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Controller design and robustness analysis for induction machine-based positioning system

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Abstract

This paper considers the design of a robust controller for the automatic positioning of a mechanical load actuated by an induction motor. Two main difficulties are involved herein: the first concerns the flexibility that appears in the joint between the load and the actuator; and the second focuses on the robustness to uncertainties, such as load and motor parameters. Based on a nominal model, the H_∞ "loop-shaping" method is used to design a controller that allows both insuring effective monitoring properties and rejecting perturbations. In order to prove robustness to parametric variations, a μ-analysis of the control pattern has been conducted. The ad hoc model developed includes uncertainties on both electrical and mechanical parts. Simulation and experimental results have been incorporated to display the control law performance.

Keywords: Flexible system; Induction machine; μ-Analysis; Parameter uncertainties; Robust control; Robustness analysis

1. Introduction

The induction motor is the most widely used electrical actuator. Since flux-oriented control (FOC) techniques have been introduced for accurate and fast torque control, this motor's range of applications has been extended to encompass variable speeds, for which it provides serious competition to the synchronous "brushless" motor at power levels of above 1 kW. Induction motors can be used for controlling either speed or position. When designing the speed or position controller, a very simple model of control torque loop is generally included.

In the case of indirect flux-oriented control (IFOC), flux and torque are estimated using rotor parameters. Whenever such parameters are not known with certainty, torque control errors appear (Delmotte, Robyns, & Lemaire-Semail, 1996; Semail, Mendes, Bouillault, & Razek, 1990; Nordin, Novotny, & Zinger, 1985). Nevertheless, it can be shown that IFOC maintains the stability of the controlled torque loop regardless of parameter estimation errors. This is not the case, however, when speed or position control loops are added. In de Wit, Ortega, and Mareels (1996), Ortega, Nicklasson, and Espinosa-Pérez (1996), Canudas de Wit and Seleme (1997) and Bazanella and Reginatto (2000), it is observed that for speed control using a PI controller, stability is maintained in spite of large variations in rotor parameters.

When the mechanical load is connected via a flexible joint, the system becomes more complex and features flexible modes. PI and PID controllers are no longer efficient at this point. H_∞ design methods have demonstrated good results for flexible systems (Balas & Doyle, 1994).

In this paper, we will consider the problem of positioning a mechanical load connected to an induction motor via a flexible joint. Torque control is performed

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using IFOC and our goal is to design a position controller that is robust with respect to mechanical and electrical parametric uncertainties. This study has been motivated for practical reasons, as many industrial systems may include induction machines and flexibility. The controller has been designed according to the H_∞ loop-shaping method; the robustness analysis is conducted using the μ-analysis. This paper is structured as follows: in Section 2, the positioning system is described and the model of the plant with IFOC is developed. Section 3 explains the controller design method; simulation and experimental results are also given. The μ-analysis-based robustness analysis is then presented in Section 4. Section 5 provides the paper's concluding remarks.

2. Description of the positioning system

2.1. The electromechanical plant

A diagram of the experimental set-up is given in Fig. 1. A 2.2 kW induction machine is fed by an inverter which is controlled by a digital signal processor (DSP Motorola 96000 with floating point) with a sampling frequency of 8 kHz. Two stator currents i_a and i_b and motor angular position θ_1 are measured in order to control motor torque by applying the IFOC algorithm.

The mechanical load is a pure inertial load and has been connected to the motor via a flexible joint. Load inertia is assumed to vary over a broad range, from 10% to 100% of its rated value. The flexible joint is assumed to exhibit a linear torque/angle characteristic with $\pm 10\%$ uncertainties on the elasticity modulus. The load angle θ_2 is measured.

In the model of the mechanical part, the actuator (of inertia J_1 and position θ_1) is submitted to viscous friction torque $f_1\dot{\theta}_1$ and motor torque T; the load (of inertia J_2 and position θ_2) is submitted to viscous friction torque $f_2\dot{\theta}_2$. The torque provided by the actuator with stiffness ratio $K = 1/\kappa$ to the load is $K(\theta_1 - \theta_2)$.

