$

在线自适应模糊调制可以看作是连续增益调整过程。增益调整的基本思想是：在不同的运行阶段对系统进行线性化处理，使用线性化控制策略对每个阶段分别进行控制，控制器参数决定于所处的运行阶段。在自适应模糊调制中，可以将离线自适应模糊调制看作是传统的增益调整过程：通过监测网络服务品质来选择模糊逻辑调制器的参数，以使得预先定义的评价指标函数为最小。然而，在线自适应模糊调制可以看作是“有教师”的控制器，可以连续观测系统和网络服务品质的状态，根据自适应控制律更新模糊调制器参数，以提高闭环系统的性能，实现期望的网络服务品质。

3 应用实例

以无刷直流电机为被控对象进行网络控制系统的仿真研究，验证模糊 PI 时滞补偿算法的有效性。若令状态向量 $x = [x_1 \ x_2]^T = [i_a \ \omega]^T$ ，则由无刷直流电机的数学模型^[8]可得被控对象的状态空间方程：

$$\dot{x} = \begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} \frac{di_a}{dt} \\ \frac{d\omega}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L-M} & -\frac{K_b}{L-M} \\ \frac{K}{J} & -\frac{B}{J} \end{bmatrix} x + \begin{bmatrix} \frac{1}{L-M} \\ 0 \end{bmatrix} u$$

$$y = [0 \ 1]x$$

其中： i_a 为电枢绕组电流， ω 为电机机械转速， R 为电枢绕组电阻， L 为电枢绕组电感， M 为电枢绕组互感， J 为转动惯量， B 为阻尼系数， K 为转矩常量， K_b 为反电动势常量。

设网络时滞随机，且最大时滞不超过 10 个采样周期，即 $\tau < 10h$ 。仿真中，系统参数设置为：采样周期 $h = 0.001s$ ，电枢绕组电阻 $R = 1\Omega$ ，自感 $L = 0.02H$ ，互感 $M = -0.0067H$ ，转动惯量 $J = 0.005Kg \cdot m^2$ ，网络时滞在 $[0 \ 10h]$ 内随机分布。系统带 $2N\cdot m$ 负载转矩启动，待进入稳态后，在 $t = 0.2s$ 时突加负载转矩至 $5N\cdot m$ ，在 $t = 0.4s$ 时突减负载转

矩至零，系统进入空载运行，在 $t = 0.5s$ 时改为反转运行，带有 $-2N\cdot m$ 的负载转矩，在 $t = 0.7s$ 时突增负载转矩至 $-5N\cdot m$ ，在 $t = 0.9s$ 时突减负载转矩至零，系统再次进入空载运行，可得到系统在参考转速为 $2000r/min$ 时的转速、a 相电流波形如图 4-7 所示。

仿真结果表明：采用模糊 PI 时滞补偿算法的网络控制系统，在 $2000r/min$ 的参考转速下，响应

快速且平稳，相电流和转速波形较为理想；在 $t = 0.2s$ 或 $0.7s$ 时突加负载，转速发生突降，但又能迅速恢复到平衡状态，同样在 $t = 0.4s$ 或 $0.9s$ 时将负载转矩突减至零，转速发生突增，但也能够迅速恢复到平衡状态，稳态运行无静差，动、静态性能令人满意。较传统 PI 控制，这种新型控制方法响应快、超调小、鲁棒性较强、脉动幅度小、抗干扰能力好，仿真结果证明了该方法有效性和可行性。

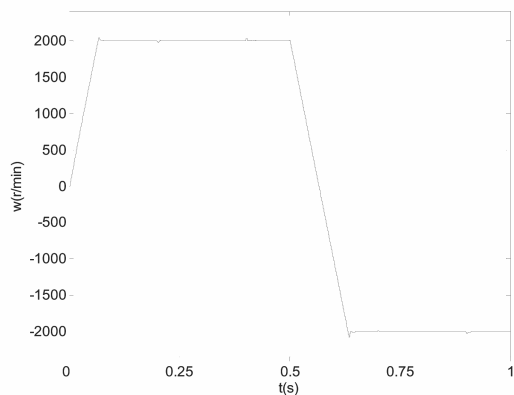


图 4 电机转速波形 (模糊 PI 控制)

