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Experimental analysis of the sensorless traction drive system with DTC-SVM algorithm and MRAS^{CC} estimator

***Abstract**. In the paper the sensorless DTC-SVM induction motor drive system for tram application is described. For the rotor speed, electromagnetic torque and stator flux vector reconstruction the MRAS^{CC} estimator was applied. This estimator is less sensitive to the motor parameter variation than other observers and is stable in the wide range of the speed reference changes as well as it is simple in practical implementation. Experimental tests, typical for traction applications, were performed for 50kW induction motor drive in the whole speed and torque ranges.*

***Streszczenie.** W pracy przedstawiono analizę bezczujnikowego układu wektorowego sterowania silnikiem indukcyjnym z wykorzystaniem metody DTC-SVM dla trakcji miejskiej. Do estymacji strumienia stojana, momentu elektromagnetycznego i prędkości kątowej wykorzystano estymator MRAS^{CC}, charakteryzujący się zwiększoną odpornością na zmiany parametrów schematu zastępczego silnika indukcyjnego oraz stabilnością w szerokim zakresie zmian prędkości kątowej wirnika i prostotą realizacji sprzętowej. Wykonano obszerne badania eksperymentalne na stanowisku laboratoryjnym z silnikiem indukcyjnym o mocy 50kW w całym zakresie zmian prędkości i momentu obciążenia, typowe dla napędów trakcyjnych. (**Analiza bezczujnikowego układu wektorowego sterowania silnikiem indukcyjnym z wykorzystaniem metody DTC-SVM**)*

Keywords: induction motor, sensorless drive, speed estimation, MRAS estimator, traction drive
Słowa kluczowe: silnik indukcyjny, napęd bezczujnikowy, estymacja prędkości, estymator MRAS, napęd trakcyjny

Introduction

Recently the AC motors are more and more popular in the industrial drives, because of their robust construction and relatively low manufacturing cost (especially in a case of induction motor drives), practically maintenance-free, and at least well-matured vector control methods, which assure as good dynamical performance as in the case of DC motor drives [1]-[4]. So, these control ideas have been introduced in traction drives also, like drives of trams, trolleybuses, or metro train sets, connected with higher efficiency and reliability with simultaneous reduction of the drives' weight and size [6]-[8]. The induction motor (IM) or permanent magnet synchronous motor (PMSM) drives are used nowadays in such applications [7], [8].

Control methods, used in the traction drives systems, mainly Field Oriented Control (FOC) or Direct Torque Control (DTC), require information about state variables of the motor, especially stator or rotor flux and electromagnetic torque [1], [4], [5], [10], [11], thus fast digital signal processors (DSP) have to be applied for practical implementation [9].

To obtain the proper reconstruction of the internal electromagnetic variables of the IM, the speed information is required. Moreover the information about the rotor speed must be used in the field weakening algorithm of the traction drive control structure [7], [8] as well as in the diagnostic process [11].

Information about the rotor speed is necessary at zero or low speed operation, to realize properly the electrical braking [3]. 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 [12]. In traction drive systems without speed control loop, information about the rotor speed must be used in the field weakening algorithm [7], [8] and in the diagnostic process, as the drive reliability and safety are one of the key features of the traction vehicles. The temporary sensorless drive operation under emergency conditions (broken feedback from rotor position sensor) is another demand for the smart traction drive control.

The main goal of this paper is to present the experimental sensorless traction drive system with speed and flux estimator based on the current-based Model Reference Adaptive System (MRAS^{CC}) [5], [12]. Dynamical properties of the sensorless 50kW traction drive are investigated and examined under experimental test in the whole speed range, including field weakening and low speed regions.

Sensorless control structure

One of the most popular control drive algorithm applied in the modern traction drive systems is based on the Direct Torque Control technique with Space Vector Modulation – DTC-SVM [1], [2]. The general scheme of this control structure is presented in the Fig. 1.

