Journal of the Technical University of Gabrovo
https://mc04.manuscriptcentral.com/jtug

EXPERIMENTAL COMPARISON OF SEVERAL FLUX ESTIMATION TECHNIQUES IN INDUCTION MACHINES

Marko Rosić*, Miroslav Bjekić, Marko Šućurović, Vojislav Vujičić
University of Kragujevac, Faculty of Technical Sciences Čačak, Serbia

ARTICLE INFO

Article history:
Received 10 October 2019
Accepted 22 November 2019

Keywords:
induction machine, flux estimation, closed loop estimators, Gopinath estimator, DSP setup, MSK2812

ABSTRACT

In order to estimate AC machine torque with high accuracy, high quality machine flux estimation should be done before. The paper analyzes several basic flux estimation techniques in induction machines with their cons and pros. Four mostly used flux estimation methods are described theoretically after which experimental results are presented. Experimental results of analyzed estimation techniques are compared to the built-in estimation flux algorithm implemented DSP MSK2812 setup within application based on field-oriented control (FOC). At the end of the paper, proper discussion of experimental results and most important conclusions are drawn.

INTRODUCTION

Induction machine control techniques are very extensive and attractive issue in modern scientific literature. When it comes to the algorithms which assure high dynamic in induction machine response such as FOC (*Field Oriented Control*) or DTC (*Direct Torque Control*), information about flux orientation in the machine represents an essential issue. This is especially important in successful realization of DBDTC (*Dead-beat Direct Torque Control*) [1]. Accurate flux estimation at wide speed range is one of the most important and the most difficult task in high dynamics control algorithms. The most important because estimated machine torque and system performance are directly linked to the accuracy of estimated flux. The most difficult because estimated flux accuracy depends on many machine parameters and operating conditions, especially when it is necessary to achieve sensorless high accuracy of estimated flux at low speed.

A simple classification of sensorless control techniques can be made sorting them out into two main categories: methods based on excitation signals at the fundamental motor frequency and methods based on high-frequency (HF) injection of excitation signals whose frequency is higher than fundamental frequency [2]. Estimation flux methods at fundamental frequencies are manly based on mathematical models of induction machine and dependent on one or more machine parameters. These estimators can work with or without a feedback. Generally, flux estimators based on measurement of terminal quantities at fundamental frequencies can be divided into two categories: the first one is based on voltage machine model and the second on the current machine model.

First group of estimators is well known for its simplicity because they are based on integration of the electromotive force (EMS) and usually require only knowledge of the machine stator resistance. For this reason, these estimators are attractive in sensorless drives because they not require speed information. Nevertheless, due to lack of feedback they are sensitive to the DC component in the entrance of pure integrator and initial integration conditions especially at low speed. These problems can usually be overcome by passing the integrated signal through the high-pass filter (HPF) or replacing pure integrator with low-pass filter. Although this method eliminates both problems, filters introduce amplitude derogation and phase delay in the estimated signal especially at frequencies close to cut-off frequency ω_c. All this reflects to the machine torque accuracy and dynamics across operating speed range which mitigate quality electric drive control in overall. At high frequencies filtration effect of low pass filter (LPF) on estimation quality can be neglected but, at low speed (close to cut of frequency ω_c), phase and amplitude distortion can significantly deteriorate drive performance and stability. There are several ways, that can be found in literature, how these disadvantages can be overcome. In [3] authors propose adaptive compensation of amplitude and phase error while in [4] adaptive filters with variable cut-off frequency and sampling time depending on frequency of operation regime. Shin in [5] propose changing filter cut-off frequency proportional to stator frequency providing good estimation quality in wide speed range. However, these estimation techniques require additional processing time thanks to the complex math algorithm resulting with more or less reliable estimation results. Another simple estimation algorithm is proposed in [6] where pure integrator was used with addition of small offset which provide circle trajectory of estimated flux vector without DC component.

* Corresponding author. E-mail: marko.rosic@ftn.kg.ac.rs

Second group of estimators is based on current machine model and they rely on information of speed and several machine parameters. For that reason, these estimators are more sensitive to machine parameter variation caused by temperature and quality of measured / estimated speed. Contrary to estimators based on voltage machine model, estimators based on current machine model provide good results at low machine speed while at high speed small delay in estimated quantity was introduced. These estimation methods mostly depend on rotor time constant T_r which is dependent to temperature variation during the machine operation. In order to prevent these rotor time constant variation impact on the flux estimation quality, it is necessary to implement some of on-line identification machine parameters methods [7], [8].

