PRZEGLĄD ELEKTROTECHNICZNY

Ukazuje się od 1919 roku 1a'13

Organ Stowarzyszenia Elektryków Polskich • Wydawnictwo SIGMA-NOT Sp. z o.o.

Grzegorz TARCHAŁA, Teresa ORŁOWSKA-KOWALSKA

Politechnika Wrocławska, Instytut Maszyn, Napędów i Pomiarów Elektrycznych

Sliding Mode Speed Observer for the Induction Motor Drive with Different Sign Function Approximation Forms and Gain Adaptation

Abstract. *This paper deals with sign function continuous approximation forms influence on the performance of the classical Sliding Mode Observer (SMO). Saturation and sigmoid functions are used to reduce the chattering, introduced due to the sign function usage. The influence of the filter time constant is also being widely considered. Finally, two simple methods of the observer gain adaptation are presented and described. Simulation and experimental tests, obtained using a DSP-based system, are shown to illustrate presented issues.*

Streszczenie. *W artykule opisano wpływ zastosowania ciągłej aproksymacji funkcji znaku na pracę klasycznego ślizgowego obserwatora prędkości. Funkcje nasycenia oraz funkcja sigmoidalna użyte zostały w celu redukcji zjawiska chatteringu, który powstaje na skutek wykorzystania funkcji znaku. Szeroko przebadany został również wpływ stałej czasowej filtru. Zaprezentowane zostały także dwie proste metody adaptacji wzmocnienia obserwatora. Opisywane zagadnienia zostały zilustrowane przy pomocy badań symulacyjnych i eksperymentalnych. (**Ślizgowy obserwator prędkości dla napędu indukcyjnego z różnymi funkcjami aproksymującymi oraz adaptacją wzmocnienia**).*

Keywords: sliding mode observer, induction motor drive, chattering, continuous approximation.
Słowa kluczowe: obserwator ślizgowy, napęd indukcyjny, chattering, ciągła aproksymacja.

Introduction

The induction motor drives due to their low cost and operational reliability are becoming more and more common in the industry. Perfect dynamic performance of the drives can be assured by one of the field-oriented control methods. Additional cable reduction can be assured by a speed estimation. Speed estimation can be also applied in applications where the speed sensor can be damaged [1].

The control structure was the first sliding modes application area for induction motors. The sliding modes (SM) as a main part of variable structure systems theory was first proposed by Izosimov in [2]. This theory can be also used for the rotor/stator flux and speed observer design like [3]. Sliding Mode Observers (SMOs) allow obtaining essential feedback values in the vector control structures (e.g. DFOC or DTC).

Simple hardware implementation, robustness over specified range of motor parameter uncertainties, disturbances and measurement noise, eventually fast dynamic response entail still growing publication number in the field of the SM applications. Model Reference Adaptive System – type SMO is proposed in [4]. Sliding mode control and observer both working simultaneously were introduced in [5]. The adaptive [6], [7] and the second-order [8] approaches were also presented. A new observer designed in a synchronous frame is introduced in [9]. An excellent overview of existing (till 2002) SMO types for different motors can be found in [10].

Few publications were published in order to compare SMOs with different estimation methods – Model Reference Adaptive System (MRAS) based observers in [11], [12], extended Kalman filters [13] and, together with Luenberger style observer, in [14].

In recent years special consideration has been also focused on the IM parameters estimation methods utilizing the sliding-mode approach. In [15] stator and rotor winding resistances estimation method is presented. Immeasurable rotor parameters can be also estimated, as in [16], [17], also with the second-order sliding modes [18]. The Luenberger-sliding mode type observer was proposed for stator resistance and rotor time constant estimation [19].

All of the above-mentioned solutions take the advantage of the sign function in the SM algorithm. Therefore slow-variable estimated signals, i.e. motor speed or winding resistance parameters become the high frequency, discontinuous values. Due to these rapid changes, called the chattering phenomenon, the equivalent values must be extracted. There are many different ways to reduce the chattering in the field of the variable structure control systems, what was compared in [20]. In case of the estimation, a low-pass filter seems to be the simplest solution. However, there appeared an idea of applying a continuous approximation instead of the sign function in order to eliminate or at least to reduce the chattering. The saturation function was first proposed for the nonlinear plants control in [21] and further investigated in [22]. The sigmoid function has been proposed in [23]. These two ideas can be applied in sliding mode observers theory as well – the saturation function or a sigmoid function can replace the sign function successfully. In literature many authors only refer to this possibility, while this paper tries to look more insightfully into these problems. The standard SMO [10] will be used to illustrate described issues.

The paper is organized in eight chapters. The IM mathematical model is presented first. Then, the speed observer design is introduced. Next, the filtration problem of the estimated speed is described, the filter time constant influence is investigated. Sign function continuous approximation forms and simple, linear adaptation methods are presented afterwards. Load torque value influence on performance of the observer and short conclusion are shown at the end of the paper. All described issues are illustrated by simulation and experimental tests.

