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Original article

# Sliding-mode direct torque control and sliding-mode observer with a magnetizing reactance estimator for the field-weakening of the induction motor drive

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**Abstract**

The paper deals with the sliding-mode control and the sliding-mode speed observer for the induction motor drive. The main interest of the paper is high speed operation, during the field-weakening, where the machine magnetizing characteristic is of great importance. Therefore the magnetizing reactance estimator, based on the magnetizing curve identification is used. The sliding mode technique is applied to design the direct control of the induction motor torque. A unified designing approach for control as well for the state space variables estimation is shown. Simulation and experimental results are shown to illustrate described problems.


*Keywords:* Induction motor drive; Sliding-mode control; Sliding-mode observer; Field-weakening; Magnetizing reactance

## 1. Introduction[1]

Induction motor (IM) drives are the most reliable and the least expensive electric drives. However, the most complicated control systems are required to obtain superb dynamics of the drive. Additionally, the above mentioned complex control structures must be extended with proper estimators of the non-measurable state variables [16]. Speed estimation applied in sensorless drives, causes reduction of the price, decrease of the total dimensions of the machine, minimization of cabling, etc. [30], and therefore such control is a point of interest of many research teams.

The above mentioned superb dynamics can be ensured using the sliding-mode control (SMC). The first SMC applications for the IM drive appeared at the turn of 1970s and 1980s as a result of Sabanovic and Izosimov's works [9,21,22]. In the following years many papers enriched the IM sliding-mode control theory, e.g. Utkin's paper [29], another one about the IM position control [31] and others [23]. In recent years many new, various approaches to the SMC have appeared. Among them a novel SMC algorithm with optimized torque response and efficiency [20], conventional DTC and sliding-modes combined in [13] and integral nested SMC [19,32], also for sensorless drives

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[1] The notation is used in this paper: small letters indicate the per unit system [16] (except for stator frequency and number of pole pairs), vectors are expressed using bold letters, in the stationary $\alpha-\beta$ frame. The '^' sign indicates estimated values. The symbols used in the article are given under list of symbols section.

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**Nomenclature**

*Notation*

$f_s$ stator frequency [Hz]
$\mathbf{i_s} = i_{s\alpha} + ji_{s\beta}$ stator current vector [p.u.]
$\mathbf{i_r} = i_{r\alpha} + ji_{r\beta}$ rotor current vector [p.u.]
$J$ moment of inertia [kg m$^2$]
$m_e$, $m_L$ motor and load torque [p.u.]
$p_p$ pole pairs
$r_s$, $r_r$ stator and rotor resistances [p.u.]
$\mathbf{s} = [s_1, s_2, s_3]^T$ switching function vector [p.u.]
$T_M = J\Omega_b/(p_p M_b)$ mechanical time constant [s]
$T_N = 1/(2\pi f_{sN})$, time constant, the result of the per unit system usage [s]
$u_{DC}$ constant voltage of the DC circuit [p.u.]
$u_{AN}$, $u_{BN}$, $u_{CN}$ motor phase voltages [p.u.]
$\mathbf{u_s} = u_{s\alpha} + ju_{s\beta}$ stator voltage vector [p.u.]
$x_s = x_m + x_{s\sigma}$, $x_r = x_m + x_{r\sigma}$,$x_m$, $x_{s\sigma}$, $x_{r\sigma}$ stator, rotor, magnetizing and leakage reactances [p.u.]
$\Delta$ estimation error [p.u.]
$\gamma_{\psi s} = \mathrm{atan}(\psi_{s\beta}/\psi_{s\alpha})$ stator flux vector angle [rad]
$\sigma = 1 - x_m{}^2/(x_s x_r)$ total leakage factor
$\boldsymbol{\psi}_\mathbf{s} = \psi_{s\alpha} + j\psi_{s\beta}$ stator flux vector [p.u.]
$\boldsymbol{\psi}_\mathbf{r} = \psi_{r\alpha} + j\psi_{r\beta}$ rotor flux vector [p.u.]
$\boldsymbol{\psi}_\mathbf{m} = \psi_{m\alpha} + j\psi_{m\beta}$ magnetizing flux vector [p.u.]
$\omega_m$ motor angular velocity [p.u.]

*Sub- and superscripts*

$N$ nominal value (see Table 2 in Appendix A)
$b$ base value (see Table 3 in Appendix A)
ref reference value
fil filtered value

[3,5] can be found. Low and zero-speed action is concerned in [10]. The exponential control law [25] and the High Order Sliding-Mode Control [36], can be also used for the IM drives.

The first application of the sliding mode theory in IM observers was also a result of Izosimov's work [8]. Simple hardware implementation, robustness over a specified range of motor parameter uncertainties, disturbances and measurement noise, eventually fast dynamic response entail still growing publication number in the field of the Sliding Mode Observer (SMO) applications. Model Reference Adaptive System – type SMO is proposed in [4]. SMC and SMO working simultaneously were presented in [1,7,33]. Stability analysis of the closed loop sliding mode controller-observer system for the induction motor drive was presented in [7]. The adaptive [18] and the second-order [24] approaches of the sliding observer were also presented. A new observer designed in a synchronous frame was introduced in [12]. An excellent overview of existing (till 2002) SMO types for different motors can be found in [34].

There were few publications comparing the SMOs with different estimation methods – Model Reference Adaptive System (MRAS) based observers in [11,15], extended Kalman filters [2] and, together with Luenberger type observer, in [35].

The Authors' recent attention was also focused on the comparison of different flux and speed estimation methods for induction motor drives, including the classical Sliding Mode Observer [34] and the observer defined in a synchronous reference frame [12]. These estimators were compared with different solutions in [26]. The classical SMO main features were its simplicity and robustness over motor parameter changes. However, the conducted tests indicate clearly that the SMO is quite sensitive to the magnetizing reactance changes. Therefore this estimator was chosen for further tests with additional magnetizing reactance estimator.