Online ISSN 1848-3380, Print ISSN 0005-1144
ATKAFF 54(3), 329–336(2013)

*Mateusz Dybkowski, Teresa Orlowska-Kowalska, Grzegorz Tarchała*

# Sensorless Traction Drive System with Sliding Mode and MRAS$^{CC}$ Estimators using Direct Torque Control

DOI 10.7305/automatika.54-3.169
UDK 681.532.6.015.075:621.313.333(621.33)
IFAC 2.1.4; 5.5.4

**Original scientific paper**

In the paper two types of speed, torque and flux estimators are described. The Sliding Mode Observer (SMO) and the Model Reference Adaptive System (MRAS) type estimators are applied in the sensorless Direct Torque Control with Space Vector Modulation algorithm (DTC-SVM) of Induction Motor (IM) drive. Dynamical performance of the drive and the estimator properties in field weakening and low speed regions for traction drive system are presented.

**Key words:** Induction motor, DTC-SVM, Sensorless control, Traction, SMO, MRAS

**Bezsenzorski pogon za vuču s estimatorima u kliznom režimu i MRAS$^{CC}$-u koristeći izravno upravljanje momentom.** U članku su opisana dva tipa estimatora brzine, momenta i toka – observer u kliznom režimu (SMO) i adaptivni sustav reference modela (MRAS). Oba tipa estimatora su primijenjena u bezsenzorskom izravnom upravljanju momentom s modulacijom prostornih vektora (DTC-SVM) na pogonu s asinkronim motorom (IM). Prikazane su dinamičke karakteristike pogona i estimatora u režimima slabog polja i male brzine za slijedni sustav.

**Ključne riječi:** asinkroni motor, DTC-SVM, bezsenzorsko upravljanje, vuča, SMO, MRAS

## 1 INTRODUCTION

The Direct Torque Control with Space Vector Modulation (DTC-SVM) is one of the most popular control algorithms for the Induction Motor (IM) drives [1], [2]. The main advantage of this method is very fast torque response to load torque changes. The main disadvantage of the classical approach (DTC-ST), the switching table, is eliminated using the Space Vector Modulation (SVM) [1].

Information about stator flux vector, motor torque and speed is necessary for proper work of this control algorithm [3], [4]. The stator flux can be estimated using different algorithmic methods, e.g. using the Sliding Mode Observer (SMO) [5], Model Reference Adaptive System (MRAS) type estimators [6], neural networks or Kalman Filters [3], [4]. Motor speed and torque can be also estimated using these methods, or measured directly. However, elimination of the speed and torque sensors minimizes the cost of the drive, decreases driven motor dimensions, reduces cabling and increases system reliability [3], [4], [7], [8]. These advantages cause that the speed-sensorless drives are applied in traction drive systems [9]. Thus, developing and application of robust solutions for IM state variables estimation is an important task.

Traction drive systems must operate in a wide reference speed range, in the constant-flux region, for very low speeds and in the field weakening region with maximal possible torque [10], [11]. Information about the rotor speed is necessary at zero or low speed operation, to realize properly the electrical braking.

During the start up to the nominal speed with nominal (or bigger) load torque, as well as during the breaking operation, electromagnetic torque must be controlled perfectly [2]. In traction drive systems without speed control loop, information about the rotor speed must be used in the field weakening algorithm [11], [15] and in the diagnostic process.

Well known voltage simulator, based on stator currents and voltages can be used in the estimation process [4]. Although this algorithm does not require information about the rotor speed, it cannot be applied in drives working with low speeds. Only more complicated algorithms can guarantee stable work in a wide speed range.

The applied estimator must be robust to motor parameter changes or extended with on-line parameter updating procedures. Sensorless drive system should be stable when starting from the standstill, for low speed region and in the regenerating mode [4],[6]-[8],[12].

The main goal of this paper is to present and compare two estimators which enable proper operation of the DTC-SVM sensorless IM drive in a wide speed range. The MRAS$^{CC}$ [6] estimator and the SMO [5] are used for speed, torque and flux reconstruction. Dynamical properties of the sensorless drive are widely examined under simulation and experimental test.

## 2 MODEL OF THE INDUCTION MOTOR AND DIRECT TORQUE CONTROL ALGORITHM

Direct Torque Control with Space Vector Modulation algorithm (DTC-SVM) [1] without any outer speed control loop can be applied in the traction drive systems. The general scheme of this control structure is presented in Fig. 1.