Mathematical model of the Induction Motor

Mathematical model of the induction motor is essential for the Sliding Mode Observer design, as the observer is one of the algorithmic speed estimation methods. The model of the squirrel-cage induction motor can be derived using the commonly-known assumptions [1], [24] (3 phase symmetry, magnetizing linearity etc.) in a stationary reference frame α–β and per unit system:

– voltage equations:

(1) $$\mathbf{u_s} = r_s \mathbf{i_s} + T_N \frac{d}{dt}\boldsymbol{\psi}_\mathbf{s}$$

(2) $$\mathbf{0} = r_r \mathbf{i_r} + T_N \frac{d}{dt}\boldsymbol{\psi}_\mathbf{r} - j\omega_m \boldsymbol{\psi}_\mathbf{r}$$

– current-flux equations:

(3) $$\boldsymbol{\psi}_\mathbf{s} = x_s \mathbf{i_s} + x_M \mathbf{i_r}$$

(4) $$\boldsymbol{\psi}_\mathbf{r} = x_r \mathbf{i_r} + x_M \mathbf{i_s}$$

– and the equation of motion:

(5) $$\frac{d\omega_m}{dt} = \frac{1}{T_M}\left(m_e - m_o\right)$$

(6) $$m_e = \mathrm{Im}\left(\boldsymbol{\psi}_\mathbf{s}^{*} \mathbf{i_s}\right) = \psi_{s\alpha} i_{s\beta} - \psi_{s\beta} i_{s\alpha}$$

where: $\mathbf{u_s}=u_{s\alpha}+ju_{s\beta}$, $\mathbf{i_s}=i_{s\alpha}+ji_{s\beta}$, $\boldsymbol{\psi}_\mathbf{s}=\psi_{s\alpha}+j\psi_{s\beta}$ – space vectors of the stator voltage, current and flux, $\mathbf{i_r}=i_{r\alpha}+ji_{r\beta}$, $\boldsymbol{\psi}_\mathbf{r}=\psi_{r\alpha}+j\psi_{r\beta}$ – space vectors of the rotor current and flux, r_s, x_s, r_r, x_r, x_M, T_M – induction motor parameters: stator and rotor winding resistances, reactances, magnetizing reactance and mechanical time constant, ω_m, m_e, m_o – motor speed, electromagnetic and load torque, T_N – result of the per unit system introduction, $T_N=1/(2f_{sN})$, f_{sN} – nominal frequency.

Motor nominal values, its parameters and base values necessary to make the conversion between physical and per unit systems are shown in the Appendix.

Speed and rotor flux sliding-mode estimator design

Presented Sliding Mode Observer (SMO) is based directly on the IM equations shown in previous section (1)-(4). Rotor flux estimation equation can be obtained combining (2) and (4):

(7) $$T_N \frac{d\boldsymbol{\psi}_\mathbf{r}}{dt} = -\frac{r_r}{x_r}\boldsymbol{\psi}_\mathbf{r} + \frac{x_M r_r}{x_r}\mathbf{i_s} + j\omega_m \boldsymbol{\psi}_\mathbf{r}$$

The stator current vector dynamics can be expressed from (1),(3) and (4), as follows:

(8) $$T_N \frac{d\,\mathbf{i_s}}{dt} = \frac{1}{x_s\sigma}\left(\mathbf{u_s} - r_s\mathbf{i_s} - \frac{r_r x_M^2}{x_r^2}\mathbf{i_s} + \frac{x_M}{x_r}\frac{r_r}{x_r}\boldsymbol{\psi}_\mathbf{r} - j\frac{x_M}{x_r}\omega_m\boldsymbol{\psi}_\mathbf{r}\right)$$

In the observer equations mechanical speed is replaced by the estimated one, and an additional variable μ is introduced. This forms a slightly modified version of [10]. Estimated rotor flux vector:

(9) $$T_N \frac{d\hat{\boldsymbol{\psi}}_\mathbf{r}}{dt} = -\left(\frac{r_r}{x_r} + \hat{\mu}\right)\hat{\boldsymbol{\psi}}_\mathbf{r} + \frac{x_M r_r}{x_r}\mathbf{i_s} + j\hat{\omega}_m\hat{\boldsymbol{\psi}}_\mathbf{r}$$

where: '^' indicates estimated quantities.

Speed estimation, since it relies on the stator current estimation error, demands the stator current vector to be estimated, and this can be realized using:

(10)
$$T_N \frac{d\,\hat{\mathbf{i}}_\mathbf{s}}{dt} = \frac{1}{x_s\sigma}\left(\mathbf{u_s} - r_s\hat{\mathbf{i}}_\mathbf{s} - \frac{r_r x_M^2}{x_r^2}\hat{\mathbf{i}}_\mathbf{s} + \frac{x_M}{x_r}\left(\frac{r_r}{x_r} + \hat{\mu}\right)\hat{\boldsymbol{\psi}}_\mathbf{r} - j\frac{x_M}{x_r}\hat{\omega}_m\hat{\boldsymbol{\psi}}_\mathbf{r}\right)$$

where: σ – total leakage factor, $\sigma=1-x_M^2/(x_s x_r)$.