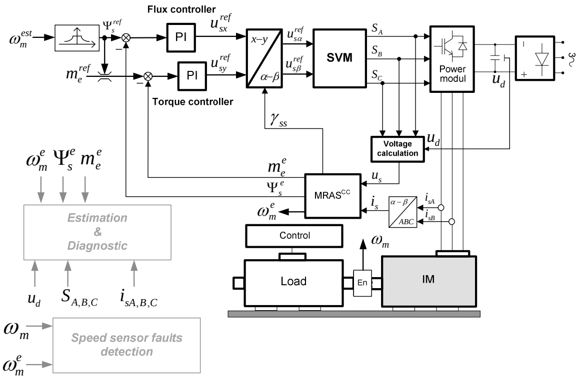

Fig. 1. Sensorless DTC-SVM with MRAS type estimator

In the DTC-SVM structure, the electromagnetic torque and stator flux vector magnitude are controlled by PI controllers in the synchronous reference frame. The essential stator flux angle information, necessary for the coordinate transformation, is obtained from the speed and flux observer. 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 speed and flux estimator MRAS^{CC} [5] applied in the analyzed control structure is based directly on the IM mathematical model [4].

This estimator is based on two well-known flux simulators [1], [4] – voltage model and current model of the rotor flux. They are rearranged to obtain the stator current estimator [5]. Rotor flux is estimated by the current model.

The stator current estimator used in the MRAS^{CC} is obtained by the equation:

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

The rotor flux is calculated from the equation:

$$\frac{d}{dt}\mathbf{\Psi}_r^i = \left[\frac{r_r}{x_r}(x_m\mathbf{i}_s - \mathbf{\Psi}_r^i) + j\omega_m^e\mathbf{\Psi}_r^i\right]\frac{1}{T_N} \tag{2}$$

Both stator current model (1) and rotor flux model (2) are adjusted by the estimated rotor speed [3], [5]:

$$\omega_m^e = K_P\left(e_{i_{s\alpha}}\Psi_{r\beta}^i - e_{i_{s\beta}}\Psi_{r\alpha}^i\right) + K_I\int\left(e_{i_{s\alpha}}\Psi_{r\beta}^i - e_{i_{s\beta}}\Psi_{r\alpha}^i\right)dt \tag{3}$$

where: $e_{i_{s\alpha,\beta}} = i_{s\alpha,\beta} - i_{s\alpha,\beta}^e$

The MRAS^{CC} estimator stability and sensitivity analysis were presented in detail in [5]. The general scheme of the MRAS^{CC} estimator is presented in Fig. 2.

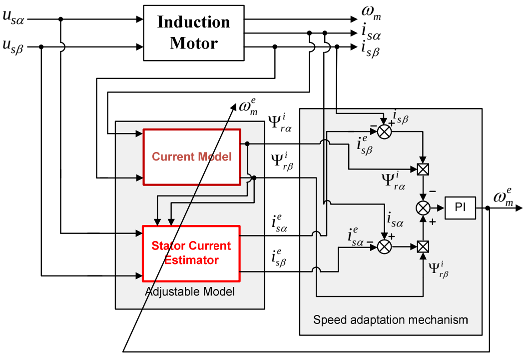

Fig. 2. Block diagram of the MRAS^{CC} estimator

Stator flux vector, required in the flux control loop of the DTC-SVM structure, can be calculated using the estimated rotor flux and the measured stator current vectors:

$$\mathbf{\Psi}_s^e = \frac{x_m}{x_r}\mathbf{\Psi}_r^e + x_s\sigma\mathbf{i}_s \tag{4}$$

The main advantage of those estimators is low sensitivity to the motor parameter changes [5], [12].

Experimental tests

In this section the chosen experimental results of the sensorless traction drive system with 50kW induction motor and MRAS^{CC} estimator are presented. DTC-SVM algorithm without speed control loop was applied to the torque control. Described estimation and control algorithms were tested using specially developed laboratory set-up. Control algorithms have been implemented in a control computer that is based on a Power PC 750GX and TMS320F240 DSP of the DS1103 board.

The general scheme and photo of the laboratory set-up is presented in the Fig. 3.