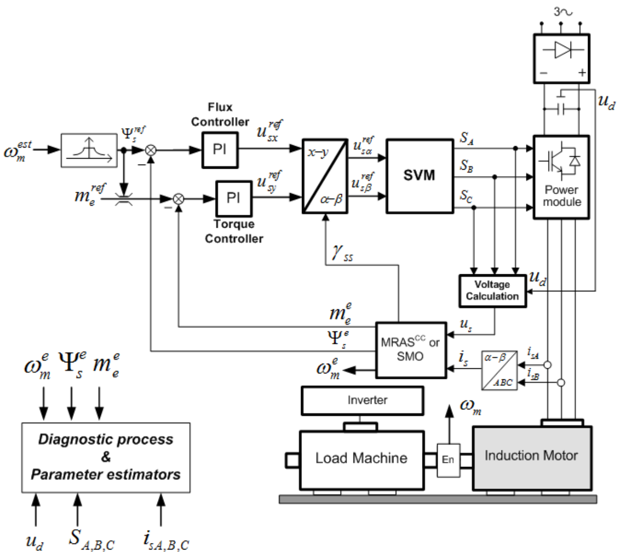



*Fig. 1. Sensorless DTC-SVM structure with SMO or MRAS$^{CC}$ estimators.*

In this scheme motor torque and stator vector amplitude are controlled by PI regulators in the synchronous reference frame. The essential stator flux angle information, necessary for the coordinate transformation, is obtained from the speed and flux observers. The estimated speed signal is used in the field-weakening algorithm and in the diagnostic process of the traction drive (Fig. 1). Information about the rotor speed, stator flux vector, electromagnetic torque, DC bus voltage, signals from the inverter and stator currents are used in the diagnostic process of the traction drive system. When these signals become bigger than the safety values, the drive should be stopped. Especially in an extremely low speed region these values must be observed. Any oscillations and abnormal transients are not allowed, too.

The observers, considered in this paper, are based directly on the IM mathematical model (1)–(4). This model can be derived using the commonly-known assumptions and can be expressed in the stator-stationary frame, using per unit system [4]:

$$T_N \frac{d\mathbf{i}_s}{dt} = \frac{1}{x_s\sigma}\left(\mathbf{u}_s - \alpha\mathbf{i}_s + \frac{x_m r_r}{x_r^2}\mathbf{\Psi}_r - j\frac{x_m}{x_r}\omega_m\mathbf{\Psi}_r\right) \quad (1)$$

$$T_N \frac{d\mathbf{\Psi}_r}{dt} = -\frac{r_r}{x_r}\mathbf{\Psi}_r + \frac{x_m r_r}{x_r}\mathbf{i}_s + j\omega_m\mathbf{\Psi}_r \quad (2)$$

$$\frac{d\omega_m}{dt} = \frac{1}{T_M}\left(m_e - m_L\right) \quad (3)$$

$$m_e = x_m/x_r\left(i_{s\beta}\Psi_{r\alpha} - i_{s\alpha}\Psi_{r\beta}\right) \quad (4)$$

where: $\omega_m, m_e, m_L, T_M$ – motor angular velocity, electromagnetic and load torques, and mechanical time constant, respectively, *rs, rr* - stator and rotor resistances, $x_m$, $x_s = x_m + x_{s\sigma}$, $x_r = x_m + x_{r\sigma}$ – magnetizing, stator and rotor reactances, $x_{\sigma s}, x_{\sigma r}$, – stator and rotor leakage reactances, $T_N = 1/2\pi f_{sN}$, $\alpha = r_s + r_r x_m^2/x_r^2$, $\sigma = 1 - x_m^2/x_s x_r$, $f_{sN}$ – motor nominal frequency.

## 3 SMO AND MRAS$^{CC}$ SPEED AND FLUX ESTIMATORS

In this section the mathematical models of the SMO and MRAS$^{CC}$ type speed and flux estimator are presented.

The rotor speed can be calculated by the SMO as follows [5]:

$$\omega_m^e = \omega_0 \operatorname{sign} s_\omega \quad (5)$$

where: $\omega_0$ – positive constant.

The auxiliary variable $\mu$ can be introduced in order to reduce the stator flux steady-state error [5]:

$$\mu = \mu_0 \operatorname{sign} s_\mu \quad (6)$$

where $\mu_0$ – positive constant.

The switching functions are obtained by the following equations:

$$\begin{aligned} s_\omega &= \left(i_{s\beta} - i_{s\beta}^e\right)\Psi_{r\alpha}^e - \left(i_{s\alpha} - i_{s\alpha}^e\right)\Psi_{r\beta}^e \\ s_\mu &= \left(i_{s\alpha} - i_{s\alpha}^e\right)\Psi_{r\alpha}^e + \left(i_{s\beta} - i_{s\beta}^e\right)\Psi_{r\beta}^e \end{aligned} \quad (7)$$

Thus the rotor flux vector can be estimated from:

$$T_N \frac{d\mathbf{\Psi}_r^e}{dt} = \frac{x_m r_r}{x_r}\mathbf{i}_s - \left(\frac{r_r}{x_r} + \mu\right)\mathbf{\Psi}_r^e + j\omega_m^e\mathbf{\Psi}_r^e \quad (8)$$

and the stator current:

$$T_N \frac{d\mathbf{i}_s^e}{dt} = \frac{1}{x_s\sigma}\cdot \\ \cdot\left(\begin{array}{l} \mathbf{u}_s - r_s\mathbf{i}_s^e + \\ -\frac{x_m}{x_r}\left(r_r\frac{x_m}{x_r}\mathbf{i}_s^e - \left(\frac{r_r}{x_r} + \mu\right)\mathbf{\Psi}_r^e - j\omega_m^e\mathbf{\Psi}_r^e\right) \end{array}\right) \quad (9)$$