In the above equations (9), (10), the estimated speed and the additional factor $\hat{\mu}$ take the advantage of the sign function. The discontinuous signal of the speed can be calculated by:

(11) $$\hat{\omega}_m = K_\omega \,\mathrm{sign}\, s_\omega$$

where: K_ω – positive constant. Speed switching function is as follows:

(12) $$s_\omega = \left(\hat{i}_{s\beta} - i_{s\beta}\right)\hat{\psi}_{r\alpha} - \left(\hat{i}_{s\alpha} - i_{s\alpha}\right)\hat{\psi}_{r\beta}$$

The auxiliary variable can be introduced to reduce the error caused by mistaken determination of the rotor time constant:

(13) $$\hat{\mu} = K_\mu \,\mathrm{sign}\, s_\mu$$

where: K_μ – positive constant, and the switching function of the auxiliary variable:

(14) $$s_\mu = \left(\hat{i}_{s\alpha} - i_{s\alpha}\right)\hat{\psi}_{r\alpha} + \left(\hat{i}_{s\beta} - i_{s\beta}\right)\hat{\psi}_{r\beta}$$

As the auxiliary parameter is used only in the SMO tuning, there is no need to replace the sign function in (13) by its continuous approximation.

If the stator flux vector components are needed (e.g. in a DTC structure) they can be estimated by:

(15) $$\hat{\boldsymbol{\psi}}_\mathbf{s} = \frac{x_M}{x_r}\hat{\boldsymbol{\psi}}_\mathbf{r} + x_s\sigma\mathbf{i_s}$$

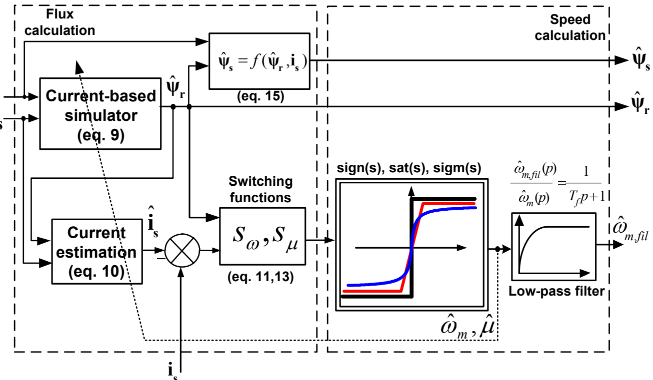

Fig.1. Block diagram of the presented sliding-mode speed observer

The block diagram of the described SMO is presented in Fig. 1. Vectors of stator current and voltage are the input variables of the observer. Voltage values are estimated using the DC-link voltage and the inverter transistors positions (not shown in the figure). Stator or rotor flux vector and estimated speed are the outputs of the observer. Estimated, high-frequency signals of speed and μ are used for tuning the flux and current estimators. However, this high-frequency speed signal is unsuitable for use and analysis, therefore it must be filtered.

Filtration problem in SM Observer

The discontinuous speed estimation signal (11) obtained using the sign function:

(16) $$\mathrm{sign}(s)=\begin{cases}1, & \text{where } s\geq 0\\ -1, & \text{where } s<0\end{cases}$$

is inconvenient as a close-loop feedback in the speed control algorithms (e.g. field-oriented methods) as well as in diagnostics or for field-weakening operation (as the speed information is required in the field-weakening algorithm).