A DSP control board is installed in the extension box connected with the PC using fiber optic, which includes multi-channels of ADC, DAC, PIO and encoder interface circuits. Digital filter and frequency multiplied by four circuits are built into the encoder interface circuits to increase the precision of the speed and the position feedback signals and coordinate transformations.

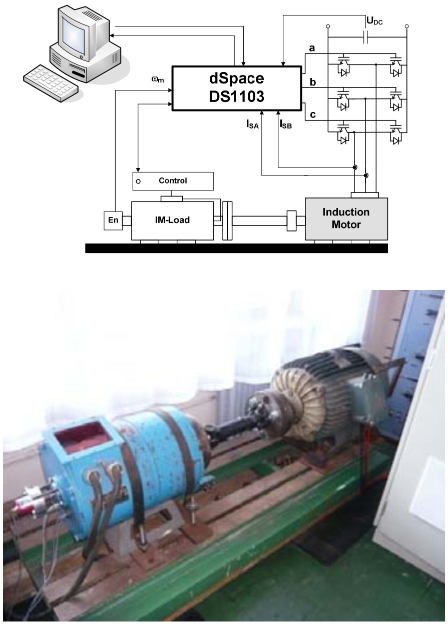

Fig. 3. Scheme and photo of the 50kW laboratory set-up

The sampling rate is chosen as 100 μs and hence, the carrier frequency of the PWM inverter is 3 kHz. The control interval of the torque control loop and estimation algorithm are connected with the sampling time.

Fig. 4 – Fig. 9 chosen experimental results of the sensorless DTC drive without speed control loop and with MRAS^{CC} speed estimator 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 estimator.

First, in the Fig. 4 transients of the sensorless DTC-SVM with MRAS^{CC} estimator for cyclic torque reverse operation are presented.

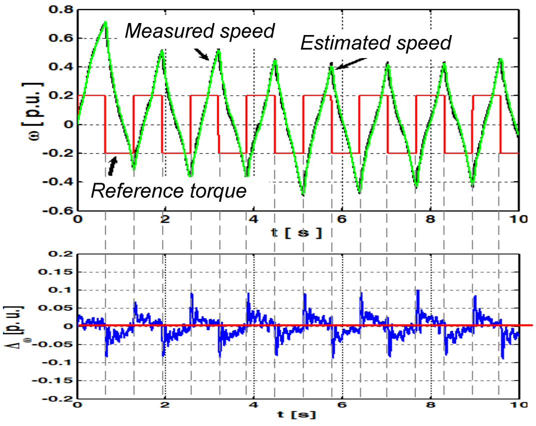

Fig. 4. Experimental transients of the DTC-SVM with MRAS^{CC} for $m_{ref} = \pm 0.2 m_{LN}$

During this fast cyclic torque reverse operation the speed changes can be observed. When the torque is positive the speed increases, when the torque is negative – rotor speed decreases. What is important, the estimated speed tracks its measured value and the s[eedestimation error is close to zero.

The sensorless DTC–SVM works also properly for the start up operation with load torque ($m \approx 3m_N$) – Fig. 5. When the developed electromagnetic torque is smaller than the load torque, the drive is stopped. When the reference and electromagnetic torques are bigger than the load torque, the rotor speed increases and the drive is started. After reduction of the reference value the speed is stabilized (electromagnetic torque is exactly the same like the load torque).

