Chinese Journal of Aeronautics, (2014),27(6): 1527–1537

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

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# PI controller relay auto-tuning using delay and phase margin in PMSM drives

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Received 13 October 2013; revised 29 June 2014; accepted 5 August 2014
Available online 18 October 2014

**KEYWORDS**

Auto-tuning;
EMA;
Matrix converters;
PI control;
PMSM

**Abstract** This paper presents an auto-tuning method for a proportion plus integral (PI) controller for permanent magnet synchronous motor (PMSM) drives, which is supposed to be embedded in electro-mechanical actuator (EMA) control module in aircraft. The method, based on a relay feedback with variable delay time, explores different critical points of the system frequency response. The Nyquist points of the plant can then be derived from the delay time and filter time constant. The coefficients of the PI controller can then be obtained by calculation while shifting the Nyquist point to a specific position to obtain the required phase margin. The major advantage of the auto-tuning method is that it can provide a series of tuning results for different system bandwidths and damping ratios, corresponding to the specification for delay time and phase margin. Simulation and experimental results for the PMSM controller verify the performance of both the current loop and the speed loop auto-tuning.



## 1. Introduction

The permanent magnet synchronous motor (PMSM) has received increasing acceptance in industrial applications, due to its features of high efficiency, low noise, high performance and robustness. It plays a fundamental role in manufacturing automation, such as robotics, hybrid vehicles, electric scooters, elevators and applications in aircraft.[1,2] A high-performance PMSM drive generally requires an estimation of the motor parameters, such as armature inductance and resistance, as well as moment of inertia of the whole system including the motor and the load. Any variation of parameters such as the moment of inertia will affect and degrade the drive's performance.[3] So it is important to have the correct value while performing the motor control. It is not an easy task however to obtain a good estimation of all the required parameters in a motor drive system.

One of the most popular controllers is the proportional plus integral (PI) type, which is widely used in the field-orientated control of PMSMs. Since it is often difficult to measure the PMSM parameters, manipulation tuning is a frequently-used way to determine the PI coefficient instead of theoretical

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Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2014.10.019
1000-9361 

calculations. It takes even experienced engineers time and effort to regulate the PI coefficients to guarantee good performance. As a result, there exists a growing demand for auto-tuning of the PI controller, without knowing the varying operating parameters. Auto-tuning is a powerful control technique used to solve the above problem and is based on an adaptive estimation algorithm.[4,5]

During the past decades, the theory of auto-tuning has developed in a variety of directions. The pioneering work can be traced to the 1940s. Ziegler et al.[6] tuning relations and Cohen and Coon[7] tuning rules are among the earliest published methods. Since then, the subject has been extensively explored and it is still under investigation.[8–10] The popularity of these controllers has led to research on tuning methods, resulting in hundreds of publications on this topic. Tuning relations based on error criteria, as well as more recent model-based tuning rules such as internal model control (IMC) and direct synthesis,[11] offer improvements over earlier tuning methods. Tuning rules also exist for unstable processes[12] as well as for tuning in the presence of plant-model mismatch. In Ref. [13] a sensorless vector-control design and tuning strategy is introduced based on state observer, phase-locked loop, tracking controller, etc. Many developments have been reported to extend the relay auto-tuning method. It transpires that more accurate information on process dynamics can be obtained from the same relay test with the help of new identification techniques and can be used to improve the tuning of PI controllers.[14–18]

In this paper, an auto-tuning method based on relay feedback for both current loop and speed loop is presented. By specifying the delay time and phase margin, the system bandwidth and damping ratio can be regulated. Firstly, the modeling of the PMSM and the PI controller is introduced, which shows the connection of the PI controller settings and system performance. Secondly, the proposed relay auto-tuning strategy is presented. The changes in the delay time and the phase margin cause a shifting of the plant's Nyquist point to the position of the specific phase margin on the unit circle in the *s*-domain, from which the tuning formulas are derived. The qualitative analysis is illustrated and simulated, in order to show the connection between the settings of the delay time/phase margin and the system response. Finally, experiments are carried out in a electro-mechanical actuator (EMA) for PMSM and permanent-magnet flux-switching machine (PMFSM). In both cases an Indirect Matrix Converter is implemented to drive the machines. The experimental results show the validity of the proposed auto-tuning method.

## 2. Modeling of the drive system

### 2.1. Electrical and mechanical model of PMSM

The control block diagram for the current loop and the speed loop can be generally derived. The current loop of a PMSM can be simplified as shown in Fig. 1. Where $L_s$ is the inductance of surface mounted PMSM; $R_s$ is the resistance of surface mounted PMSM; $i$ is the current to be controlled and $i_{ref}$ is the reference current. Assume that $L_q = L_d = L_s$ in a surface mounted PMSM, where $L_q$ is the $q$-axis inductance, and $L_d$ is the $d$-axis inductance. The back-electromotive force (EMF) equals $(L_d\omega_r i_d + \omega_r\psi_f)$ for the $q$-axis current loop

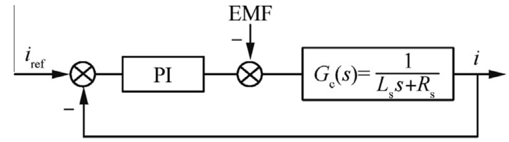


**Fig. 1** Simplified model of current loop of PMSM.

whereas $(-L_q\omega_r i_q)$ for the $d$-axis current loop, where $\omega_r$ is the mechanical rotating speed, $\Psi_f$ is the excitation flux, $i_q$ is the $q$-axis current, and $i_d$ is the $d$-axis current. The plant in the current loop is finally simplified as a first-order system with the time constant $L_s/R_s$.[19] In the practical servo system, the power converter delays the current response at least one pulse width modulation (PWM) period. It is neglected in Fig. 1 and considered as a part of the current loop transfer function $G_c(s)$ in the paper, and the delay could be tuned by means of the method proposed.

The speed loop can be simplified as shown in Fig. 2. $G_{cl}(s)$ represents the current closed loop transfer function including the power converter, the dead-time and the PMSM current loop. $T_L$ represents the load torque, and $\omega$ is the speed to be controlled while $\omega_{ref}$ is the reference speed. Considering that the time constant in the current loop is much smaller than the one in the speed loop, $G_{cl}(s)$ is assumed to be 1 to simplify the analysis. This is not quite accurate for most system modelings. However in this paper, it is not based on an accurate modeling and allows the simplification to assume it as a part of the plant. Then the plant in the speed loop can be assumed as a first-order system with the time constant $J/B$, where $J$ is the total inertia of PMSM, and $B$ is the friction.

### 2.2. PI calculation based on system bandwidth and damping ratio

The PI controller in the time domain has the expression as

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{1}$$

where $K_p$ and $K_i$ are the proportional and the integral coefficients, respectively; $e(t)$ is the error between the reference and the feedback signal.

In the $s$-domain, the PI controller will be expressed by Eq. (2) as

$$P_{PI}(s) = K_p + \frac{K_i}{s} = K_p\left(1 + \frac{1}{T_i s}\right) \tag{2}$$

with $T_i = K_p/K_i$.

Considering that both the plants of the current loop and the speed loop are first-order systems, they can be represented in a normalized form

$$P(s) = \frac{k}{s+p} \tag{3}$$

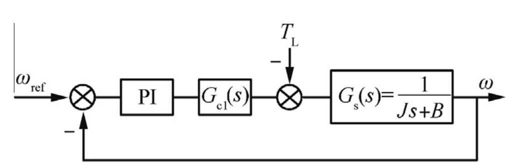


**Fig. 2** Simplified model of speed loop of PMSM.