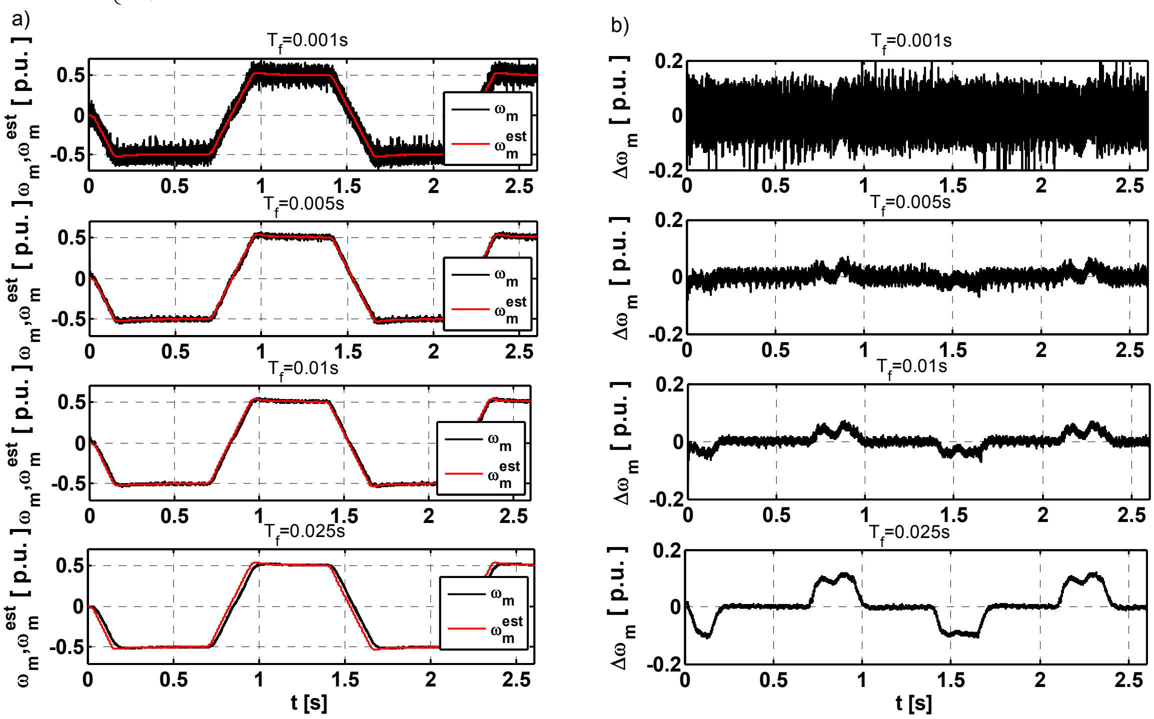

Fig.2. Speed estimation process for different filter time constants: a) real and estimated speed, b) speed estimation errors, sign function, K_{ω}=1, experimental results

The equivalent value of the real speed signal of the SMO must be extracted from the discontinuous signal, using a low-pass filter. The simplest filter to use is the first-order transfer function as follows:

(17) $$\frac{\hat{\omega}_{m,fil}(p)}{\hat{\omega}_m(p)}=\frac{1}{T_f p+1}$$

where: T_f – filter time constant, the filter settling time $T_s=3T_f$ and p – Laplace operator.

The filter time constant influence on the performance of the drive, during experimental tests, is shown in Fig. 2. It can be seen, that the bigger the time constant the smaller the oscillation level. However, the dynamical error during fast speed reversions becomes bigger. In such situation a compromise is necessary, taking into account the dynamics of the drive and its application. The oscillation level can be reduced, for a specific time constant, using the sign function continuous approximation.

Sign function approximation forms

The sign function (16) can be replaced with its approximation – a continuous form. There are two different approaches possible, i.e. saturation and sigmoid functions.

The saturation function can be described as follows:

(18) $$\mathrm{sat}(s)=\begin{cases}\dfrac{s}{\varepsilon}, & \text{where } |s|\leq\varepsilon\\ \mathrm{sign}(s), & \text{where } |s|>\varepsilon\end{cases}$$

There exists a great variety of the sigmoid type functions. Some of them are listed below (normalized in such way that their values are between ±1):

(19a) $$\mathrm{sigm}_1(s)=\frac{2}{1+e^{-s/\varepsilon}}-1$$

(19b) $$\mathrm{sigm}_2(s)=\tanh(s/\varepsilon)$$

(19c) $$\mathrm{sigm}_3(s)=\frac{2}{\pi}\arctan(s/\varepsilon)$$

(19d) $$\mathrm{sigm}_4(s)=\frac{s}{\varepsilon+|s|}$$

(19e) $$\mathrm{sigm}_5(s)=\frac{s/\varepsilon}{\sqrt{1+(s/\varepsilon)^2}}$$

Another parameter appears, ε, defining the slope of the *sat(s)* and *sigm(s)* functions.

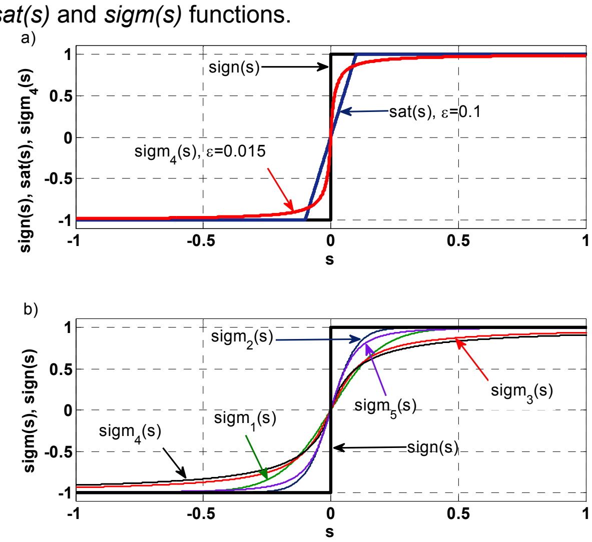

Fig.3. Sign function continuous approximation forms: a) a comparison of sign, sat and one of the sigmoid functions, b) different sigmoid functions for the same value of ε

In Fig. 3a a comparison of the sign, saturation and sigmoid functions is presented. Set of sigmoid functions is presented in Fig. 3b. Despite the significant divergence between mentioned characteristics from the Fig. 3b, for specific ε values (different for each function) the functions become very similar. In such situation the speed observer performance is practically the same for each of the above functions – it can be shown in experimental tests. If one form of (19) is to be chosen, the *sigm₄(s)* seems to be the optimal solution – computations are the simplest then.