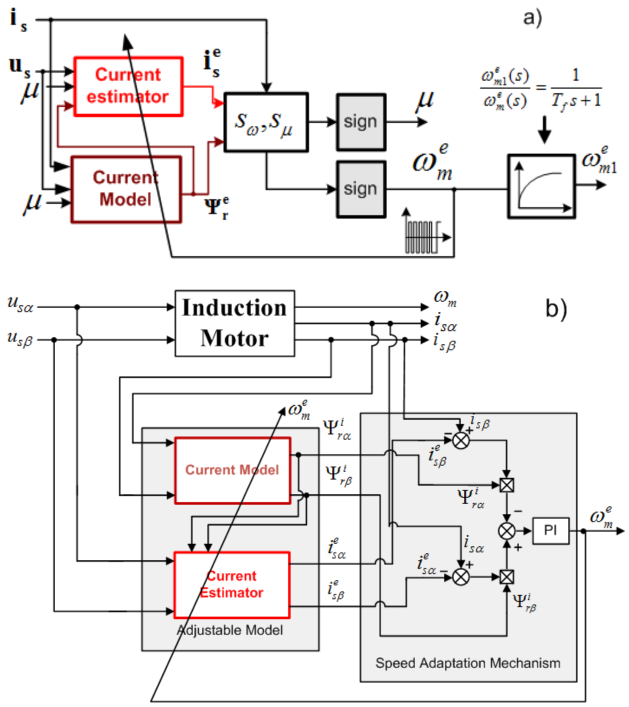



*Fig. 2. Block diagram of the sliding-mode speed observer (SMO) (a) and MRAS$^{CC}$ estimator (b).*

The general scheme of the SMO is presented in Fig. 2a. It can be noticed that the high-frequency speed signal is used directly in the observer. To apply it in the diagnostic system and field-weakening algorithm, the low-pass filter must be used (Fig. 2a).

The MRAS$^{CC}$ estimator was presented in detail in [6]. This estimator is based on two well-known flux simulators [4] (voltage model and current model of the rotor flux). They are rearranged to obtain the stator current estimator. Rotor flux is estimated by the current model.

Stator current estimator used in the MRAS$^{CC}$ is obtained by the equation:

$$T_N \frac{d\mathbf{i}_s^e}{dt} = \frac{1}{x_s\sigma}\left( \begin{array}{l} \mathbf{u}_s - r_s \mathbf{i}_s^e + \\ -\frac{x_m}{x_r}\left( r_r \frac{x_m}{x_r}\mathbf{i}_s^e - \frac{r_r}{x_r}\mathbf{\Psi}_r^e - j\omega_m^e \mathbf{\Psi}_r^e \right) \end{array} \right) \tag{10}$$

Rotor flux can be calculated from the equation:

$$\frac{d}{dt}\mathbf{\Psi}_r^i = \left[ \frac{r_r}{x_r}(x_m \mathbf{i}_s - \mathbf{\Psi}_r^i) + j\omega_m^e \mathbf{\Psi}_r^i \right] \frac{1}{T_N} \tag{11}$$

Both stator current model (10) and rotor flux model (11) are adjusted by the estimated rotor speed [6]:

$$\begin{aligned} \omega_m^e = {} & K_P \left( e_{i_{s\alpha}} \Psi_{r\beta}^i - e_{i_{s\beta}} \Psi_{r\alpha}^i \right) + \\ & + K_I \int \left( e_{i_{s\alpha}} \Psi_{r\beta}^i - e_{i_{s\beta}} \Psi_{r\alpha}^i \right) \, dt \end{aligned} \tag{12}$$

where $e_{i_{s\alpha,\beta}} = i_{s\alpha,\beta} - i_{s\alpha,\beta}^e$ – error between the estimated and measured stator current vector components.

The general scheme of the MRAS$^{CC}$ estimator is presented in Fig. 2b.

Stator flux vector can be calculated using the estimated rotor flux and the measured stator current vectors, from:

$$\mathbf{\Psi}_s^e = \frac{x_m}{x_r}\mathbf{\Psi}_r^e + x_s \sigma \mathbf{i}_s \tag{13}$$

The main advantage of those estimators is low sensitivity to the motor parameter changes [6], [13], [14].

## 4 SIMULATION AND EXPERIMENTAL RESULTS

Described estimation algorithms were tested using MATLAB SIMULINK software and experimentally on a laboratory set-up with dSPACE DS1103 processor. The schematic diagram of the experimental test bench is shown in Fig. 3.

