ISA Transactions 60 (2016) 333–347

Contents lists available at ScienceDirect

ISA Transactions

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

Research Article

# DSP-based adaptive backstepping using the tracking errors for high-performance sensorless speed control of induction motor drive

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ARTICLE INFO

*Article history:*
Received 9 January 2015
Received in revised form
28 September 2015
Accepted 19 November 2015
Available online 3 December 2015
This paper was recommended for publication by Dr. Prof. A.B. Rad.

*Keywords:*
Induction motor (IM)
Backstepping
Adaptive observer
Sensorless control
Vector control
PI control
Digital signal processor (DSP)
Space vector
Pulse width modulation (SVPWM)
dSpace DS1104

ABSTRACT

This paper presents a modified structure of the backstepping nonlinear control of the induction motor (IM) fitted with an adaptive backstepping speed observer. The control design is based on the backstepping technique complemented by the introduction of integral tracking errors action to improve its robustness. Unlike other research performed on backstepping control with integral action, the control law developed in this paper does not propose the increase of the number of system state so as not increase the complexity of differential equations resolution. The digital simulation and experimental results show the effectiveness of the proposed control compared to the conventional PI control. The results analysis shows the characteristic robustness of the adaptive control to disturbances of the load, the speed variation and low speed.



## 1. Introduction

The induction motor has many advantages over other types of electric motors as their high efficiency, high speed and lifetime. These advantages and technological advances in power electronics fields and signal processing have allowed the induction motor to work in the most difficult environments and have a low maintenance cost [1,2].

In variable speed applications that require accurate dynamic despite different types of disturbances and parametric uncertainties, conventional linear controllers as PI and PID are difficult to adjust with a nonlinear problem. In this case, performance can be improved by nonlinear control techniques. Recent years have seen rapid progress in the control of nonlinear systems. In particular several accurate linearization techniques have been applied to the control of asynchronous machines. These techniques require the knowledge of system parameters, which is not generally the case for electric machines [3,4]. To improve the robustness of the control towards the parametric variations, especially the rotor resistance, many researches have proposed the nonlinear control laws and nonlinear speed observer. Among them, the sliding mode control and the backstepping control. The sliding mode technique was applied to the induction machine, but the main drawback of this type of control is gains adjustment even if the maximum value can be formulated from the upper bounds of uncertainties [5], and appearance of the chattering phenomenon [6,7]. Other researches use the backstepping method for the control design and rotor speed estimation.

Backstepping method has recently appeared allowing the design of the control law and also the estimation of motor parameters [8,9]. In [10], the authors present a new control scheme using a novel dynamical model of the induction motor based on the classical backstepping control with the unknown of the motor inertia, the damping coefficient, the load torque and the uncertainty of the rotor resistance without applying a load torque in the tests carried out. However, the comparative study presented in [11] shows that this type of control present a high bandwidth for the speed signal which is not close to the reference speed, and does not guarantee a total rejection of the disturbance (load

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http://dx.doi.org/10.1016/j.isatra.2015.11.021
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**Nomenclature**

| | |
|---|---|
| $v_{sd},\ v_{sq}$ | d and q components of stator voltage |
| $i_{sd},\ i_{sq}$ | d and q components of stator current |
| $\psi_{rd},\ \psi_{rq}$ | Rotor flux components |
| $T_e,\ T_l$ | Electromagnetic and load torque |
| $d-q$ | Synchronous axis reference frame quantities |
| $\alpha-\beta$ | Stationary axis reference frame quantities |
| $\omega,\ \omega_{sl}$ | Rotor and slip angular angular velocity |
| $\Delta\omega$ | Difference between real and estimated rotor speed |
| $L_s,\ L_r$ | Stator and rotor inductances |
| $R_s,\ R_r$ | Stator and rotor resistances |
| $M$ | Mutual inductance |
| $J$ | The inertia of motor and load |
| $\sigma$ | Total linkage coefficient |
| $n_p$ | Number of pole pairs |
| $f$ | Friction coefficient |
| $^*,\ \hat{}$ | Reference value and estimated value |
| $k_q,\ k_q',\ k_d,\ k_d'$ | Positive constants of the proposed backstepping control algorithm |
| $\tau_0$ | Estimator time constant of the load torque |
| $\tau_r,\ \tau_s$ | Rotor and stator time constant |
| $s$ | Laplace variable |
| $k_p,\ k_i$ | Positives constants of the PI controller for the rotor speed estimation |

torque).In [11,12], the authors propose an integral version of the control and an adaptive observer using the backstepping technique. The obtained results show the good performance of the control law and the observer, but it may be noted that the problem with this method is the complexity of solving differential equations, which require more computing time for processor, since the model will be increased by two states. Also, we can notice that the tests are performed at a low speed approximately of 8% of the nominal speed unlike the work presented in [13], where the author validates the Z-type observer with less than 1% of the nominal speed.