Simulation results

Speed estimation results obtained during simulation tests are presented in Fig. 4. It can be seen (Fig. 4a) that the high frequency signal must be filtered, when the sign function is used.

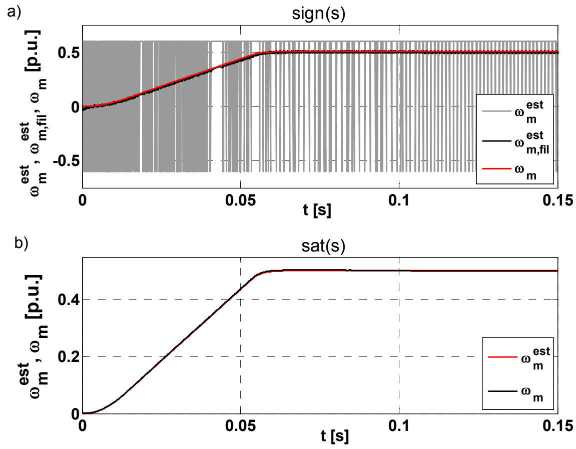

Fig.4. Estimation process during simulation tests: a) using sign function, b) using saturation function

Filtered estimated speed follows the real speed almost exactly. Usage of the continuous approximation, the *sat(s)* function in this case, allows eliminating the filter completely (Fig. 4b). However, this situation can be observed only during simple simulation tests.

Experimental tests

Experimental tests indicate clearly that in a real drive complete filter elimination is impossible. It can be noticed in Fig. 5. Oscillation of the estimated, non-filtered speed can be reduced significantly (Fig. 5b) using the sign function approximation. However, the bigger slope of the sigmoid function, ε, the bigger dynamical error appears. This can be seen clearly in Fig. 5c. Again, the choice of the parameter ε must be a compromise between the oscillation level and dynamical error.

When comparing sign and sigmoid function with small ε parameter, it can be seen that the maximum dynamical error remains the same while the oscillation level is reduced. Laboratory trials indicate also that using any type of the approximation function – the saturation or the sigmoid one with similar slopes (as in Fig. 3a), gives almost the same results.

Gain adaptation methods for sliding-mode observer

It seems clear that for a constant value of the observer gain K_ω in (11), the oscillation level of the estimated speed is the same for whole speed range. It means that for small speed values the vibrations become relatively large. When K_ω is set too high the drive can become even unstable. Oscillation level of estimated values can be reduced if the mentioned gain is different for different operation points. One of possible simple methods of K_ω adapting is to change it with the reference speed:

$$K_\omega = K_0 + K_1 \cdot \left|\omega_m^{ref}\right| \tag{20}$$

where: K_0, K_1 – positive constants.

The observer operation using this adaptation method is shown in Fig.6 (second line). The undesired situation can appear when there exists a big difference between actual (estimated) and reference speed, e.g. during rapid reversions, as after about 5.5 s. A large, short estimation error can be seen in Fig. 6c (second line).

This problem can be solved using second adaptation method. Also, when there is no information about the reference speed – e.g. in traction drives with direct torque control without any outer control loop, the parameter K_ω can be adapted directly with the estimated speed:

$$K_\omega = K_0 + K_1 \cdot \left|\omega_m^{est}\right| \tag{21}$$

Speed estimation for this adaptation method is shown in Fig. 6 (third line). There is no longer large estimation error during rapid speed changes.