All previously mentioned bring the conclusion that machine flux estimator which combine all good properties of voltage and current machine model would be the best solution. Estimator based on combination of voltage and current machine model rely on current model at low frequencies and on voltage model at high frequencies. Sensitivity and dependence analysis on the machine parameters variation of such kind of estimators was conducted in [9], [10], [11]. It is shown that the estimator performs small sensitivity and very good characteristics at wide range of frequencies.

In this paper, a basic theoretical background for 4 mentioned estimation techniques is given at first. Consequently, experimental verification and comparison of these methods with estimation method built-in at FOC algorithm is presented and obtained results are discussed.

FLUX ESTIMATION IN OPEN AND CLOSED LOOP

Algorithm 1: Voltage model flux estimator in open loop

Estimator based on the voltage machine model rely on stator back electromotive force (EMF) integration and can be presented with block diagram in Fig.1.

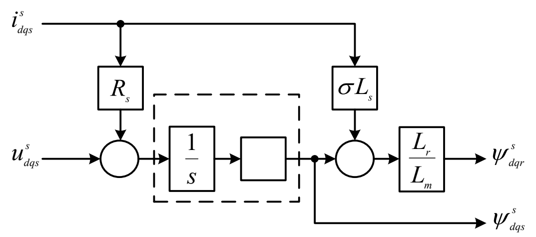

Fig. 1. Block diagram of voltage model-based estimator with high pass filter

where: u^s_{dqs} - stator voltage, i^s_{dqs} - stator current, R_s - stator resistance, L_s - stator inductance, L_m - mutual inductance, L_r - rotor inductance, $\sigma = 1 - \frac{L_m}{L_s L_r}$, ψ^s_{dqs} - stator flux, ψ^s_{dqr} - rotor flux. Superscript „s" refers to stator dq referent coordinate system.

Induced back EMF in practical application unavoidably include small DC offset which usually have its origin in imperfect current measurement, distorted inverter output voltage due to dead time effect etc. This offset introduces rise of DC component of estimated quantity after integration. Passing integrated signal through high pass filter (HPF) can remove this DC component and eliminate the problem. On the other hand, it will introduce relatively small amplitude distortion and phase delay the estimated flux. Cut-off filter frequency ω_c is usually set in the range of 0,5-3Hz depending of the offset level. Drive performances based on this flux estimator decreasing for the frequencies less than 2-3 times ω_c, while operation is practically impossible for the frequencies closed to zero. Results that will be presented in the next chapter correspond to the cut-off frequency of 3Hz for this estimator.

Algorithm 2: Current model flux estim. in closed loop

Estimator based on the current machine model can be presented with block diagram shown in Fig. 2.

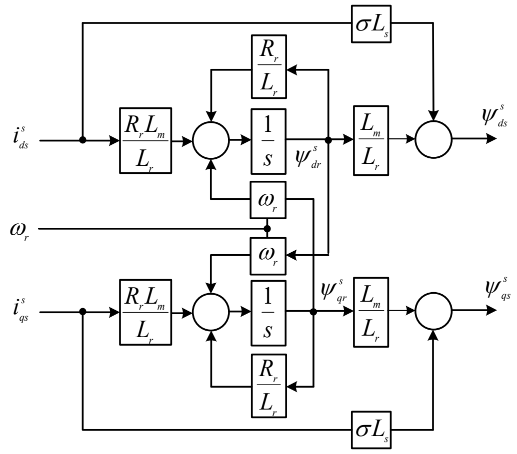

Fig. 2. Block diagram of current model-based estimator

where: ω_r - rotor speed, R_r - rotor resistance.

This flux estimator contrary to the voltage model-based estimator has estimated quantity in the close loop and it is less sensitive to DC component in integrated signal. This characteristic provides very good estimation results at operation frequencies closed to zero. Accuracy of this estimator mostly depend on the machine parameters, particularly on mutual inductivity L_m and rotor resistance R_r. For instance, at machine parameter mismatch by 50% the angular error of estimated flux will be 10° max [10]. This error grows with rise of the operation frequencies which makes this kind of flux estimator relatively bad choice for implementation in high speed electric drives.