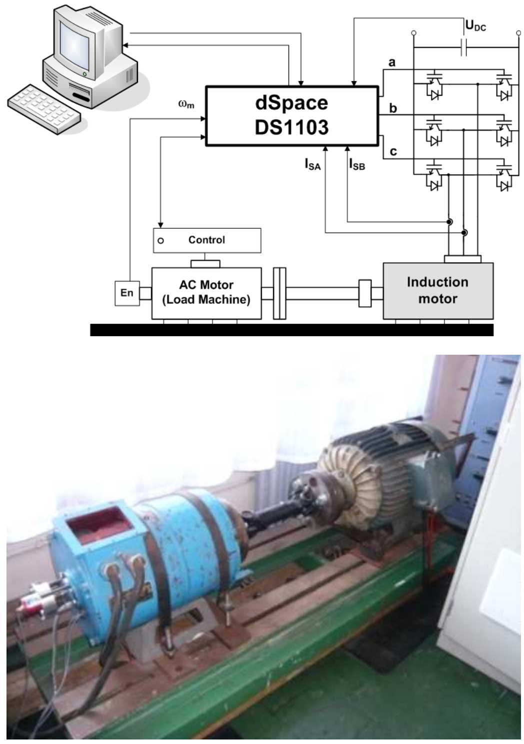



*Fig. 3. Schematic diagram of the laboratory test bench and the photo of the traction drive system.*

The experimental set-up is composed of the 50 kW IM (fed from the voltage source inverter (VSI)) and a load machine (IM supplied from an AC inverter). The speed and position of the drive are measured by the incremental encoder (100 imp./rev.), only for comparison with the estimated speed in the sensorless drive system.

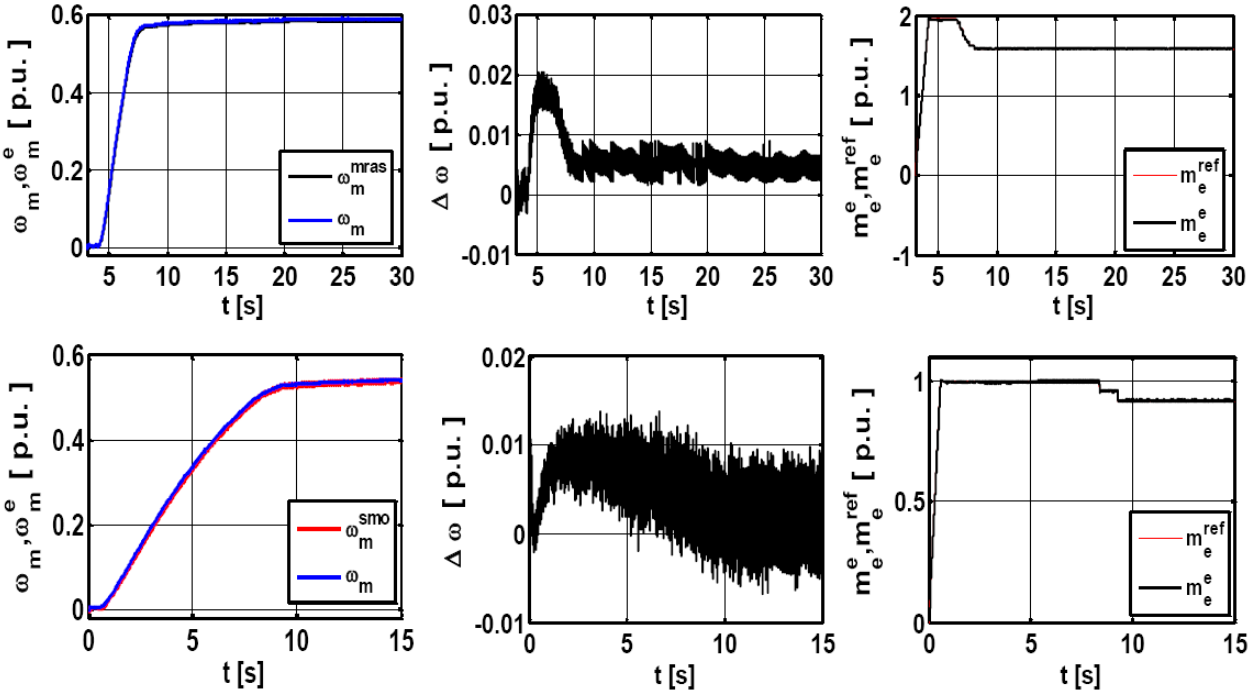



*Fig. 4. Start-up operation of the DTC-SVM drive under bigger than nominal load torque with MRAS$^{CC}$ (a) and SMO (b) estimators; (experimental tests).*