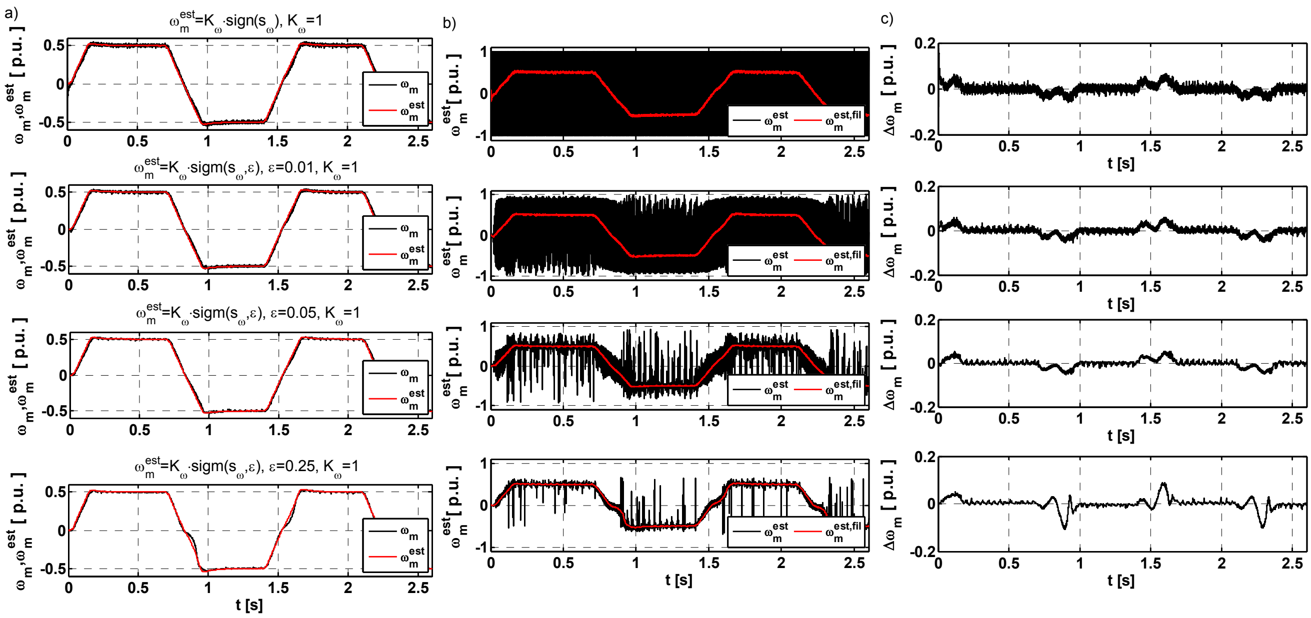

Fig.5. Speed estimation for sign function and sigmoid function (different values of parameter ε): a) real and estimated speed, b) non-filtered and filtered estimated speed, c) speed estimation error, experimental results, T_f=0.005s

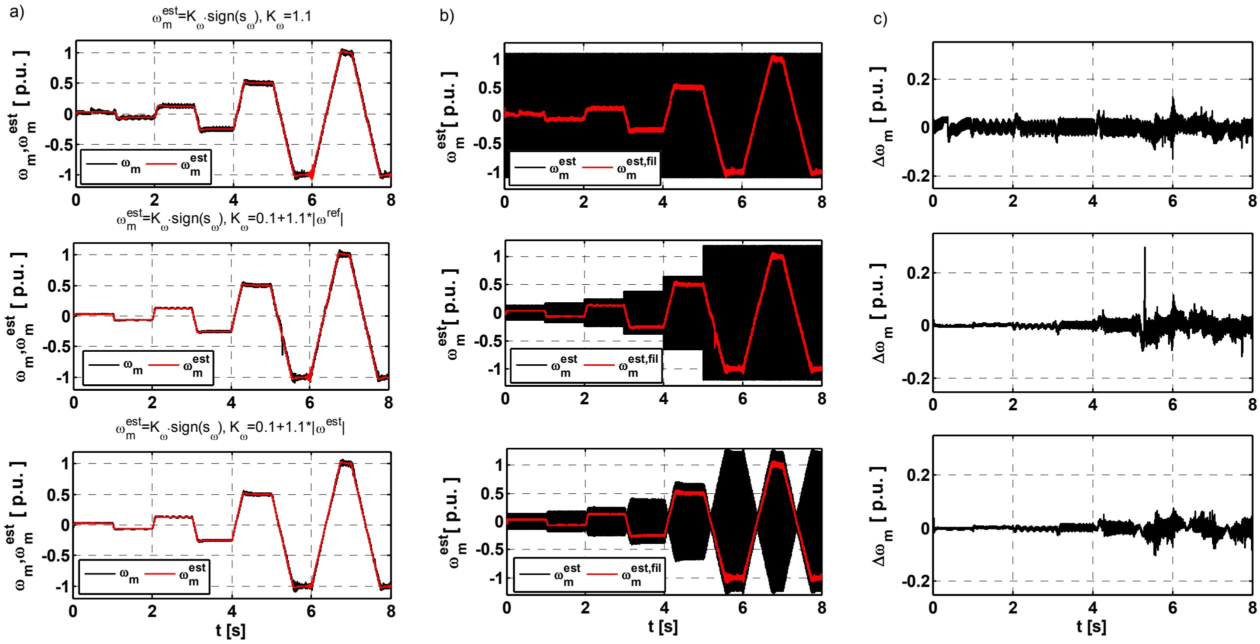

Fig.6. Speed estimation for different observer gain adaptation methods, for constant gain (first line), changed with the reference (second line) and estimated speed (third line): a) real and estimated speed, b) filtered and non-filtered speed, c) speed estimation error, experimental results

The adaptation constants K_0, K_1 can be found quite easily - K_1 should be set slightly above one and K_0 should be greater than zero. The last condition must be fulfilled when the adaptation method (21) is applied – when $K_0=0$ the speed estimation is unrealizable.

In Fig. 6 the difference between constant and adaptive gain approaches is shown. This difference can be seen especially for the low speed range – the greater the speed the more similar the transients become. It is clearly connected with the equations (20)-(21).

Load torque influence

Load torque influence on the classical Sliding Mode Observer operation is presented in Fig. 7. Two different situation are presented – with nominal and without load torque (estimated electromagnetic torque is shown in Fig. 7c). In both cases estimated speed follows the real speed almost ideally.

The observer was tested using the sigmoid function with the observer gain adaptation according to the equation (21). It can be seen that the estimation error (Fig. 7b) is slightly bigger with nominal torque operation than under the idle running. Analogous conclusions can be made for the remaining aspects of the observer designing – filter time constant and sign function approximation parameter ε influence – estimated speed oscillations become slightly bigger in case of the full load torque operation.