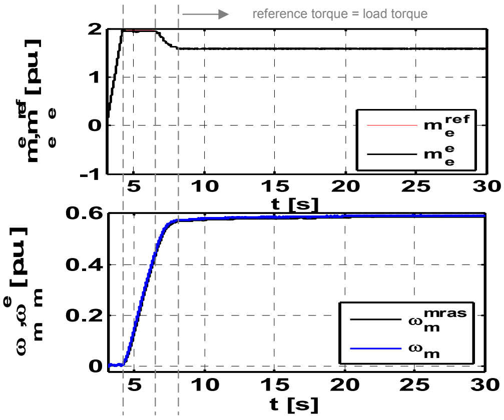

Fig. 5. Start up operation of the sensorless DTC-SVM with load torque

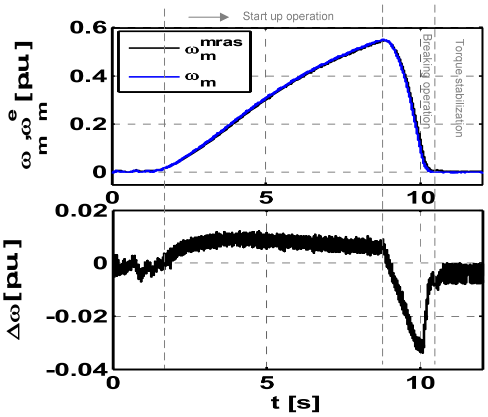

Fig. 6. Start up and breaking operation of the DTC-SVM with load torque

In Fig. 6 experimental results for start up and breaking operation with load torque is presented. In both cases the estimated speed is almost the same like the measured value, except of fast braking transient. Dynamical properties of the drive are very good.

Those processes are the most important from the safety point of view. Any oscillations and abnormal situations are not allowed. It is visible that the estimated speed tracks its measured value, and the torque is controlled perfectly in the whole speed range. Breaking operation is very fast. Drive is stopped with the full load torque from ~1000 rpm in 2 s.

In the tram application the maximum speed (70km/h) is much bigger than the nominal speed of the electrical drive (30km/h). It means, that in the control structure the field weakening algorithm must be applied. In the Fig. 7 the start up operation to the 200% of the nonimal speed is demonstrated. Drive is working in the field weakening region from 2,5s. Dynamical properties are good, the electromegnetic torque response to its reference value is very fast, the estimated speed is equal with the measured speed.

From the speed estimation quality point of view the most important task is the operation in the extremely low speed region. So in the Fig. 8 the traction drive operation with small speed and with full load torque is demonstrated. It is clearly visible that the estimated speed is equal with the measured value. On the measured speed the oscillations and small impulses are visible. They are connected with the encoder resolution, typical for tram application – 100imp/rev.

The safety is a priority in the automotive application. Thus completely sensorless application, as the main control structure, is not allowed. The speed sensors must be applied and used in the control structure.

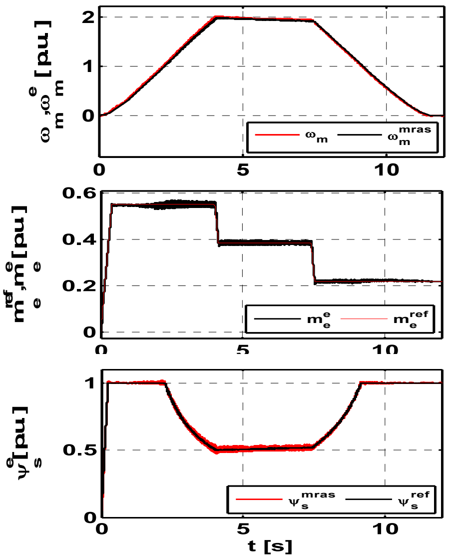

Fig. 7. Eksperimental transients of the sensorless DTC-SVM with MRAS^{CC} estimator for start up and breaking operation ($\omega_m = 2\omega_{mN}$, $m_o = 0.75m_{oN}$)