Other researchers use a control strategy and observation based on fuzzy logic or neural networks [14–16]. Other work has been presented based on hybrid structures, for example combining the fuzzy logic with the sliding mode or MRAS (Model Reference Adaptive System) [17–19], and the backstepping with the sliding mode [20,21].

The topic of this paper is to design a simple control law compared to the works presented in [11,13] for three phases induction motor allowing high static and dynamic performance. This technique is based on backstepping methodology that establishes successive relationships to build iteratively a systematic and robust control law, asymptotically stable according to the Lyapunov stability theory [22]. The effect of variation of certain parameters and load disturbance can be significantly reduced by adding an integral action of the tracking errors at each step of the control and speed observer design, without increasing the state model of induction motor with another two states like the works presented in [11,13]. This technique will ensure a high accuracy of control vis-a-vis parametric uncertainties, and low speed estimation in transient and steady states. The sensorless speed control is validated experimentally through Matlab-Simulink (R2011b'7. 13.0.564') environment and the dSpace DS 1104 card based on real-time data acquisition control system. The backstepping control using the integral action of the tracking errors is compared to the classical control using a PI controller, to show the effectiveness of the proposed algorithm.

## 2. IM state space model

The dynamic model of the three phases induction motor according to the assumptions of linearity can be expressed in a synchronous reference frame by [12]:

$$\frac{d}{dt}\begin{bmatrix} i_s \\ \psi_r \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}\begin{bmatrix} i_s \\ \psi_r \end{bmatrix} + \begin{bmatrix} B_1 \\ 0_{2x2} \end{bmatrix} v_s$$

$$i_s = C\begin{bmatrix} i_s \\ \psi_r \end{bmatrix} \tag{1}$$

where

$i_s = \begin{bmatrix} i_{sd} & i_{sq} \end{bmatrix}^T$ : Stator current, $\psi_r = \begin{bmatrix} \psi_{rd} & \psi_{rq} \end{bmatrix}^T$ : Rotor flux, $v_s = \begin{bmatrix} v_{sd} & v_{sq} \end{bmatrix}^T$ : Stator voltage,

$$A_{11} = \begin{bmatrix} -\gamma & \omega_s \\ -\omega_s & -\gamma \end{bmatrix}, A_{12} = \begin{bmatrix} \frac{\delta}{\tau_r} & \delta\omega \\ -\delta\omega & \frac{\delta}{\tau_r} \end{bmatrix}, A_{21} = \begin{bmatrix} \frac{M}{\tau_r} & 0 \\ 0 & \frac{M}{\tau_r} \end{bmatrix},$$

$$A_{22} = \begin{bmatrix} -\frac{1}{\tau_r} & \omega_{sl} \\ -\omega_{sl} & -\frac{1}{\tau_r} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}, B_1 = \begin{bmatrix} \frac{1}{\sigma L_s} & 0 \\ 0 & \frac{1}{\sigma L_s} \end{bmatrix},$$

$$0_{2x2} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, \gamma = \frac{1}{\sigma}\left(\frac{1}{\tau_s} + \frac{1-\sigma}{\tau_r}\right)$$

$$\delta = \frac{M}{\sigma L_s L_r}, \sigma = 1 - \frac{M^2}{L_r L_s}, \tau_r = \frac{L_r}{R_r} \text{ and } \tau_s = \frac{L_s}{R_s}.$$

The mechanical equation can be written as follows:

$$J\frac{d}{dt}\omega = T_e - T_l - f\omega \tag{2}$$

where the electromagnetic torque developed by the IM is

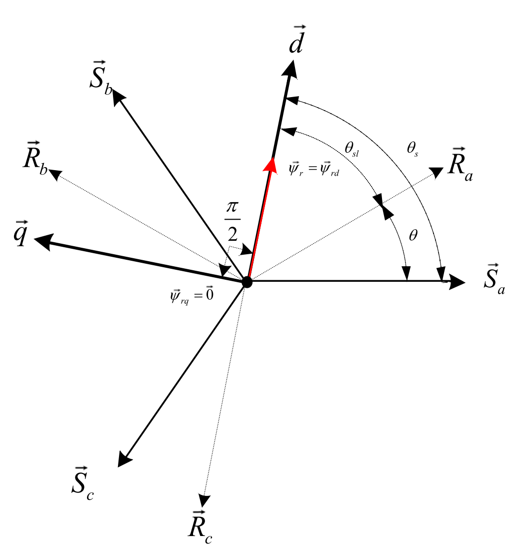


**Fig. 1.** Reference frame ($d$–$q$) orientation according to the rotor flux vector.