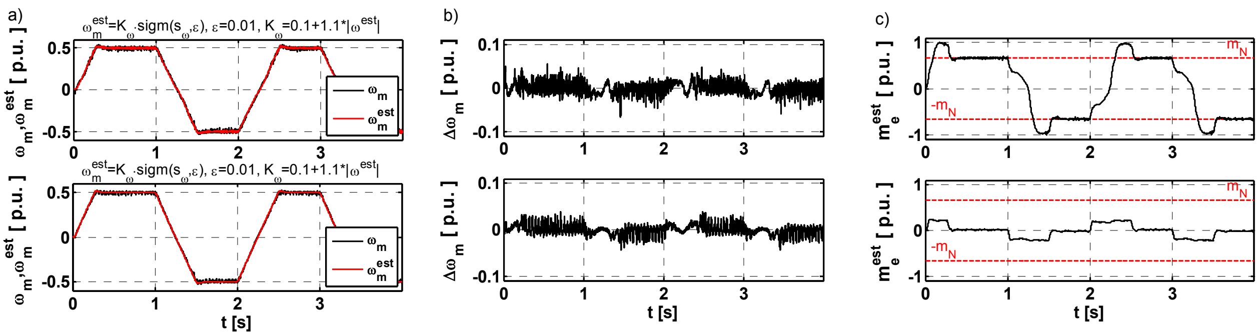

Fig.7. Load torque influence on the speed observer operation, full (first line) and no load operation (second line), respectively: a) real and estimated speed, b) speed estimation error, c) estimated motor torque

Conclusions

Several aspects of the sliding mode speed observer operation were discussed in this paper and illustrated using simulation and experimental results. First, the influence of different filter time constants on the speed estimation error value was shown. It was shown that the bigger the time constant the oscillation level of the estimation error becomes smaller. However, there appears simultaneously a significant dynamic error during fast transients. Therefore the choice of the time constant must be a compromise, taking into account the dynamics of the drive and the estimated speed oscillations.

Second investigated problem was the influence of two simple sign function approximation forms: saturation and sigmoid function on the performance of the estimator. There is almost no difference in operation of these two functions, however the choice of the slope parameter ε becomes an interesting issue. Usage of the sign function approximation with small ε allows to decrease the value of oscillations with the same dynamical error, comparing to the sign function.

However, together with increasing slope ε the dynamical error is augmenting. It was shown that there is a possibility to eliminate the low pass filter of the estimated speed only during simulation tests.

Finally, two observer gain adaptation methods were introduced. First of them utilized linear adaptation with the reference speed, however large error can appear when the real speed is significantly different than the reference one. Second of them eliminated mentioned drawback of the previous method, and the observer gain were dependent on the estimated speed value.

Appendix

Base values for conversion from the physical [ph.u.] to per unit [p.u.] systems are shown in Table 1. Induction motor parameters and its nominal values are presented in Table 2 and Table 3, respectively. Mechanical time constant of the drive:

(22)
$$T_M = J\frac{\omega_b}{p_p M_b}$$

where: J – moment of inertia, p_p – pole pairs, base values are presented in Table 3.

Table 1. Base Values

Power [kW]	Torque [Nm]	Speed [rpm]	Voltage [V]	Current [A]
$S_b=3/2U_bI_b$	$M_b=p_pS_b/\omega_b$	$n_b=60f_{sN}/p_p$	$U_b=\sqrt{2}\ U_{sN}$	$I_b=\sqrt{2}I_{sN}$
4.8	30.56	1500	565.7	5.657
Frequency [Hz]	Velocity [rad/s]	Flux [Wb]	Impedance [Ω]	
$f_b=f_{sN}$	$\omega_b=2\pi f_{sN}$	$\Psi_b=U_b/\omega_b$	$Z_b=U_b/I_b$	
50	314.16	1.8	100	

Table 2. Motor nominal values

Power	Torque	Speed	Voltage	Current
3.0 [kW]	20.46 [Nm]	1400 [rpm]	400 [V]	4.0 [A]
0.625 [p.u.]	0.67 [p.u.]	0.93 [p.u.]	0.707 [p.u.]	0.707 [p.u.]
Frequency	Stator flux	Rotor flux		
50 [Hz]	314.16 [Wb]	1.8 [Wb]		
1 [p.u.]	0.80 [p.u.]	0.73 [p.u.]		

Table 3. Parameters of the IM equivalent circuit

R_s	R_r	X_m	$X_{s\sigma}$	$X_{r\sigma}$
7.1 [Ω]	5.4 [Ω]	167.8 [Ω]	9.8 [Ω]	9.8 [Ω]
0.071 [p.u.]	0.054 [p.u.]	1.678 [p.u.]	0.098 [p.u.]	0.098 [p.u.]

REFERENCES

[1] Orłowska-Kowalska T., *Sensorless Induction Motor Drives*, Wrocław University of Technology Press, (2003).