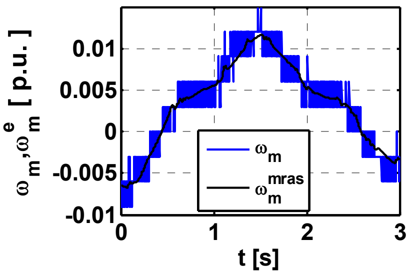

Fig. 8. Low speed operation of the sensorless DTC-SVM traction drive

The estimation algorithm of the rotor speed should work as a redundant device in the drive system. When the speed sensor is disabled (or broken), the drive must be switched to the sensorless operation. This situation cannot be visible for the users. In the following Fig. 9 breaking operation from 150% of the nominal speed to zero speed is demonstrated. At the beginning of this process, in the field weakening algorithm and in the flux estimator the measured speed is used. At t=3s, the speed sensor is faulted and the drive system is switched to the speed estimated value, obtained form MRAS^{CC} estimator. From this time in the field weakening algorithm and in the flux estimator the estimated speed is used. When the diagnostics system start the switching operations, the small impulse on the electromagnetic torque and stator currents is visible. But this disturbance does not cause instability or even change in the smooth speed transient. Measured speed is equal with the estimated one. It can be said that the proposed control structure is a fault tolerant system, which work perfectly under the speed sensor damage.

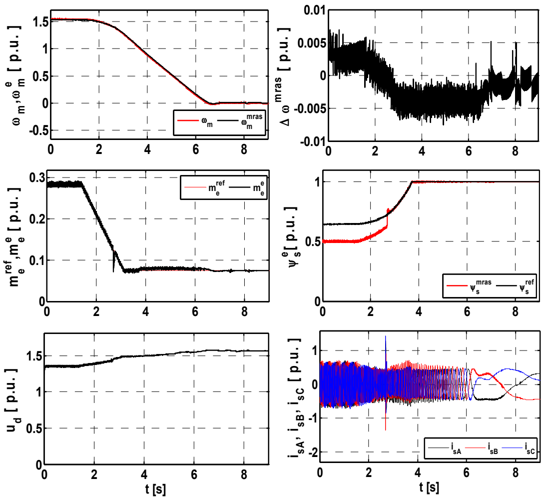

Fig. 9. Experimental transients of the sensorless DTC-SVM with MRAS^{CC} estimator (speed sensor fault at t=3s) for breaking operation from $\omega_m = 1.5\omega_{mN}$, $m_o = 0.5m_{oN}$

Conclusion

In the paper the sensorless traction drive system is demonstrated. To the proper torque control the DTC-SVM algorithm is used. To the speed and flux reconstruction the MRAS^{CC} estimator is applied.

Sensorless DTC-SVM drive works correctly in the whole range of the reference torque changes. Stator flux and torque are estimated and used directly in the control structure. Estimated speed is used in the field-weakening and in diagnostic algorithms.

Analysed speed estimator works stable as well for low speeds as for the field-weakening region and can be applied in the traction drive system without information about speed from any sensor. Analysed estimation system can be applied in the fault tolerant system. Proposed solutions can be implemented in the simple microprocessor systems.

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REFERENCES

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

[2] J.W. Finch, and D. Giaouris, “Controlled AC electrical drives," *IEEE Trans. Industrial Electronics,* vol. 55, no. 2, pp. 481-491, Feb. 2008.

[3] 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. Ind. Applications,* vol. 38, no. 4, pp. 1081-1086, 2002.

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

[5] 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

[6] C. Colinh, M. Pietrzak-Dawid, “Sensorless traction system with low voltage high current induction machine for indoor vehicle”, Proc. of the IEEE/PEDS’2005 Confer., pp.50-55, 2005

[7] 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

[8] 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

[9] T. Sukegawa, K. Kamiyama, T. Matsui, T. Okuyama, “Fully digital, vector-controlled PWM VSI-fed AC drives with an inverter dead-time compensation strategy*”, Conf. Rec, of the 1988 IEEE Industry Appl. Soc. Annual Meeting,* vol.1, 1988, , pp. 463-469, 1988.

[10] E. Levi*,* M. Sokola, S. N. Vukosavic, “A Method for Magnetizing Curve Identification in Rotor Flux Oriented Induction Machines”, *IEEE Trans. Energy Conversion*, vol. 15, no. 2, pp. 157-162, 2000.

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

[12] M. Dybkowski, T. Orlowska-Kowalska, G. Tarchała, “Sensorless Direct Torque Control of the Induction Motor Drive with Sliding Mode and MRAS^{CC} estimators”, *Proc. 17th Int. Conf. on Electrical Drives and Power Electronics EDPE’2011, High Tatras, Slovak Rep.*, pp.73-78, 2011

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