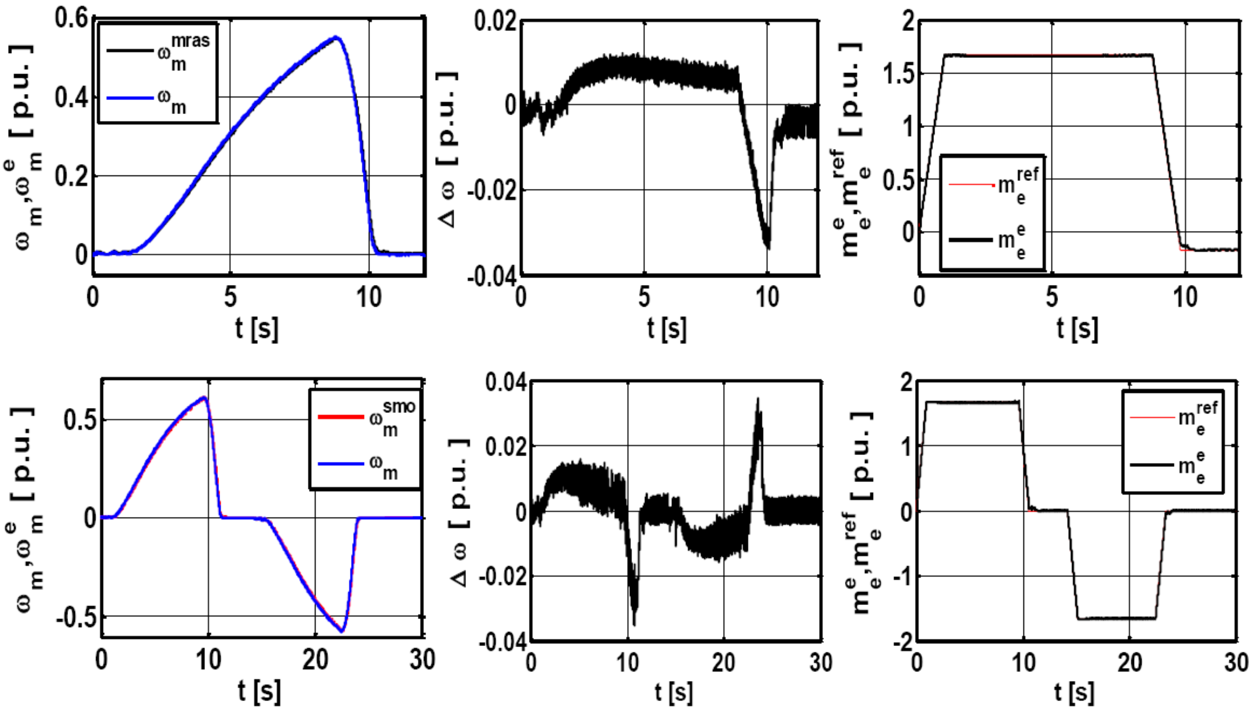



*Fig. 5. Breaking operation of the DTC-SVM drive under nominal load torque with MRAS$^{CC}$ (a) and SMO (b) estimators (experimental tests).*

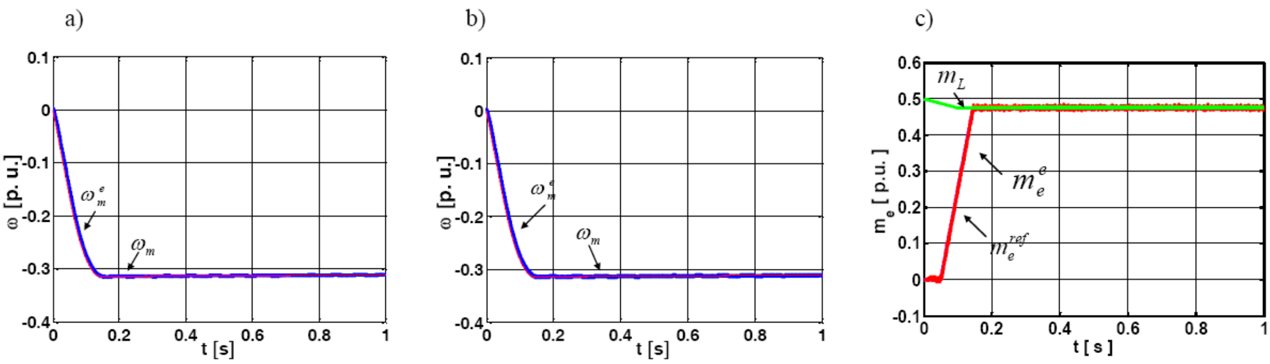


*Fig. 6. Start-up operation of the DTC-SVM drive under active nominal load torque with MRAS$^{CC}$ (a) and SMO (b) estimators.*

In Fig. 4 – Fig. 6 chosen simulation results of the sensorless DTC drive without speed control loop, with MRAS$^{CC}$ and SMO are presented. The drive was tested for different load torque conditions, typical for traction systems. Estimated speed was used only in the field weakening algorithm and to adjust the flux estimators.

