Contents lists available at ScienceDirect

ISA Transactions

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

Adaptive two-degree-of-freedom PI for speed control of permanent magnet synchronous motor based on fractional order GPC

Wenjun Qiao, Xiaoqi Tang*, Shiqi Zheng, Yuanlong Xie, Bao Song

School of Mechanical Science and Engineering, Huazhong University of Science and Technology, 1037 Luoyu Road, Wuhan, China

ARTICLE INFO

Article history:
Received 18 October 2015
Received in revised form
26 April 2016
Accepted 7 June 2016

Keywords:
Permanent magnet synchronous motor
Two-degree-of-freedom PI
Just-in-time learning
Fractional order generalized predictive control
Adaptive speed control

ABSTRACT

In this paper, an adaptive two-degree-of-freedom (2Dof) proportional-integral (PI) controller is proposed for the speed control of permanent magnet synchronous motor (PMSM). Firstly, an enhanced just-in-time learning technique consisting of two novel searching engines is presented to identify the model of the speed control system in a real-time manner. Secondly, a general formula is given to predict the future speed reference which is unavailable at the interval of two bus-communication cycles. Thirdly, the fractional order generalized predictive control (FOGPC) is introduced to improve the control performance of the servo drive system. Based on the identified model parameters and predicted speed reference, the optimal control law of FOGPC is derived. Finally, the designed 2Dof PI controller is auto-tuned by matching with the optimal control law. Simulations and real-time experimental results on the servo drive system of PMSM are provided to illustrate the effectiveness of the proposed strategy.

1. Introduction

Permanent magnet synchronous motor (PMSM) has played an important role in high-performance motion control applications due to its outstanding features such as super power density, high torque to current ratio, and easy maintenance [1]. Moreover, in the vector-controlled servo system of PMSM, the traditional proportional-integral (PI) controller is widely used to accomplish the speed tracking task because of its relatively simple structure and comprehensive principle. However, in practice, the speed reference may change regularly at different stages, and the PMSM systems often suffer from different disturbances and uncertainties [2]. As a result, both the fast response to the time-varying reference and the good robustness to the disturbances should be considered in the controller design. Since there is only one-degree-of-freedom in the traditional PI controller, it is difficult to satisfy these two conditions simultaneously even if the controller parameters have been well tuned [4]. To deal with this problem, the two-degree-of-freedom (2Dof) PI controller can be a more suitable choice, in which one degree is aimed at responding swiftly to the speed reference changes and the other degree is designed for offering enough robustness against the uncertainties [3–7]. Nevertheless, there are four parameters in the 2Dof PI controller, which makes the tuning more complicated and challenging. Therefore, the adaptive tuning strategy for the 2Dof PI controller should be further investigated.

In the past decades, many efforts have been made towards the auto-tuning strategies for the PI/PID-type controllers, and these strategies can be mainly classified into the rule-based ones and the model-based ones. Fuzzy logic theory and neural network algorithm have been broadly researched to auto-tune the controller parameters on the basis of the prior rules [11–14]. However, large amounts of learning cost may be needed in these methods. Moreover, sometimes the sub-optimal results are unavoidable. These potential disadvantages limit the real application of the rule-based strategies [4,14]. From the perspective of simplicity and feasibility, the model-based self-tuning strategies appear to be more suitable for the real-time applications [8]. Among which, generalized predictive control (GPC) has been widely utilized to adjust the controller parameters [15–17]. For example, the GPC-based PID controller is adopted to improve the trajectory tracking performance for a weigh feeder [15]. GPC employs a dynamic model of the controlled plant to forecast the future behavior of states, and determines the future control law according to the optimization of a quadratic performance index. Then, the controller parameters are acquired by matching with the optimal control law [10]. Hence, the adoption of GPC not only guarantees the optimal tracking performance of the control system but also tunes the controller parameters automatically with respect to the variations of the operation environments. Furthermore, the procedure of calculating the solution of optimization is relatively

* Corresponding author.
E-mail address: xqtang1000@163.com (X. Tang).

http://dx.doi.org/10.1016/j.isatra.2016.06.008
0019-0578/© 2016 ISA. Published by Elsevier Ltd. All rights reserved.

simple and fixed. As the advanced development of computing hardware, it is possible to apply GPC to auto-tune the controller parameters under the real-time constraint. However, for the high speed and high precision requirements in the speed control system of PMSM, the following three challenges in GPC should be further researched.

Firstly, as GPC relies on the controlled plant model, both the accuracy and efficiency of the model identification approach have a significant influence on the performance. In [18,19], the recursive least squares method is selected to capture the dynamic of the industrial process. However, one drawback of the recursive least squares method is its inherent assumption of stationary model parameters, while the dynamic of PMSM is highly nonlinear and changes rapidly. Recently, a new modeling technique named just-in-time learning (JITL) has been developed and investigated extensively because of its prediction capability for nonlinear systems and inherent adaptive nature [20–22]. For example, Kansha et al. [20] endow GPC with adaptive capacity via introducing JITL to identify the model parameters. In [22], Zheng et al. utilize the improved JITL to model the speed control system of PMSM and obtain high accuracy results. To build models, the JITL method should search the relevant data samples from the historical database in a real-time manner. However, the computational burden for searching relevant data samples is directly related to the size of database. When the size of the database is extremely large, the JITL method will be invalid in satisfying the real-time requirement of the servo system. Hence, the searching efficiency of the JITL method should be enhanced.