Algorithm 3: Voltage model flux estim. in closed loop

Elimination of DC component in integrated signal with pure integrator can be provided by injection corresponding offset before the integrator. Holtz in [6] use simple estimator with pure integrator thereby retaining high bandwidth of the estimator and avoiding filter caused disadvantages. By adding appropriate DC offset u_{offset} to the EMF signal, before integration, a circle trajectory of estimated flux can be obtained without saturation. The added voltage u_{offset} is proportional to difference between referent ψ^{ref}_{dqs} and estimated flux ψ_{dqs} and provides elimination of DC component from estimated flux ψ^s_{dqs}. Block diagram of the voltage model estimator with described closed loop is shown in Fig. 3.

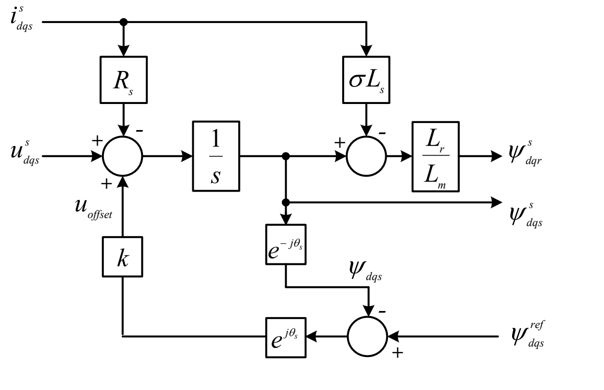

Fig. 3. Voltage model-based estimator with closed loop

where: θ_s – angle of synchronous coordinated system, k – coefficient defining offset level compensation.

For the experimental purposes in this paper this gain value is set k=15.

Algorithm 4: Volt.-current based estim. in closed loop

This estimator, in literature also known as "Gopinath style" estimator [9], provides high drive performances and in comparison to other estimation techniques represent optimal flux estimation solution where machine parameter mismatch exist. Moreover, it ensures good quality of flux estimation at wide speed range (including zero speed) without significant impact on estimator dynamics which represents very important characteristic of electric drives designed for wide speed range. Flux estimation here is based on comparison of rotor flux obtained from current machine model with rotor flux obtained from voltage machine model. Block diagram is shown in Fig. 4.

Current model part of the estimator is realised in rotor coordinate system. Proportional K_p and integral K_i gain of the regulator between current and voltage model define frequency range of transition process form current model which is dominant at low speed to the voltage model which is dominant at high speed [11], [3]. Frequency response analysis (FRF – *frequency response function*) of estimated machine flux given in [9] shows overview of estimated flux amplitude and phase dependence on machine parameters variation [10], [11]. It has been shown good robustness of the estimator on variation of the machine parameters. For experimentation purposes and results shown in next chapter, gain vales for proportion and integral gain of the regulator are tuned as follows K_p=20, K_i=10.