In Fig. 4 the start-up operation under bigger than nominal load torque is presented, for both estimators. During the start-up operation reference and electromagnetic torques are bigger than the load torque. Later the reference torque becomes identical as the load torque. Measured and estimated speeds are equal during this process. Both estimators work properly, but the sensorless drives with MRAS type speed estimator can work with much bigger load than the drive with SMO.

Start-up and breaking to the zero operations are presented in Fig. 5. Drive works stable in wide speed range, as well as for zero speed operation with nominal load torque.

Next in Fig. 6 the start up operation with active load torque is presented (sliding down the small slope). At $t = 0$ s the drive is loaded and the motor speed starts decreasing. The electromagnetic torque is lower than the load torque until $t = 0.18$ s. After this time the electromagnetic and load torques become equal and the speed remains constant. Measured and estimated speed values are equal.

Next chosen experimental results of the sensorless DTC with SMO and MRAS$^{CC}$ estimator are presented in Fig. 7 – Fig. 10, for step changes of the load torque. In Fig. 7 transients of the sensorless DTC-SVM with MRAS$^{CC}$ and SMO estimator (for very low speed region are presented. In the low speed region both estimators work correctly, error between measured and estimated speed oscillates around zero. In case of the SMO, high frequency oscillations, introduced by the chattering phenomenon, are visible.

The DTC–SVM works also properly for cyclic reverse operation of the reference torque. In Fig. 7 experimental results for $m_{ref} = \pm 0.2 m_{LN}$ are presented in the case of both estimators.

In both cases the estimated speed is almost the same like the measured value. Small errors in the dynamical states are visible. Drive is stable during the reverse and for zero speed operation. However in the case of SMO, speed estimation error is slightly bigger than for the MRAS$^{CC}$ estimator.

Sensorless control structure works also correctly in the field-weakening region. In Fig. 8 results for start up operation with nominal load torque to the field weakening region are presented in the case of the drive system with SMO and MRAS$^{CC}$ estimator.

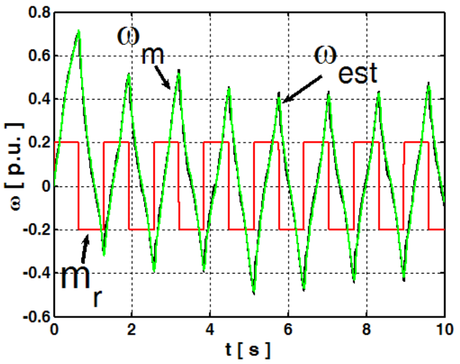
During the field weakening operation (Fig. 9) the estimated electromagnetic torque is exactly the same like reference value. In both cases speeds are estimated corectly. Small speed error in SMO during the start up operation is visible. Oscillations in the estimated speed is noticaeble.

Field weakening operation of the system with the SMO estimator and with MRAS$^{CC}$ are presented in Fig. 9. Motor speed is estimated properly, however small dynamical error is visible. Both estimators work correctly for the field weakening operations. Some oscillations on the estimated speed (for SMO) are visible.

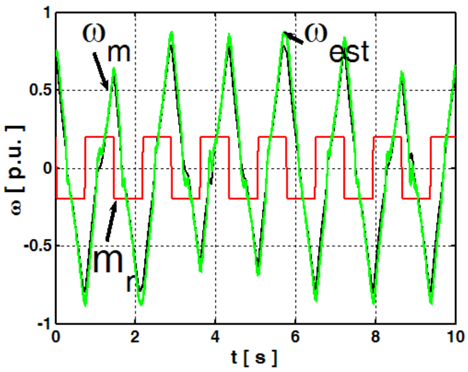
For extremally low speeds the MRAS$^{CC}$ estimator works better than SMO (Fig. 10), during the field-weakening operation the SMO estimates the motor speed with bigger osscillations than MRAS$^{CC}$. In both cases (especially for MRAS$^{CC}$) in the field-weakening region the additional magnetizing reactance estimator in the control structure should be added.

## 5 CONCLUSION

Sensorless DTC-SVM drive works correctly in the whole reference torque changes with the SMO and the MRAS$^{CC}$ estimators. Stator flux and torque are estimated




a)




b)

*Fig. 7. Experimental transients of the DTC-SVM drive with with MRAS$^{CC}$ (a) and SMO (b) estimators for $m_{ref} = \pm 0.2 m_{LN}$.*

and used directly in the control structure. Estimated speed is used in the field-weakening and in diagnostic algorithms.

The described estimators were tested in simulations and experimentally as well. Both estimators work stable for low speeds and for the field-weakening region and can be applied in the traction drive system without information about speed from any sensor.

In the sensorless drive system, operating in wide speed range, the estimators (especially MRAS$^{CC}$) should be extended with the magnetizing reactance estimator. Proposed solutions can be implemented in simple microprocessor systems.

