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Design and sensitivity analysis of a reduced-order rotor flux optimal observer for induction motor control

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Abstract

This paper aims to give simple and effective design criteria of rotor flux reduced-order observers for motion control systems with induction motors. While the observer is optimized for rotor and stator resistance variations, a sensitivity analysis is carried out in the presence of variations of all the motor parameters by means of either transfer function from true to observed rotor flux or simulation in a MATLAB-SIMULINK environment, assuming the voltages supplying the motor to be different from those supplying the observer. The sensitivity analysis makes it possible to establish design criteria for the observer in question. The behaviour of the proposed reduced order observer is compared with current model and voltage model observers. Experimental results are also given, with the dual aim of confirming the validity of this design method and showing that the observer can be implemented on microprocessor-based devices.

Keywords: Induction motors; Reduced-order observers

1. Introduction

As is well known, the implementation of a control law for induction motors based on rotor flux control requires estimation of modulus and phase of the rotor flux vector in the stationary frame. In order to estimate rotor flux components in the desired frame, either open loop observers, such as current model and voltage models, or closed loop observers, such as full and reduced order observers, can be implemented.

The full-order observer makes it possible to estimate stator current and rotor flux components from measurements of stator voltages, stator currents and speed (Hinkkanen & Luomi, 2003; Jansen & Lorenz, 1994; Schreier, DeLeon, Glumineau, & Boisliveau, 2001). The principal advantage of this observer is the availability of observed stator currents that are less noisy than the measured ones; consequently, filtering is not required, thus avoiding time delays in the variables involved in the control law processing. Full-order observers for sensorless direct field-oriented control have also been recently proposed (Hinkkanen, 2004).

The reduced-order observer makes it possible to estimate only the rotor flux components starting from measurements of stator currents and speed. Filters of suitable bandwidth can be employed in order to reproduce output signals having a higher signal-to-noise ratio than the input ones and negligible delays. The use of filters is necessary to avoid aliasing considering that the observer has to be implemented on digital devices. The same filters can be used for both objectives, i.e. to reduce noise and avoid aliasing.

Various structures of reduced order-rotor flux observers have been proposed using different approaches, assuming nominal values for the motor parameters (Alonge & Raimondi, 1990; Bellini, Figalli, & Ulivi, 1988; Kubota, Matsuse, & Nakano, 1993; Verghese & Sanders, 1988). In these papers the choice of the adjustable parameters of the observer is effected using various methods, such as trial and error and pole assignment, in order to obtain satisfactory dynamic and steady-state behaviours also in the presence of motor parameter variations. A description

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Nomenclature

i_a (i_b)	stator current component along a-axis (b-axis) in the stationary frame, A
v_a (v_b)	stator voltage component along a-axis (b-axis), V
$\boldsymbol{\phi}_e$	rotor flux vector
$\boldsymbol{\phi}$ $(=L_m/L_r(\boldsymbol{\phi}_e))$	scaled rotor flux vector
ϕ_a (ϕ_b)	component of $\boldsymbol{\phi}$ along a-axis (b-axis), Wb
ϕ_d	amplitude of $\boldsymbol{\phi}$, Wb
v_d (v_q)	stator voltage component along d-axis fixed with $\boldsymbol{\phi}$ (q-axis), V
i_d (i_q)	stator current component along d-axis (q-axis), A
$V(I)$	maximum amplitude of stator voltage (current) vector, V (A)
ω	speed, rad/s
$\omega_s(\omega_e-\omega)$	slip frequency (supply frequency), Hz
$R_s(L_s)$	stator resistance (inductance), Ω (H)
$R_r(L_r)$	rotor resistance (inductance), Ω (H)
L_m	magnetizing inductance, H
$\tau_r(=L_r/R_r)$	rotor time constant, s
$L_e(=L_s-(L_m^2/L_r))$	stator transient inductance, H
F	viscous friction coefficient, Nms
$t_m(t_r)$	motor (load) torque, Nm
J_m	inertia coefficient, Nms^2
p	pole pairs

Subscripts

"0"	nominal parameters

of some pole placement techniques and a comparison between them is given in Kojabadi and Chang (2005).

Besides the above-mentioned deterministic observers, full- and reduced-order stochastic observers based on the Kalman filter approach have also been proposed (cf. for example, Du, Vas, & Stronach, 1995; Duval, Clerc, & Le Gorrec, 2006). The above observers have also been designed for parameter identification and estimation of speed and load torque. However, it has been recognized that the implementation of these observers is very time consuming and consequently requires high sampling times.

The present paper aims to give a systematic procedure for designing a deterministic reduced-order observer for motion control systems with an induction motor whose processing requires the knowledge of stator currents, speed and stator voltages. Stator currents are measured using Hall effect transducers usually integrated in the inverter module supplying the motor. Stator voltages are assumed to be the reference voltages given by the system controller and utilized by the PWM module to generate the PWM voltages supplying the motor. The speed can be either measured, using an incremental encoder, or obtained, for example, as described in Kubota et al. (1993), thus realizing a sensorless system.

The above procedure consists of: (a) choice of the observer structure; (b) sensitivity analysis to both parameter variations and differences of the voltages supplying the motor and those supplying the observer; (c) choice of the free parameters using the results of the previous analysis.

The structure of the observer is chosen so as to minimize both the effects of rotor and stator resistances and the differences of the voltages supplying the motor and those utilized for processing the observer (Alonge, D'Ippolito, Giardina, Raimondi, & Scaffidi, 2005).

The sensitivity analysis of parameter variations is carried out using an analytical approach based on the construction of a transfer function from the true rotor flux to the observed one (Hinkkanen & Luomi, 2003; Hinkkanen, 2004; Jansen & Lorenz, 1994; Kim, Choi, & Sul, 2002). The effects of differences of the voltages supplying the motor and those supplying the observer are analysed by means of simulation, via implementation of the mathematical models of the motor and the observer in a MATLAB–SIMULINK environment and computation of responses corresponding to specified inputs.

The sensitivity analysis and the approach used for determining the observer structure brings us to only one parameter free of the observer. Some simple criteria are discussed for choosing this free parameter.

The proposed observer is compared to current model and voltage model observers which, as is well known, give the best results at low speed and high speed, respectively. Even though these last observers are open loop, the comparison is useful because they are often considered in the literature as references for testing other observers.

Experimental results are given in order to test the validity of the approach followed. Since the true rotor flux cannot be measured, this is tested indirectly, i.e. by means of both examination of waveforms relative to measured variables, for example, speed, and implementation of the mathematical models of the motor and the observer on the same DSP board: the rotor flux computed by the mathematical model of the motor is assumed as the true rotor flux and, consequently, with a certain approximation, an observation error can be defined as the difference of the flux computed by the model and that given by the observer.

In the experiments, the mathematical models of both the motor and the observer are implemented on a floating-point DSP using the fourth-order Runge–Kutta method. However, the proposed observer can be easily implemented on a fixed-point DSP by means of look-up tables which give the values of the terms of the observer model at the actual speed. This causes the processing time of the observer to be small, which contributes to the choice of small sampling times for the whole controller of the motion