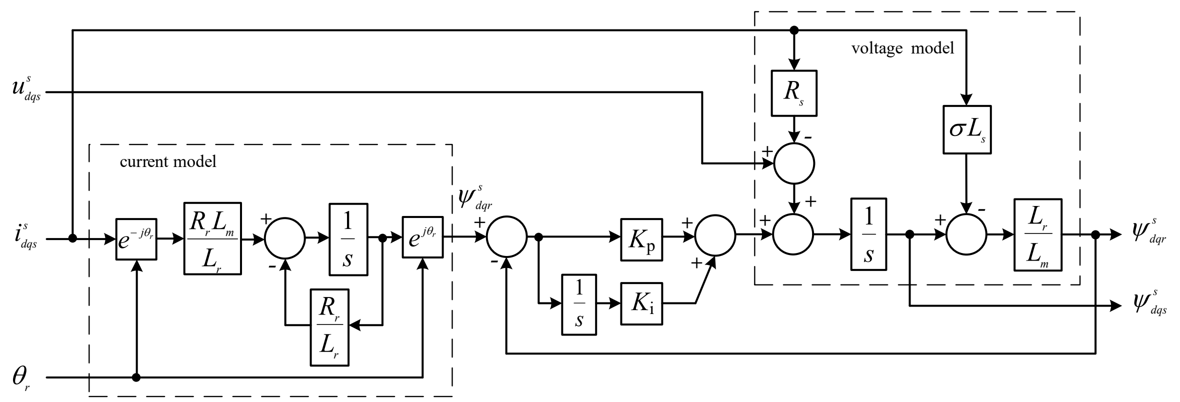

Fig. 4. Voltage-current machine model-based estimator

EXPERIMENTAL COMPARISON OF 4 FLUX ESTIMATION TECHNIQUES WITH FOC CONTROLLED IM

Experimental results comparison of 4 previously described flux estimators with flux estimator implemented in IMVC (*Induction Motor Vector Control*) application [12] (based on FOC) is show in this chapter. Rotor field orientation in the IMVC application is determined knowing rotor speed and calculated slip according to (1) while estimated torque is determined by (2). Control algorithm with flux estimators is implemented in DSP TMS320F2812 fixed point processor running at 150MHz (6.67ns). The experiment is performed with unloaded induction motor SIEBER 0.4kW (motor parameters given in the appendix). PWM switching frequency is set to 20kHz (50µs). Control algorithm sampling time is set to T_s=100µs while measured values on Fig.5-Fig.10 are recorded with frequency of 1kHz (1ms).

$$\Delta\theta_{IMVC} = \Delta\theta_r + \frac{1}{T_r}\frac{i_{qs}}{i_{ds}} \cdot T_s \tag{1}$$

$$T_e = \frac{3}{2} p \frac{L_m}{L_r}\left(\psi_{dr} i_{qs} - \psi_{qr} i_{ds}\right), \tag{2}$$

where: θ_{IMVC} - rotor field position in reference to d-axis, θ_r - rotor position, $T_r = \frac{L_r}{R_r}$ - rotor time constant, T_e - estimated torque, p - number of pole pairs.

Fig. 5 shows estimated rotor fluxes (alpha and beta components) together with their circle trajectories in dq coordinate system. Top part of Fig.5 refers to estimated rotor flux by algorithm 1 without and with HPF filter and consequently are shown results for obtained by algorithms 2, 3 and 4 respectively.

Fig. 5a shows that algorithm 1 without a HPF filter exhibits relatively high DC flux component. Algorithm 1 with HPF filter eliminate DC component form estimated flux but introduce a large phase delay deteriorating quality of the estimated flux at low speed. This is why cut-off filter frequency should be carefully determined. Results obtained with Algorithm 2 exhibits no DC component but flux amplitude variation can be noticed at circle trajectory graph. Algorithm 3 based on voltage model eliminate DC component after some time bringing back the centre of circle trajectory back to the origin. However, Algorithm 3 at the beginning gives unreliable results since big difference between reference and estimated flux exists. Algorithm 4 gives results with circle trajectory with centre at the origin of the coordinate system with lowest variation of estimated flux amplitude comparing it with previous 3 algorithms.

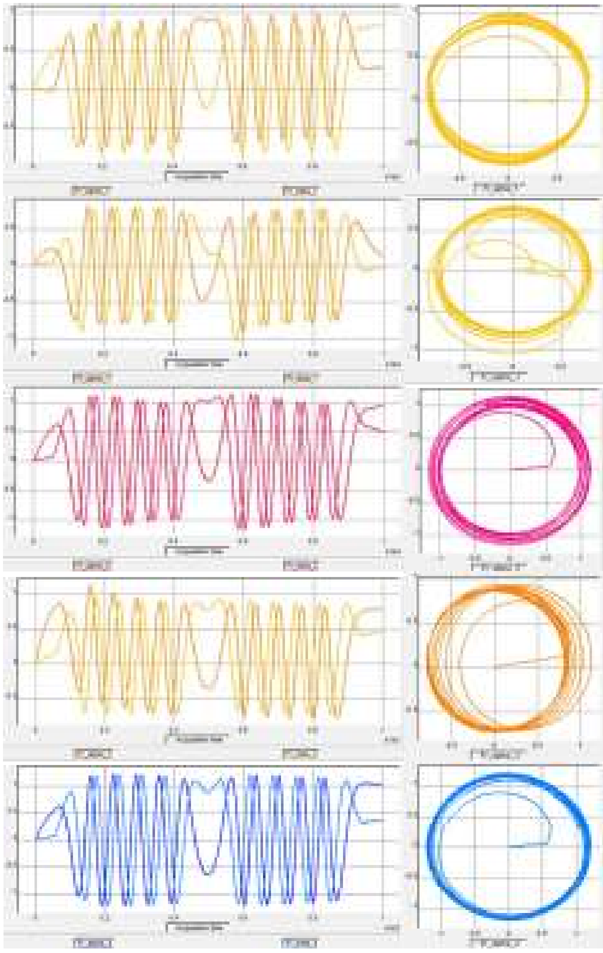

Fig. 5. Estimated rotor fluxes: algorithm 1, algorithm 1 with HPF filter, algorithm 2, algorithm 3 and algorithm 4 respectively from top to bottom

Comparison overview of estimated rotor flux position (angle) for all 4 analysed estimation algorithms in reference to the rotor flux position obtained with IMVC application (green line) is shown in Fig. 6.