## ACKNOWLEDGMENT

This research work was partially supported by the Ministry of Science and placeCityHigher Education, country-regionPoland, under Grant N R01 0001 06/2009 (2009-2012).

## REFERENCES

[1] M. P. Kazmierkowski, F. Blaabjerg, R. Krishnan, “Control in power electronic – selected problems”, Academic Press, USA, 2002

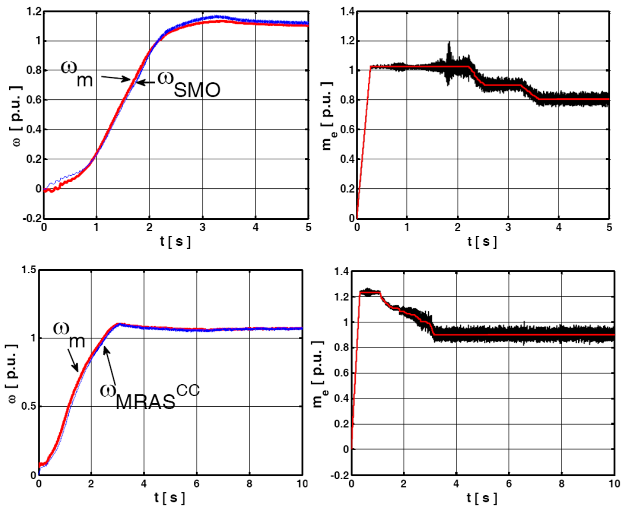



*Fig. 8. Experimental transients of the DTC-SVM with SMO and MRAS$^{CC}$ estimators for start with full load (field weakening region).*

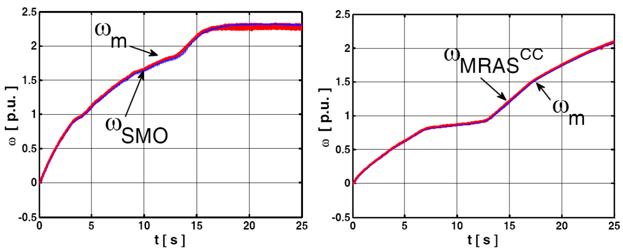



*Fig. 9. Experimental transients of the DTC-SVM drive with SMO and MRAS$^{CC}$ for field weakening operation with load torque.*

[2] J. Maes; J. A. Melkebeek, “Speed-sensorless direct torque control of induction motors using an adaptive flux observer”, IEEE Trans. Ind. Applications, vol. 36, no. 3, pp. 778-785, 2000

[3] P. Vas, “Sensorless vector and direct torque control”, Oxford University Press, New York, 1998.

[4] T. Orlowska–Kowalska, “Sensorless induction motor drives”, Wroclaw University of Technology Press, Wroclaw, Poland, 2003 (in Polish)

[5] Z. Yan, Ch. Jin, V. Utkin, “Sensorless sliding-mode control of induction Motors”, IEEE Trans. Industrial Electronics, vol. 47, no. 6, pp. 1286-1297, 2000

[6] T. Orlowska-Kowalska, M. Dybkowski, “Stator current-based MRAS estimator for wide range speed-sensorless induction motor drive”, IEEE Trans. Industrial Electronics, vol. 57, no. 4, pp. 1296-1308, 2010

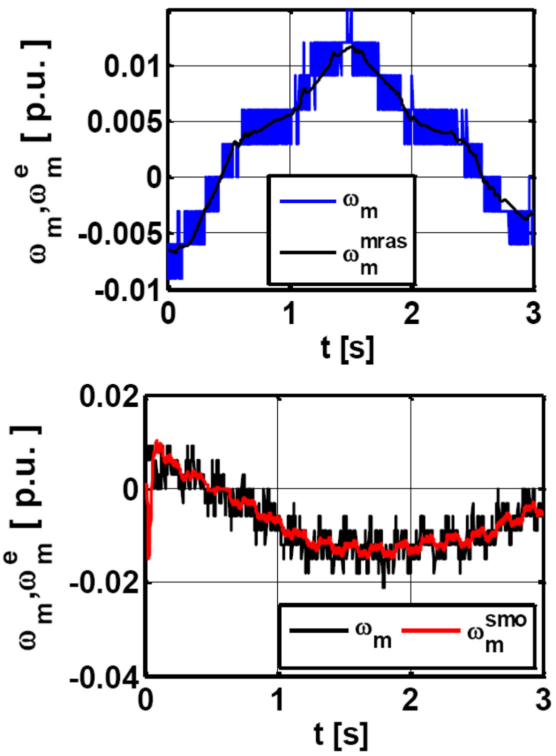



*Fig. 10. Experimental transients of the DTC-SVM drive with SMO and MRAS$^{CC}$ for the low speed region with load torque.*

[7] J. Holtz, "Sensorless control of induction machines - with or without signal injection?", IEEE Trans. Industrial Electronics, vol. 53, no. 1, pp. 7-30, 2006