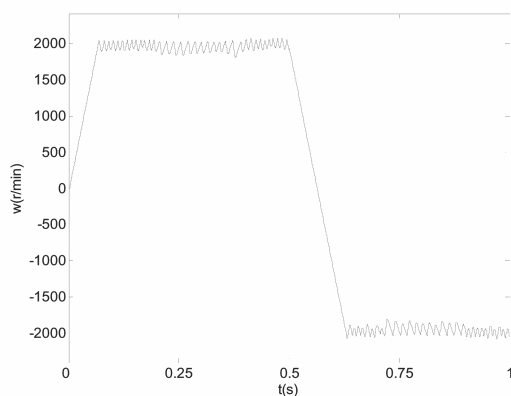


图 5 电机转速波形 (传统 PI 控制)

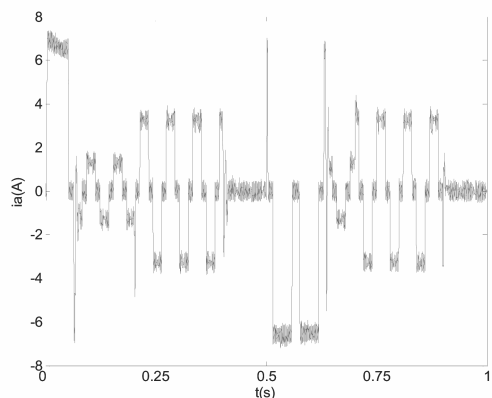


图 6 a 相电流波形 (模糊 PI 控制)

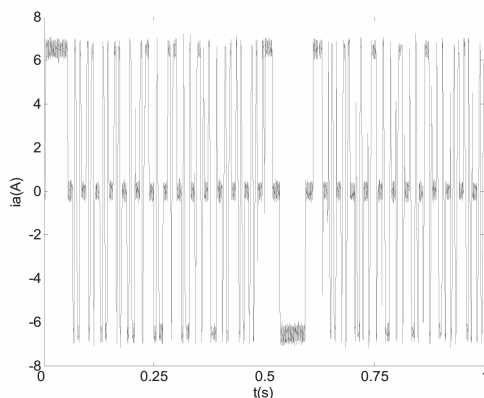


图 7 a 相电流波形 (传统 PI 控制)

4 结论

为了克服不确定性变化的网络时滞对运动控制系统的影响，基于模糊逻辑理论，设计了模糊 PI 时滞补偿算法，模糊调制器充分利用了模糊控制理论规则少、应用简单灵活的特点，将离线寻优与在线自适应相结合，在保持系统稳定性的同时，有效削弱了控制系统中由不确定性时滞造成的脉动与振荡，在改善远程网络控制系统的动、静态性能方面表现出了较传统 PI 控制更强的功能特性。将

这种新型的补偿算法应用于实时性要求较高的无刷直流电机远程调速系统，仿真结果证明了该方法的正确性和有效性，它为分析和设计远程网络控制系统提供了有效的手段和新的思路。

参考文献

- [1] 王飞跃, 王成红. 基于网络控制系统的若干基本思考和分析. 自动化学报, 2002, 28(sup): 60-65.
- [2] Wei Zhang, Branicky M.S. and Phillips S.M.. Stability of networked control systems[J]. IEEE Control Systems

- Magazine, 2001, 21(1): 84-99.
- [3] 戴冠中, 郑应平. 网络化系统及其建模、分析、控制与优化. 自动化学报, 2002, 28(S1): 60-65.
- [4] Halevi Y. and Ray A.. Integrated communication and control systems: Part - Anasysis[J]. Dynamic Systems, Measurement and Control, 1988, 110: 367-373.
- [5] Lucy R. and Ray A.. Experimental verification of a delay compensation algorithm for integrated communication and control systems[J]. International Journal of Control, 1994, 59: 1357-1372.
- [6] Chan H. and Ozguner U. Closed-loop control of systems over a communication network with queues[J]. International Journal of Control, 1995, 62: 493-510.
- [7] Walsh G.C. and Hong Ye. Scheduling of networked control systems[J]. IEEE Control Systems Magazine, 2001, 21(1): 57-65.
- [8] 纪志成, 沈艳霞, 姜建国. 基于 Matlab 无刷直流电机系统仿真建模的新方法[J]. 系统仿真学报, 2003, 15(12): 1745-1749.