Results presented in Fig. 6 confirms previously drawn conclusions about poor estimation results with algorithm 1 at low speed. It is important to notice that algorithm 2 gets larger flux position delays with rise of the motor speed. Flux angle estimated with algorithm 4 matches to a flux angle estimated with IMVC application to a great extent at low speed, while at high speed leads with small positive angle. This effect will be analysed in more detail later.

It is obvious that high estimation errors by algorithms 1 and 3 will affect estimated torque and significantly deteriorate drive performances at low speed. This is why only algorithms 2 and 4 will be further analysed in the rest of the paper. Results of estimated torque obtained by (2) with algorithms 2 and 4 as well with algorithm IMVC are presented in Fig. 7.

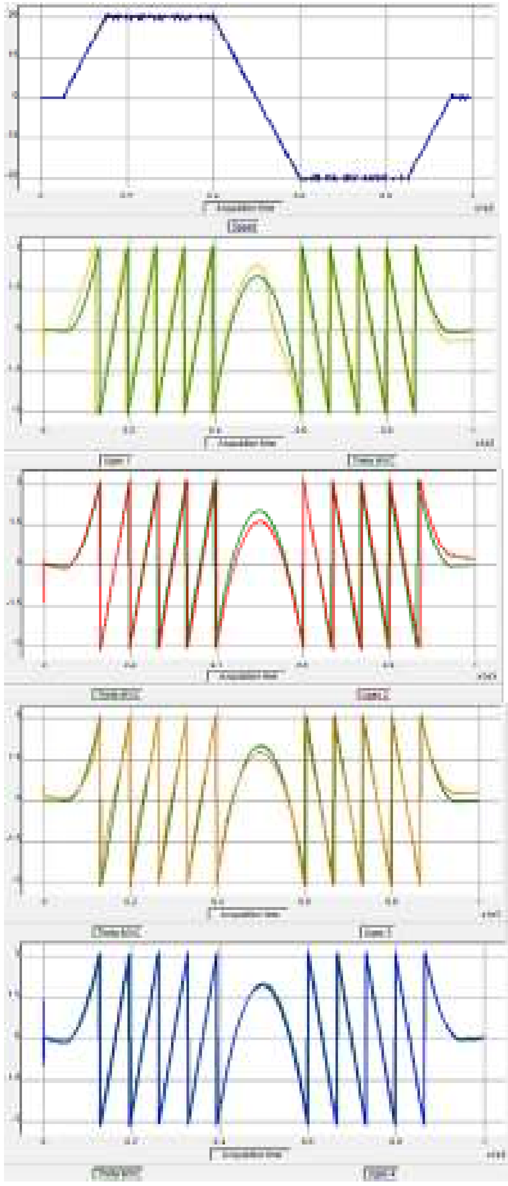

Fig. 6. Motor speed and estimated angles of rotor fluxes with algorithms from 1 to 4 respectively for top to bottom.

Fig. 7 shows that estimated torque with algorithm 2 doesn't match to speed profile. This non-match is expected having in mind estimated flux delay at higher speed with algorithm 2. Estimated torque with algorithm 4 matches to the speed profile and slightly vary from estimated torque with IMVC algorithm. It should be noted that present high torque ripple at Fig.7 originates from small encoder resolution (only 500 pulses per revolution) where measured speed ripple has a direct impact on the estimated torque through I_q current regulation loop.

In order to compare in more detail quality of estimated torque with algorithms 4 and IMVC algorithm the following experiment is performed. IMVC application is modified to allow control of the stator current in *q*-axes (I_q) by cyclic change between 0,3A; 0A; -0,3A; while I_d=0,94A=const. These stator current I_q values correspond to the torque reference of 0,48Nm, 0Nm and -0,48Nm respectively. Speed response, estimated motor torque and rotor flux angles are analysed having in mind set torque reference with IMVC application. The results are shown in Fig. 8.