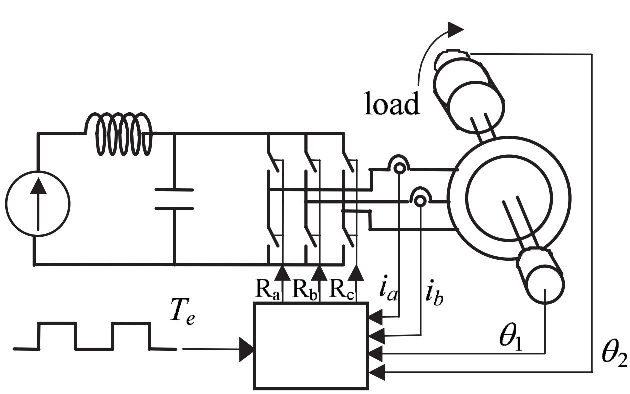

Fig. 1. Scheme of the experimental set-up.

The mechanical equations from Dynamics are

$$J_1\ddot{\theta}_1 = T - f_1\dot{\theta}_1 - K(\theta_1 - \theta_2),$$
$$J_2\ddot{\theta}_2 = -f_2\dot{\theta}_2 + K(\theta_1 - \theta_2). \tag{1}$$

Transfer function $H(s)$ from T to θ_2 is ("s" being the complex variable associated with Laplace transform)

$$H(s) = \frac{\theta_2(s)}{T(s)} = \frac{1}{as^4 + bs^3 + cs^2 + ds} \tag{2}$$

with

$$a = \kappa J_1 J_2, \quad b = \kappa(J_1 f_2 + J_2 f_1),$$
$$c = J_1 + J_2 + \kappa f_1 f_2, \quad d = f_1 + f_2. \tag{3}$$

Physical parameters have been estimated by frequency least-squares method (Johansson, 1993) for the system with full load and tuned IFOC. For a sinusoidal input $T(j\omega_k)$, angular speed $\dot{\theta}_2(j\omega_k)$ is measured. Structural parameters a, b, c and d are computed in order to minimize the following criterion corresponding to the input error

$$J = \sum_k \| T(j\omega_k) - ((j\omega_k)^3 a + (j\omega_k)^2 b + j\omega_k c + d) \times \dot{\theta}_2(j\omega_k)\|^2. \tag{4}$$

Since the inverse model is linear. The parameters verify the following system of equations:

$$\begin{bmatrix} (j\omega_1)^3\dot{\theta}_2(j\omega_1) & (j\omega_1)^2\dot{\theta}_2(j\omega_1) & j\omega_1\dot{\theta}_2(j\omega_1) & \dot{\theta}_2(j\omega_1) \\ \vdots & \vdots & \vdots & \vdots \\ (j\omega_n)^3\dot{\theta}_2(j\omega_n) & (j\omega_n)^2\dot{\theta}_2(j\omega_n) & j\omega_n\dot{\theta}_2(j\omega_n) & \dot{\theta}_2(j\omega_n) \end{bmatrix} \times \begin{bmatrix} a \\ b \\ c \\ d \end{bmatrix} = \begin{bmatrix} T(j\omega_1) \\ \vdots \\ T(j\omega_n) \end{bmatrix}. \tag{5}$$

Eq. (5) can be rewritten as $M[a\ b\ c\ d]^T = B$ and the solution minimizing (4) is $[a\ b\ c\ d]^T = (M^T M)^{-1} M^T B$. Since five physical parameters are to be identified from four structural parameters, one degree of freedom must be arbitrarily assigned. We have elected to set $f_1 = f_2$, corresponding to a balanced distribution of friction. In Fig. 2, the transfer functions are shown with the identified physical parameters and measurements. It can be noted that the model and measurements match one another closely.

2.2. Indirect flux-oriented torque control

Introduced by Blaschke (1972), IFOC is now a classical strategy for controlling flux and torque in induction machines and has led to many industrial developments. In this subsection, we briefly recall the IFOC equations; further details can be found in the literature on the subject (Caron & Hautier, 1995; Leonard, 1996; Vas, 1990).