Secondly, the speed reference is essential for GPC and is acquired from the master controller through the bus-communication. In practice, the speed loop control cycle is much shorter than the bus-communication cycle, therefore, the speed reference is unavailable at the interval of two bus-communication cycles. In [9], Lu et al. restrict the speed reference to be a sinusoid-type signal and propose a formula for predicting the future speed reference. However, this formula may be not suitable for other kinds of signals. Actually, to reduce the severe force impact on the servo system, the speed reference is always smooth and continuous, which can be interpolated by the small segments after speed planning. Therefore, the future speed reference at the interval of two bus-communication cycles can be predicted according to these small segments.

Finally, the performance of the GPC-based auto-tuning strategy can be further improved by incorporating fractional calculus. Fractional calculus, which can be defined as a generalization of derivatives and integrals to non-integer orders, is a mathematical tool to enhance the control system performance [23–25]. Fractional order GPC (FOGPC) is an extension of GPC with an arbitrary real–order cost function. By including two unique weight matrices, the FOGPC is much more flexible and comprehensive than the traditional GPC [25–27]. Hence, a better performance can be obtained by employing the FOGPC to auto-tune the 2Dof PI controller.

In this paper, three main contributions in the FOGPC-based strategy for auto-tuning the 2Dof PI controller are presented. First, a novel searching algorithm consisting of a rough searching engine and a refined searching engine is presented in the enhanced JITL (EJITL) method, which can estimate the model parameters of the speed control system timely and accurately. The rough searching engine is designed to increase the efficiency, while the refined searching engine is developed to improve the precision. Second, because of the unavailability of the speed reference at the interval of two bus-communication cycles, a general formula is proposed to forecast the future speed reference. Third, the FOGPC including two unique weight matrices is introduced to calculate the optimal control law. And the parameters of the 2Dof PI controller are determined by matching with the optimal control law. Simulations and real-time experiments are provided to illustrate the feasibility and effectiveness of the proposed strategy.

The remainder of this paper is organized as follows. Section 2 presents the model of the speed control system, structure of the 2Dof PI controller and fractional order calculus briefly. Section 3 illustrates the EJITL technique and the general formula. Meanwhile, the FOGPC is discussed in detail. Finally, the controller parameters matching results are given. Simulations and real-time experimental results are presented in Sections 4 and 5, respectively. Section 6 contains some conclusions.

2. Background

2.1. Model of speed control system

Assume that the magnetic circuit is unsaturated, hysteresis and eddy current loss are ignored and the distribution of the magnetic field is in sine space. Under this condition, in the vector-controlled servo system of PMSM, an average model of the speed loop is depicted in Fig. 1. Usually, the current loops have considerable wide bandwidths, which ensure a great tracking performance. As a result, the transfer function of the current loops is usually regarded as unity. Therefore, the transfer function of the controlled plant in the dashed box is given as follows:

$$\frac{\omega(s)}{k_f i_q(s) - T_L(s)} = \frac{1}{Js + f_r} \tag{1}$$

where ω is the actual angular speed; k_f is the torque current coefficient; i_q is the torque current; T_L is the external load torque; J is the rotor inertia; f_r is the viscous friction coefficient.

Because of the variations in rotor inertia, friction, load torque and other nonlinear dynamics, the actual model of the controlled plant may be more complex and of high-order. Here, a simplified first-order controlled auto-regressive and moving average (CARMA) model is adopted to describe the dynamic of the controlled plant [20]:

$$\Delta A(z^{-1})\omega(k) = \Delta B(z^{-1}) i_q(k-1) \tag{2}$$

$$A(z^{-1}) = 1 + a_1 z^{-1} \tag{3}$$

$$B(z^{-1}) = b_0 \tag{4}$$

where a_1 and b_0 are the identified model parameters; Δ is differential operator and $\Delta = 1 - z^{-1}$; k represents the present sampling instant.

It is noted that the CARMA model is rebuilt in real-time by the model identification approach, therefore, it can well approximate and describe the speed control system with the time-varying and nonlinear characteristics.

2.2. 2Dof PI controller

The 2Dof PI controller is presented by Horowitz in 1963 [3], and its control structure is illustrated in Fig. 2.

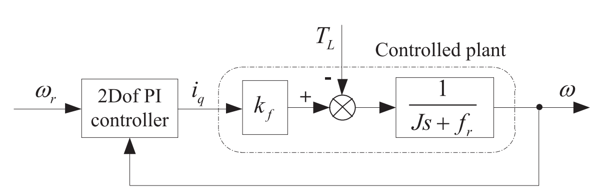

Fig. 1. Average model of the speed loop.