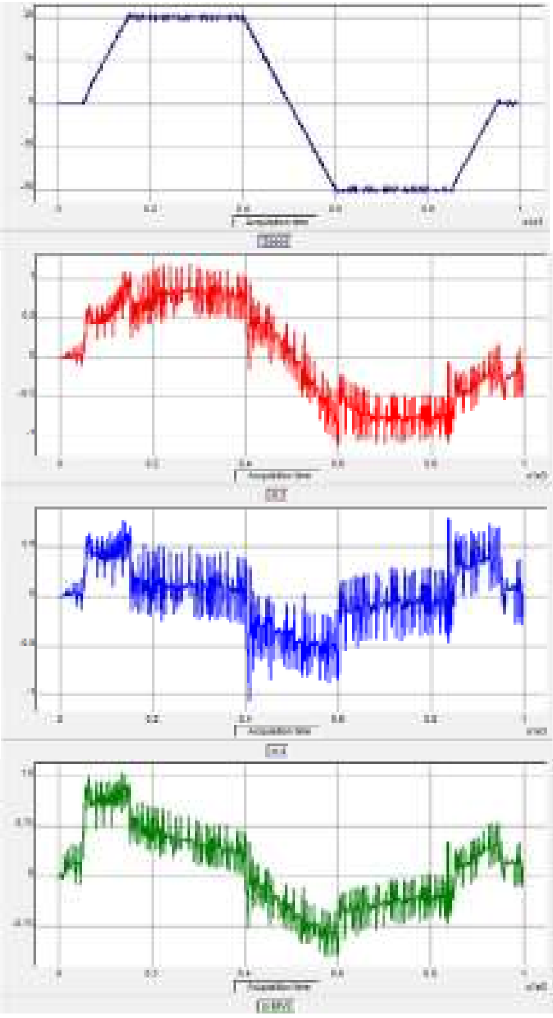

Fig. 7. Regulated speed profile and estimated torque with algorithm 2, algorithm 4 and with IMVC application respectively

Fig. 8 shows speed response for given cyclic torque reference with IVMC application (green line) and comparison with the results of estimated torque and rotor angle obtained with algorithm 4 (blue line). It can be noticed that small angle error between estimated rotor fluxes with algorithms 4 and IMVC existing especially at low speed. Consequently, significant mismatch of estimated torque between these two algorithms is present. Since induction motor doesn't have possibility to implement flux sensors inside its magnetic core, quality of estimated flux and torque, in this case, must be obtained by analysing torque and speed response of the motor. Namely, it is clear that during the constant torque reference the motor doesn't exhibits constant acceleration. At the torque reference of 0Nm (around 0.5s) the motor has deceleration which is too high to be consequence of shaft friction torque. If we neglect friction losses the motor should keep the speed constant or slowly decelerate in presence of small friction losses. Moreover, by analysing the overall motor speed profile (acceleration and deceleration) it can be concluded that speed response corresponds more to the torque estimated with algorithm 4 than in case with referent torque set by IMVC. This is particularly obvious during the zero-torque reference.

By comparing rotor flux angles, it can be seen that rotor flux estimated with algorithm 4 leading the rotor flux estimated with IMVC application. Here should be emphasized that during the speed direction change over, at one moment with speed close to zero, an overlap of two estimated rotor flux happens. In that moment both estimated torques are the same as well. Zoomed view, shows that torque and flux overlap happen at *t*=370ms while change of motor speed direction happens at *t*=405ms. In other cases, bigger difference between estimated rotor fluxes corresponds to the bigger differences in estimated torques of these two algorithms.