基于 X-Y 平台的自适应模糊摩擦补偿

王洪瑞, 王霞, 姜春娣, 唐予军

(河北大学 电子信息工程学院 河北省保定市 071002)

E-mail: gglcc2002@yahoo.com.cn

摘要: 用模糊逻辑系统逼近摩擦力与速度的非线性关系, 进行不基于模型的摩擦补偿, 避免了复杂的模型参数辨识。自适应方法实时调整模糊规则库中的参数, 赋予了模糊系统自动寻优的能力以及适应环境变化的能力, 使摩擦补偿具有鲁棒性。模糊补偿控制稳定性得到了证明, 仿真结果说明了方法的有效性。

关键词: 自适应模糊控制; 摩擦补偿; X-Y 平台

Adaptive Fuzzy Friction Compensation for X-Y Table

Wang Hongrui, Wang Xia, Jiang Chundi

(Hebei University, Baoding, Hebei 071002)

Abstract: An adaptive fuzzy system is used to approach the relationship between friction and velocity. Non-model based compensation method avoids the complicated identification of parameters. The adaptive mechanism enables the fuzzy system to adjust fuzzy logic automatically and to adapt to the changes of environment. Thus, the compensation is robust itself. The stability of the control law with fuzzy friction compensation is proved and simulation results verified the efficiency of the method.

Keywords: Adapting Fuzzy Control, Friction Compensation, X-Y table

1 引言

众所周知, 摩擦是影响系统性能的一个重要因素。原因在于摩擦力在零速附近具有强烈的非线性, 并且受多种因素影响, 难于把握。X-Y 平台广泛应用于机械制造和加工领域, 一般的 PID 能很好的控制 X-Y 平台。但是, 对高精度控制, 摩擦的非线性影响使经典的控制策略不再适用, 摩擦可能导致稳态误差或目标位置的极限环。对于轨迹跟踪控制, 零速附近的强烈非线性会使轨迹变得不平滑, 如 X-Y 平台在画圆时的过象限误差。随着加工精度要求的不断提高, 摩擦补偿变得越来越迫切。

对摩擦的补偿方法大致可以分成两类: 基于模型的补偿和不基于模型的补偿。前者是根据一个摩擦模型计算出摩擦力的大小, 在输入端加入大小一样的补偿力矩, 将摩擦的影响抵消。这种方法依赖模型的特点决定了摩擦模型的准确性直接影响控制效果。国内外学者对摩擦特性进行研究, 并提出了许多摩擦模型[3], 其中一些能反映

多种摩擦特性。但是, 越是准确的模型参数就越多, 参数辨识是一个非常棘手的问题。而且摩擦受到环境、润滑等多种因素的影响, 模型总是不断改变的。所以人们大多尝试采用各种自适应的方法辨识参数和适应参数的变化。可自适应只能辨识摩擦模型的线性参数对于非线性参数无能为力。不基于模型的补偿方法主要有神经网络、模糊等智能方法和扰动观测器法。观测器法是将摩擦视为一个外界扰动加以观测, 这种方法在实际中会受到带宽的限制。神经网络可以逼近任意的非线性函数, 但是训练时间长, 结构复杂。虽然摩擦模型还不成熟, 但人们对摩擦的定性了解已经十分深刻。注意到模糊能够有效的利用语言信息, 采用模糊来补偿摩擦的研究也比较多。模糊规则库都是一次性离线建立, 完全依赖于专家经验和已得数据, 不能适应环境的变化, 系统的稳定性也不能保证。

本文采用自适应模糊器来逼近摩擦 - 速度曲线, 自适应律根据系统误差实时调节模糊补偿器的参数, 只需要根据专家经验简单的设置初始