[2] Izosimov D.B., Matic B., Utkin V. *et al.*, Application of sliding modes in problems of electrical machine control *Doklady Akademii Nauk SSSR,* 241 (1978), n. 4, 769-772, (in Russian).

[3] Izosimov D.B., *Sliding-Mode Nonlinear State Observer of an Induction Motor*, Moscow: Nauka, (1983), 133-139.

[4] Comanescu M., Xu L.Y., Sliding-mode MRAS speed estimators for sensorless vector control of induction machine, *IEEE Trans. on Ind. Electr.,* 53 (2006), n.1, 146-153

[5] Benchaib A., Rachid A., Audrezet E. *et al.*, Real-time sliding-mode observer and control of an induction motor, *IEEE Trans. on Ind. Electr.,* 46 (1999), n.1, 128-138.

[6] Tursini M., Petrella R., Parasiliti F., Adaptive sliding-mode observer for speed-sensorless control of induction motors, *IEEE Trans. on Industry Applications,* 36 (2000), n.5, 1380-1387.

[7] Zheng Y.H., Fattah H.A.A., Loparo K. A., Non-linear adaptive sliding mode observer-controller scheme for induction motors, *Int. Journal of Adaptive Control and Signal Processing,* 14 (2000), n.2-3, 245-273.

[8] Solvar S., Le V., Ghanes M. *et al.*, Sensorless second order sliding mode observer for induction motor, *IEEE Int. Conf. on Control Applications*, (2010), 1933-1938.

[9] Lascu C., Boldea I., Blaabjerg F., A class of speed-sensorless sliding-mode observers for high-performance induction motor drives, *IEEE Trans. on Ind. Electr.,* 56 (2009), n.9, 3394-3403

[10] Yan Z., Utkin V., Sliding mode observers for electric machines - an overview, *28th IECON Annual Conf. of the IEEE Ind. Electr. Society*, (2002), 1842-1847.

[11] Lin F.J., Wai R.J., Kuo R.H. *et al.*, A comparative study of sliding mode and model reference adaptive speed observers for induction motor drive, *Electric Power Systems Research,* 44 (1998), n.3, 163-174.

[12] Khater M.M., Zaky M.S., Yasin H. *et al.*, A comparative study of sliding mode and Model Reference Adaptive Speed observers for induction motor drives, *11th MEPCON Int. Middle East Power Systems Conf.*, (2006), 434-440.

[13] Chen F., Dunnigan M.W., Comparative study of a Sliding-Mode Observer and Kalman filters for full state estimation in an induction machine, *IEE Proceedings - Electric Power Applications,* 149 (2002), n.1, 53-64.

[14] Zhang Y., Zhao Z., Lu T. *et al.*, A comparative study of Luenberger Observer, Sliding Mode Observer and Extended Kalman Filter for sensorless vector control of induction motor drives, *IEEE Energy Conversion Congress and Exposition*, (2009), 2720-2727.

[15] Picardi C., Scibilia F., Sliding-mode observer with resistances or speed adaptation for field-oriented induction motor drives, *32nd IECON Annual Conf. on IEEE Ind. Electr.*, (2006), 1481-1486.

[16] Proca A.B., Keyhani A., Sliding-mode flux observer with online rotor parameter estimation for induction motors, *IEEE Trans. on Ind. Electr.,* 54 (2007), n.2, 716-723.

[17] Derdiyok A., Yan Z., Guven M. *et al.*, A sliding mode speed and rotor time constant observer for induction machines, *27th IECON Annual Conf. of the IEEE Ind. Electr. Society,* 2 (2001), 1400-1405.

[18] Rao S., Buss M., and Utkin V., Simultaneous State and Parameter Estimation in Induction Motors Using First- and Second-Order Sliding Modes, *IEEE Trans. on Ind. Electr.,* 56 (2009), n.9, 3369-3376.

[19] Nayeem Hasan S.M., Husain I., A Luenberger-Sliding Mode Observer for Online Parameter Estimation and Adaptation in High-Performance Induction Motor Drives, *IEEE Trans. on Industry Applications,* 45 (2009), n.2, 772-781.

[20] Sabanovic A., Variable Structure Systems With Sliding Modes in Motion Control - A Survey, *IEEE Trans. on Ind. Informatics,* 7 (2011), n.2, 212-223.

[21] Slotine J.J., Sastry S.S., Tracking control of non-linear systems using sliding surfaces, with application to robot manipulators, *Int. Journal of Control,* 38 (1983), n.2, 465-492.

[22] Burton J.A., and Zinober A. S., Continuous approximation of variable structure control, *Int. Journal of Systems Science,* 17 (1986), n.6, 875-885.

[23] Ambrosino G., Celentano G., Garofalo F., Variable structure model reference adaptive control systems, *Int. Journal of Control,* 39 (1984), n.6, 1339-1349.

[24] Kazmierkowski M., Krishnan R., Blaabjerg F., *Control in Power Electr. - Selected Problems*, USA: Academic Press – An imprint of Elsevier Science, (2002).