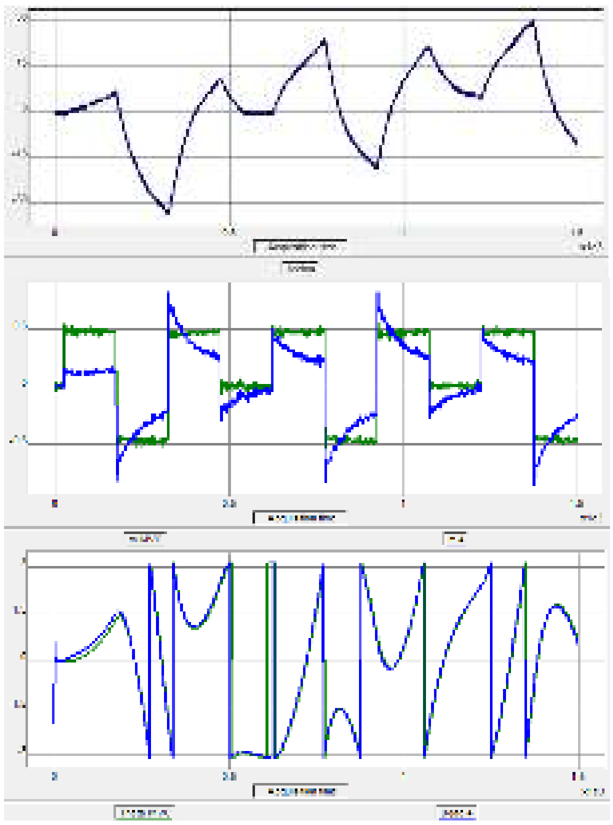

Fig. 8. Speed response on cyclic torque reference change set by IMVC application and comparison of estimated torque and rotor flux angles obtained with algorithm 4 and IMVC

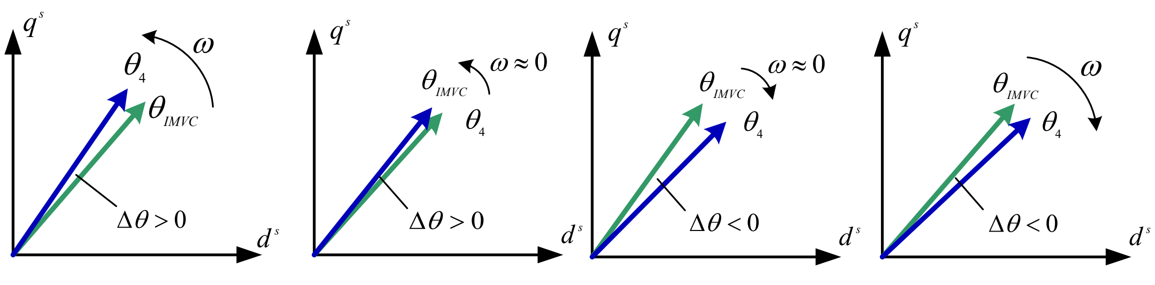

Fig. 9. Graphical representation of rotor flux positions during the speed direction change

Fig. 9 describes inert character of estimated flux by IMVC application during speed direction change in comparison to the rotor flux estimated with algorithm 4. Namely, just before speed direction change ($\omega \approx 0$), rotor flux obtained by algorithm 4 slows down and change the direction of rotation before the rotor flux estimated with IMVC application do. Later, at higher speed IMVC rotor flux reaches rotor flux estimated with algorithm 4 following it with smaller phase error. Depending on the requested machine dynamic this effect is more or less emphasized.

All previous drawn conclusions point out that algorithm 4 provides higher quality of estimated machine flux and consequently torque comparing it to the built-in IVMC application. IMVC estimation flux algorithm its obviously prone to the influence of the machine rotor time constant variation T_r (2). Better results obtained with algorithm 4 confirm smaller estimation sensitivity to machine parameter variation and mismatch over the wide speed range.

CONCULUSION

One of the most important demands of high-performance electric drives is accurate information about the machine flux. Machine torque estimation directly depends on the quality of estimated flux which further defines drives dynamic performances. Scientific literature provides a vast of flux estimation techniques with more or less estimation accuracy. Some flux estimators have better characteristic at low and other at high machine speed. In this paper characteristics of four mostly used flux estimation algorithms are analysed and compared. Estimation results are experimentally confirmed and compared with built in motor control IMVC algorithm based on conventional field-oriented control. Responses of motor speed, rotor flux angles, circle diagrams and estimated torques are compared in time domain. Particularly estimation quality of algorithm that combine voltage and current machine model is analysed and compared to the estimation algorithm of IMVC application. It has been shown that algorithm 4 gives the high-fidelity estimation results comparing it to other analysed estimation techniques.

APPENDIX

Experimental results are obtained with Technosoft DSP motion control platform MSK2812 [15] and induction motor SIEBER with parameters given in Table I.