[8] S. N. Vukosavic, A. M. Stankovic, "Sensorless induction motor drive with a single DC-link current sensor and instantaneous cctive and reactive power feedback", IEEE Trans. Industrial Electronics, vol. 48, no. 1, pp. 195-204, January 2001

[9] C. Conilh, M. Pietrzak-David, "Sensorless traction system with low voltage high current induction machine for indoor vehicle", Proc. of the IEEE/PEDS'2005 Confer., pp.50-55, 2005

[10] Z. Peroutka, K. Zeman, "Robust field weakening algorithm for vector-controlled induction machine traction drives", Proc. of the IEEE/IECON 2006, pp. 856-861, 2006

[11] Z. Peroutka, K. Zeman, "New field weakening strategy for AC machine drives for light traction vehicles", Proc. the 9th Conf. EPE'2007, Aalborg, Denmark, on CD, 2007

[12] H. Kubota, I. Sato, Y. Tamura, K. Matsuse, H. Ohta, Y. Hori, "Regenerating-mode low-speed operation of sensorless induction motor drive with adaptive observer", IEEE Trans. Industry Applications, vol. 38, no. 4, pp. 1081-1086, 2002

[13] T. Orlowska-Kowalska, M. Dybkowski, G. Tarchała, Analysis of the chosen speed estimation methods for the induction motor drives – part 1 – mathematical models, Scientific Papers of the Institute of Electrical Machines, Drives and Measurements no.64, ser. Studies and Research, no. 30, 2010, pp. 151-161 (in Polish)

[14] M. Dybkowski, G. Tarchała, T. Orlowska-Kowalska, Analysis of the chosen speed estimation methods for the induction motor drives – part 2 – test results, Scientific Papers of the Institute of Electrical Machines, Drives and Measurements no.64, ser. Studies and Research, no. 30, 2010, pp. 162-175 (in Polish)

[15] M. Dybkowski, T. Orlowska-Kowalska, G. Tarchała, Sensorless Direct Torque Control of the Induction Motor Drive with Sliding Mode and MRAS$^{CC}$ Estimators for Traction Applications, 17th Int. Conference on Electrical Drivesand Power Electronics, Slovakia, 2011, on CD

**Mateusz Dybkowski** received the M.Sc. and Ph.D. degrees from the Electrical Engineering Faculty, Wroclaw University of Technology, Wroclaw, Poland, in 2004 and 2008, respectively. Since 2008, he has been a member of the academic staff with the Electrical Drives Control, Institute of Electrical Machines, Drives and Measurements, Wroclaw University of Technology. His main field of interest is the induction motor drive control and state variable estimations, control theory applications in electrical drives, digital signal processors, and field-programmable gate array applications.

**Teresa Orlowska-Kowalska** (M'93-SM'05) received the Ph.D. and D.Sc. degrees from Wroclaw University of Technology, Wroclaw, Poland, in 1976 and 1990, respectively. Since 1993, she has been a Professor of electrical engineering and the Chair of the Electrical Drives Control, Institute of Electrical Machines, Drives, and Measurements, Wroclaw University of Technology. She is the author and coauthor of more than 200 journal papers and conference proceedings, two textbooks, and fourteen chapters in monographs. Her research interests include the mathematical modeling and microprocessor control of electrical drives and power electronic systems, the application of modern control methods to electrical drives, the state estimation of induction motors using state observers, Kalman filters, and neural networks, and, in the last few years, neural networks and fuzzy-logic techniques applied to electrical drives control. Prof. Orlowska-Kowalska is a member of the Electrical Engineering Committee of the Polish Academy of Science, the European Power Electronics Association, the International Council on Large Electric Systems (CIGRE), and international steering committees of a few well-known European conferences. Since 1997, she has been a Reviewer of the IEEE Transactions on Industrial Electronics and the IEEE Transactions on Industrial Applications. Since 2004, she has been an Associate Editor for the IEEE Transactions on Industrial Electronics.

**Grzegorz Tarchala** M.Sc., received the M.Sc. degree from Electrical Engineering Faculty, Wroclaw University of Technology, Wroclaw, Poland in 2009. Since this year he is a Ph.D. student in the Institute of Electrical Machines, Drives and Measurements. His main field of interest is the induction motor drive control and state variable estimation, control theory applications in electrical drives and digital signal processors.

## AUTHORS' ADDRESSES

**Mateusz Dybkowski, Ph.D.**
**Prof. Teresa Orlowska-Kowalska, Ph.D.**
**Grzegorz Tarchala**
**Institute of Electrical Machines, Drives, and Measurements**
**Wroclaw University of Technology**
**Wroclaw, Poland**
**email: mateusz.dybkowski@pwr.wroc.pl, teresa.orlowska-kowalska@pwr.wroc.pl, grzegorz.tarchala@pwr.wroc.pl**

Received: 2012-01-15
Accepted: 2012-11-20