Table I: *Motor parameters SIEBER LS71*

U_n [V]	400	R_s [Ω]	23,6
I_n [A]	0,95	R_r [Ω]	17,46
P_n [W]	370	L_m [H]	1,15
n_n [min^{-1}]	2860	L_s [H]	1,188
p [pole p.]	2	L_r [H]	1,188

ACKNOWLEDGEMENT

The authors want to thank the Ministry of Education, Science and Technological Development of Republic of Serbia for the support on the project TR33016

REFERENCE

[1] West N. T., Lorenz R. D., Implementation and Evaluation of a Stator and Rotor Flux Linkage-Based Dead-Beat, Direct Torque Control of Induction Machines at the Operational Voltage Limits, in 2007 IEEE Industry Applications Annual Meeting, 2007, no. 3, pp. 690–695.

[2] Betin F. et al., Trends in electrical machines control: Samples for classical, sensorless, and fault-tolerant techniques, IEEE Ind. Electron. Mag., vol. 8, no. 2, pp. 43–55, 2014.

[3] Silveira A. W. F., Andrade D. A., Bissochi C. A., Tavares T. S., Gomes L. C. S, A Comparative Study Between Tree Philosophies of Stator Flux Estimation for Induction Motor Drive, 2007 IEEE Int. Electr. Mach. Drives Conf., vol. 2, no. 1, pp. 1171–1176, May 2007.

[4] Mihalache L., A flux estimator for induction motor drives based on digital EMF integration with pre- and post- high pass filtering, in Applied Power Electronics Conference and Exposition, 2005. APEC 2005. Twentieth Annual IEEE, 2005, vol. 2, pp. 713–718.

[5] Shin M., Hyun D., Cho S., Choe S., An Improved Stator Flux Estimation for Speed Sensorless Stator Flux Orientation Control of Induction Motors, IEEE Trans. Power Electron., vol. 15, no. 2, pp. 312–318, 2000.

[6] Holtz J., Quan J., Sensorless Vector Control of Induction Motors at Very Low Speed using a Nonlinear Inverter Model and Parameter Identification, IEEE Trans. Ind. Appl., vol. 00, no. C, pp. 26614–26621, 2001.

[7] Langovsky N., Kankam D., Non-linear Flux Observer with On-line Parameter Tuning for Wide Speed Operation of Induction Machines, in Industry Applications Conference, 1995. Thirtieth IAS Annual Meeting, IAS '95., Conference Record of the 1995 IEEE, 1995, pp. 144–151.

[8] Telford D., Dunnigan M. W., Williams B. W., Online identification of induction machine electrical parameters for vector control loop tuning, IEEE Trans. Ind. Electron., vol. 50, no. 2, pp. 253–261, Apr. 2003.

[9] Jansen P. L., Lorenz R. D., A Physically Insightful Approach to the Design and Accuracy Assessment of Flux Observers for Field Oriented Induction Machine Drives, IEEE Trans. Ind. Appl., vol. 30, no. 1, pp. 101–110, 1994.

[10] West N. T., Lorenz R. D., Digital Implementation of Both a Stator and Rotor Flux Linkage Observer and Stator Current Observer, 2007 IEEE Ind. Appl. Annu. Meet., no. 5, pp. 1001–1007, Sep. 2007.

[11] Heinbokel B. E., Lorenz R. D., Robustness Evaluation of Deadbeat, Direct Torque and Flux Control for Induction Machine Drives Induction Machine Model and DB-DTFC, in EPE '09. 13th European Conference on Power Electronics and Applications, 2009, 2009, pp. 1–10.

[12] "DMCode-S(IM) for MSK2812 User Manual," 2007.

[13] Rosić M., Bjekić M., Božić M., Modelovanje Direktne Kontrole Momenta Asinhronog Motora sa diskretnim naponskim vektorima u Simulinku, in Zbornik radova 56. Konferencije za ETRAN, Zlatibor, Jun 11-14, 2012, 2012, p. EE2.3. 1-4

[14] Rosić M., Jeftenić B., Bebić M., Analiza mogućnosti smanjenja ripla momenta kod DTC sa diskretnim naponskim vektorima, in Zbornik 57. konferencije ETRAN, Zlatibor, 3-6. juna 2013, 2013, p. EE2.1. 1-6.

[15] "Technosoft Web page (MSK2812)." [Online]. Available: http://www.technosoftmotion.com/en/tools/professional-kits-with-apps/induction-motor-control-kits